National Park Service
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Natural Resource Stewardship and Science

Cape Lookout National Seashore

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2017/1491

ON THE COVER
Aerial photograph of New Drum Inlet. NPS photograph by Stephen Simon (Geologic Resources Division) taken in 2012.

THIS PAGE
Photograph of remote beach on Shackleford Banks. NPS photograph by Vickie Boutwell. Available at https://www.nps.gov/calo/learn/photosmultimedia/photo_scenery.htm.

Cape Lookout National Seashore

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2017/1491

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The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Report Series is used to disseminate comprehensive information and analysis about natural resources and related topics concerning lands managed by the National Park Service. The series supports the advancement of science, informed decision-making, and the achievement of the National Park Service mission. The series also provides a forum for presenting more lengthy results that may not be accepted by publications with page limitations.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

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Executive Summary

The Geologic Resources Inventory (GRI) provides geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. The GRI is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI.

This report synthesizes discussions from a scoping meeting held in 2000 and a follow-up conference call in 2015 (Appendix A). Chapters of this report discuss the geologic setting, distinctive geologic features and processes within Cape Lookout National Seashore, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the previously completed GRI map data. Posters (in pocket) illustrate these data.

Cape Lookout National Seashore is part of the North Carolina Outer Banks, a barrier island chain within the Atlantic Coastal Plain physiographic province. Its purpose is to preserve the outstanding features and values of an intact barrier island system, where physical, geological, and ecological processes dominate. This report describes the geologic connections to the park's Fundamental Resources and Values. These include the intact barrier island system driven by coastal geologic processes, its undeveloped character, its two National Historic Districts and the lighthouse and maritime structures there, the Shackleford Banks horse herd, opportunities for scientific study and recreation in a remote setting, and aquatic and terrestrial habitats.

The park comprises three long and narrow barrier islands: North and South Core Banks, which extend to the northeast of Cape Lookout, and Shackleford Banks, which extends perpendicularly from Core Banks west of Cape Lookout. The park is bounded by the Atlantic Ocean to the east and south; by the Pamlico, Core, and Back Sounds on its landward side; by Beaufort Inlet (to the west of Shackleford Banks), and by Ocracoke Inlet (to the north of North Core Banks. The park also includes an administrative area on Harkers Island, landward of the barrier islands.

Within the park are a diversity of coastal habitats, including estuaries, mudflats, salt marshes, freshwater marshes, ponds, maritime forest, grassland, dunes, and beaches. The habitats support aquatic and terrestrial plant and animal life including federally protected species. The seashore provides nesting, resting, and feeding habitat for a diverse assemblage of birds.

The park is one of the few remaining locations on the Atlantic coast where visitors can experience a primarily undeveloped, remote barrier island environment which can only be reached by boat. The park visitors are primarily campers, anglers, and day-use beach-goers.

The Outer Banks are relatively young, geologically speaking. The underlying geologic framework of the park was constructed by repeated changes in relative sea level. This framework controls the sediments available to the modern barrier island, and the ways in which the island responds to natural and anthropogenic processes. About 5.3 million years ago, sea level was much higher and marine sediments were deposited across much of what is now the coastal plain. Beginning 2.6 million years ago, sea level rose and fell many times as glacial ice grew and receded on the continents and rivers incised the previously deposited marine strata. This created a paleotopography reflected in the estuarine geometry and bathymetry and the location of the barrier islands. These ancient river channels were then backfilled and buried by Holocene sediments during the last 10,000 years as sea level rose to its present level. As a result, the sediments underlying the modern barrier island are a complex assemblage reflecting the various depositional environments, including compact peat and mud, and unconsolidated to semi-consolidated sands, gravels, and shell beds.

Coastal processes (storms, waves, tides, sediment transport, inlet dynamics, and sea-level change) continue to shape the landforms and rework the thick sediments. Due to the reworking of these older sediments, much of the present Outer Banks is less than 3,000 years old. Storms, waves, and winds continue to shape the islands, along with anthropogenic activities such as inlet and shoreline engineering.

This report is supported by maps of the surficial geology of Cape Lookout National Seashore. The maps were developed by two different groups using distinct methodologies and resulting in unique sets of geomorphic units. None of the maps describe the geomorphology of Harkers Island. The map developed by the North Carolina Geological Survey (Coffey and Nickerson 2008a, 2008b, 2008c, 2008d) used LiDAR data, orthophotographs, color infrared photographs, wetland delineation maps, and historical shoreline data. It describes four geomorphic features: intertidal, supratidal, relict, and anthropogenic units. The maps developed by East Carolina University (Ames and Riggs 2008) are based on field surveys, historical aerial photographs, topographic LiDAR data, subsurface cores, ground-penetrating radar, and radiocarbon age data. The portion covering Shackleford Banks also incorporated new archeological data to reinterpret the geomorphological history of that island. They describe five geomorphic groups: beach, overwash-plain, polydemic, anthropic, and sound features.

Noteworthy geologic and environmental features and processes at Cape Lookout National Seashore include the following:

- **Oceanographic Conditions**. The park is a storm- and wave-dominated barrier island system. Core Banks receives triple the wave energy and has half the tidal range of Shackleford Banks. This difference is partly responsible for the differences between the two barrier zones in terms of geographic orientation and sediment supply.
- **Sediment Transport Processes**. Sediment transport is much higher along Core Banks than it is along Shackleford Banks. Waves, wind, and storm surge move sediment through the inlets and along and across the islands. Overwash is an important process in building island elevation, expanding marsh platforms, and creating and maintaining early-succession habitat. New sediment comes from three main sources in the nearshore and inner continental shelf: ancient river channels, the Cape Lookout shoal complex, and sand-rich deposits of Pleistocene sediment.
- **Inlets**. New inlets open during storms, when storm surge breaches the island from the ocean or estuarine side. Tidal currents through the inlets deposit sediment, building flood and ebb tidal deltas, which are important for the island sediment budget, marsh building, and long-term island evolution.
- **Estuaries**. Pamlico Sound provides fish nursery, foraging habitats, and seagrass beds. Core Sound is very shallow and microtidal, with winds and tides controlling water level. Back Sound has high tidal flushing around the Beaufort Inlet.
- **Estuarine Sediments**. Estuarine sediments are derived from the eroded coast, the continental shelf, and ongoing biogenic production.
- **Groundwater**. The surficial aquifer is recharged by rainfall; freshwater floats above denser salt water. Dunes protect the freshwater lens from overwash inundation in smaller storms. Freshwater ponds occur on North Core Banks and western Shackleford Banks.
- **Geologic Framework and Barrier Evolution**. The modern coastal geomorphology results from interactions among the underlying geologic framework, relative sea-level change, coastal oceanographic processes, and anthropogenic modifications.
- **Simple and Complex Barrier Island Model**. Simple barrier islands such as Core Banks are young, sediment poor, and narrow with low topography. They are particularly vulnerable to sea-level rise and anthropogenic modifications. Complex barriers such as Shackleford Banks are older, sediment rich, and wide with higher elevations, numerous beach ridges, and large dune fields.
- **Paleontological Resources**. Quaternary fossils erode out of nearshore outcrops and wash onto park beaches. Pleistocene marine shell assemblages are abundant on North Carolina beaches, and it can be difficult to differentiate between fossils and recent remains. Black-stained or orange-colored shells are typically fossils.

Geologic resource management issues identified during the GRI scoping meeting and follow-up conference call include the following:

- **Coastal Resources Management and Planning**. NPS has developed a variety of databases and guidance for managing coastal resources and planning for the impacts of climate change.

- **Coastal Erosion**. Coastal erosion along Core Banks is lowest where the island is underlain by peat from former marshes and in locations controlled by the underlying geology. The low and narrow segments of Core Banks have periods of major erosion and accretion due to overwash and the opening or closing of ephemeral inlets. Erosion threatens facilities, historic structures, and archeological resources. There is a potential for accelerated erosion on Shackleford Banks due to human activities, such as jetty installation and dredging in Beaufort Inlet. Cape Lookout is eroding on its northern flank and accreting on the southern flank. The park is stabilizing the Harkers Island shoreline.
- **Coastal Vulnerability and Sea Level Rise**. The natural barrier island environment will evolve as sea level continues to rise. Portions of the park are highly susceptible to change due to their low topography. This increases coastal erosion and the potential for overwash, inlet formation, and wetland relocation and migration. Impacts will vary along the coast, depending on the underlying geologic framework and other factors. A considerable increase in sea level may cause the barrier islands to reach a tipping point, resulting in increased landward migration and breaching, reduction in size, and possibly even submergence. Potential climate change impacts include significantly warmer temperatures and a more variable precipitation regime, which may lead to both more frequent droughts and more severe flooding and erosion.
- **Hurricane Impacts and Human Responses**. The park is frequently impacted by storm winds, waves, and surges that move sand across and off of the islands. Future climate change may alter the frequency and intensity of storms impacting the barrier islands. The park's Storm Recovery Plan incorporates sensitivity to park natural and cultural resources in all phases of storm response and recovery.
- **Inlet Modifications**. Dredging and jetties disrupt the inlet's ability to bypass sediment between islands and to exchange sediment between flood and ebb tidal deltas. Beaufort Inlet has impacted sediment transport to and from Shackleford Banks. Ocracoke Inlet is dredged periodically but is fairly stable. Core Banks has several areas where breaching and ephemeral inlets often occur.
- **Ferry Infrastructure and Use**. Three channels and associated boat basins are maintained to allow ferry access to the park and to facilitate visitation and park management.
- **Coastal Engineering and Shoreline Armoring**. State regulations prohibit the construction of hard stabilization structures without a special permit. Beach nourishment is an expensive and temporary solution that is often implemented to maintain beach width and protect beachfront development. Alternatives to protecting infrastructure in place include adapting the design or function of a structure, relocating the structure to a less vulnerable location, and letting the structure deteriorate and abandoning it in place. As of 2009, there were 15 modification projects in and adjacent to the park: 5 navigation dredging locations, 2 beach nourishment projects, and 8 erosion control structures.
- **Grazing Horses on Shackleford Banks**. The legislatively protected horses degrade estuarine biodiversity on Shackleford Banks, and may reduce the value of marshes as nursery grounds for fishes and crabs. Management of this cultural resource may have impacts to geologic resources such as dune height and stability.
- **Recreational and Watershed Land Use**. Due to its isolation from the mainland and limited development, water quality is better inside the park than surrounding areas, but it is threatened by point source and nonpoint source pollution. The park's aquatic habitat is healthy and stable overall. Off-road vehicle use on Core Banks can have a variety of ecologic and geomorphic impacts including changes in dune morphology and evolution, and biological impacts on habitats, organisms, and ecosystems. Vehicle ramps can channelize and direct storm-generated overwash flow, causing damage, or even island breaches. Constructed boardwalks may degrade dunes. Boats have scarred seagrass beds and contributed to sound side coastal erosion. Litter, marine debris, and impacts to vegetation from beach activities remain challenges in the Back Sound area of Shackleford Banks.
- **Paleontological Resource Inventory and Protection**. There are a variety of challenges to managing fossil resources in a coastal park including determination of what constitutes a fossil and educating the public about what nonfossil materials beachcombers are allowed to collect.

- **Additional Information Needs**. Efforts to manage and protect park resources would benefit from new products related to topographic change, groundwater quality, and monitoring of sediment dynamics in and around Beaufort Inlet.
- **Additional Planning Needs**. The park will benefit from continued efforts related to the Dredged Material Management Plan for Beaufort Inlet, the off-road vehicle management plan, a transportation plan, and a resources stewardship strategy. The park is also interested in developing dredging management plans for the Great Island, Long Point, and Les and Sally's docks.

Products and Acknowledgments

The NPS Geologic Resources Division partners with the Colorado State University Department of Geosciences to produce GRI products. Geologists from East Carolina University, US Geological Survey, and North Carolina Geological Survey developed the source maps and/or reviewed GRI content.

GRI Products

The GRI team undertakes three tasks for each park in the Inventory and Monitoring program: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report (this document). These products are designed and written for nongeoscientists.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to GIS data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report. The GRI team conducts no new field work in association with their products.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 204), 2006 National Park Service Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75). The "Additional References" chapter and Appendix B provide links to these and other resource management documents and information.

Additional information regarding the GRI, including contact information, is available at http://go.nps.gov/gri. The current status and projected completion dates of products are available at http://go.nps.gov/gri_status.

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Geologic Setting and Significance

This chapter describes the regional geologic setting of the recreation area and summarizes connections among geologic resources, other park resources, and park stories.

Park Setting

Cape Lookout National Seashore, herein referred to as "the park," is the southern part of a long and narrow barrier island chain known as the North Carolina Outer Banks. Much of the northern Outer Banks are managed by NPS as part of Cape Hatteras National Seashore (see Schupp 2015). The park comprises two major sections of barrier islands (plate 1, in pocket): the longer Core Banks is oriented northeast–southwest and includes Cape Lookout at its southern end, and the shorter Shackleford Banks is oriented west–east and located west of Cape Lookout. Core Banks is sectioned by ephemeral inlets, creating stretches referred to as North Core Banks (29 km [18 mi]), Middle Core Banks (6 km [4 mi]), and South Core Banks (39 km [24 mi]). Shackleford Banks is 14 km (9 mi) long. The banks are separated from each other by inlets and from the mainland by sounds. Park headquarters are located on Harkers Island, landward of the barrier islands.

Congress authorized Cape Lookout National Seashore on March 10, 1966 (PL 89-366). The park purpose, as stated in its Foundation Document, is "to preserve the outstanding natural, cultural, and recreational resources and values of a dynamic, intact, natural barrier island system, where ecological processes dominate" (NPS 2012). Fundamental Resources and Values —those determined to merit primary consideration during planning and management processes—include several related to geologic features and processes (NPS 2012):

- intact barrier island system driven by coastal geologic processes;
- the park's undeveloped character;
- the lighthouse and other structures in its two National Historic Districts;
- the Shackleford Banks horse herd;
- aquatic and terrestrial habitats and species;
- opportunities for scientific study and for remote recreation; and
- the inter-generational human connection to the banks.

The area within the boundary of the park includes both water and land. The park's boundary extends to the mean low water (MLW) line along the Atlantic Ocean, and 48 m (150 ft) beyond the MLW line on the sound side of all park islands (NPS 2011a). The NPS Regional Solicitor determined that the boundary will move with the MLW shoreline, and the NPS Lands Office should continue to update the boundary using current data (NPS 2011a). In 1974 (amending legislation 623-20, 009 as cited in Tweet et al. 2009), the area of the national seashore was 11,943 ha (28,400 acres), including the 37-ha (91-acre) administrative site on Harkers Island. In 2011, Curdts (2011) calculated 4,882 ha (12,063 ac) of water within the park's boundary.

The park preserves a diversity of coastal habitats, including estuaries, mudflats, salt marshes, freshwater marshes, ponds, maritime forests, grasslands, dunes that rise approximately 3.7 meters (12.1 ft) above mean sea level on North and South Core Banks, and about 10–13 meters (32.8–42.7 ft) on Shackleford Banks, and 91 km (56.5 mi) of ocean beach (Burkholder et al. 2017). The habitats support aquatic and terrestrial plant and animal life including federally protected species.

The park provides nesting, resting, and feeding habitat for a variety of birds including federally protected species. In 1999, the American Bird Conservancy designated Cape Lookout National Seashore as a Globally Important Bird Area in recognition of the value the park provides to bird migration, breeding, and wintering. It is also designated as a unit of the Carolinian-South Atlantic Biosphere Reserve, United Nations Educational, Scientific and Cultural Organizations (UNESCO) Man and the Biosphere Reserve Program. The park includes nesting habitat for the federally protected piping plover (*Charadrius melodus*), as well as several species protected by the state.

Four federally protected sea turtles nest at the park: the loggerhead (*Caretta caretta*), green (*Chelonia mydas*), leatherback (*Dermochelys coriacea*), and Kemp's ridley (*Lepidochelys kempii*). One other federally protected sea turtle species, the hawksbill (*Eretmochelys imbricata*), uses the surrounding waters (NPS 2012).

Table 1. Geologic time scale and summary of geologic events.

Era	Period	Epoch	MYA	North Carolina Events
Cenozoioc	Quaternary	Holocene	0.0117–present	*See bulleted list for more Quaternary information*.* Fluvial processes, erosion of Piedmont and Appalachian Mountains, sediment deposition in Coastal Plain
Cenozoioc	Quaternary	Pleistocene	2.6–0.0117	
Cenozoioc	Neogene (Tertiary)	Pliocene	5.3–2.6	Primarily during Neogene: Deposition of fossil-rich mud, sand, and phosphates
Cenozoioc	Neogene (Tertiary)	Miocene	23–5.3	
Cenozoioc	Paleogene (Tertiary)	Oligocene	34–23	Primarily during Paleogene: Limestone deposited in Coastal Plain, erosion, and weathering continued.
Cenozoioc	Paleogene (Tertiary)	Eocene	56–34	
Cenozoioc	Paleogene (Tertiary)	Paleocene	66–56	
Mesozoic	Cretaceous	Lower and Upper	145–66	During Jurassic and Cretaceous: Ongoing erosion and weathering in Piedmont and Appalachian Mountains; deposition of riverine, deltaic, and marine sediments.
Mesozoic	Jurassic	Lower, Middle, and Upper	201–145	During Jurassic and Triassic: Rift basins formed; brittle faulting, and volcanism.
Mesozoic	Triassic	Lower, Middle, and Upper	252–201	During Triassic: Breakup of Pangaea began; Atlantic Ocean opened.

The divisions of the geologic time scale are organized with the oldest at the bottom and youngest at the top. Boundary ages are in millions of years ago (MYA). Major life history and tectonic events occurring in North Carolina are included. Dates are from the International Commission on Stratigraphy (http://stratigraphy.org/index.php/ics-chart-timescale; accessed 18 July 2017).

*Detailed events for Quaternary Period at Cape Lookout National Seashore and vicinity:

- **600–100 years before present:** As many as 20 inlets opened along Outer Banks due to northeaster storms.
- **1,100 years before present:** Large portions of Outer Banks collapsed due to hurricanes
- **3,500 years before present:** Nearly continuous barrier island system formed
- **5,000 years before present:** Initial barrier islands formed near to present locations
- **9,000 years before present:** Initial flooding and sediment deposition within present estuarine river valleys.
- **21,000 years before present:** Last Glacial Maximum (LGM); global glaciation; sea level 120–130 m (394–425 ft) lower than present; coastal plain extended to continental shelf, 97 km (60 mi) seaward of present barrier
- **125,000 years before present:** Last interglacial warm period; most of Earth's glaciers melted;sea level approximately 6–8 m (20–26 ft) higher than present

Seabeach amaranth (*Amaranthus pumilus*) is a federally listed, threatened plant species that primarily occurs on Shackleford Banks and the south end of South Core Banks (NPS 2012). It grows in overwash fans, sand flats, and low dunes—the same areas selected for nesting by shorebirds such as plovers, terns, and skimmers. It is an efficient sand binder capable of creating small sand dunes.

The park is one of the few remaining locations on the Atlantic coast where visitors can experience a primarily undeveloped and remote barrier island environment,

Table 2. Summary stratigraphic column for Cape Lookout National Seashore. Table continues on next page.

Period	Epoch	Age (MYA)*	Rock/ Sediment Unit	Description	East Central Coastal Plain Hydrogeologic Unit
Quaternary	Holocene	0.01–present	Barrier island facies	Surficial sand up to 30 m (100 ft) thick. **Core Banks**: Average 10-12 m (33-39 ft) thick. Tan, fine to very coarse grained, moderately to poorly sorted, quartz sand and shell material. Horizontal laminae of heavy minerals. Overwash units with fossil mollusk assemblage. **Cape Lookout**: Fining downward sequence, horizontal beds, shoreface environment. Light-gray fine to medium grained sand and silt with sand-sized shell material. Well sorted and burrowed.	Surficial Aquifer: fresh water
Quaternary	Holocene	0.01–present	Intertidal salt marsh deposits	**Core Banks**: Dark brown, not fossiliferous, organic rich sand, silts, and clays with peat, wood, and Spartina debris.	Surficial Aquifer: fresh water
Quaternary	Holocene	0.01–present	Back-barrier estuarine deposits	3 m to 10.6 m (9.8 to 34.8 ft) below MSL**. Light to medium gray, very fine to medium, well sorted, silty sand. Thin layers of dark gray silty clay with no shell material.	Surficial Aquifer: fresh water
Quaternary	Holocene	0.01–present	Inlet fill bodies	Core Banks: Fining-upward sequence is 2.8 m to 16.8 m (9.2 to 55 ft) thick. Inlet floor (coarse shell and pebble gravel, 0.3 to 0.6 m [1-2 ft] thick), channel (light gray, medium to coarse grained, clean pebbly quartz sand and shell material, 3 m to 13.7 m [10-45 ft] thick), and inlet margin or spit platform (light gray, clean, very fine to medium grained sand, 1.5 m to 3 m [5-10 ft] thick).	Surficial Aquifer: fresh water
Quaternary	Pleistocene	0.035–0.0212	Diamond City Clay	Sharp lithologic contact at Holocene/ Pleistocene boundary is at 9 m to 22.2 m (30 to 78 ft) below MSL under Core Banks. Regressive estuary/lagoon deposits are capped by a 12,000 year-old freshwater peat layer. Alternating beds of unfossiliferous silty to sandy clay (dark gray, saturated, cohesive) and shell hash beds in a sandy clay matrix.	Surficial Aquifer: fresh water
Quaternary	Pleistocene	?–0.035	Atlantic Sand	Not present under Shackleford Banks. **Core Banks**: 14.6 m to 19.8 m (48 to-65 ft) below MSL. Tan/gray fine- to coarse-grained, well sorted, clean quartz sand. Barrier complex. Deposited during the latter part of the mid-Wisconsin transgression.	Surficial Aquifer: fresh water
Quaternary	Pleistocene	0.12–0.08	Core Creek Sand	**Core Banks**: Down to 30 m (98 ft). Silty, clayey, fossiliferous, fine- to coarse-grained quartz sand deposited regionally as a terrace formation when sea level rose. Nearshore marine deposits.	Surficial Aquifer: fresh water
Quaternary	Pleistocene	0.2	Canepatch Formation	Under Shackleford Banks. Variety of coastal to marine settings.	Surficial Aquifer: fresh water

Table 2, continued. Summary stratigraphic column for Cape Lookout National Seashore.

Period	Epoch	Age (MYA)*	Rock/ Sediment Unit	Description	East Central Coastal Plain Hydrogeologic Unit
Quaternary	Pleistocene	1.0	James City Formation	Under Portsmouth Banks at a depth of 27.7 to 28.7 m (90.9 to 94.2 ft) and 32.9 to 34.4 m (107.9 to 112.9 ft). Shelly sand and clay unit. It may record a marine transgression. Bay to open shallow shelf, with a subtropical to temperate climate.	Surficial Aquifer: fresh water
Quaternary	Pleistocene	Lower Quaternary	Yorktown Formation	Yorktown confining unit. Clay and silt.	Yorktown Confining Unit
Neogene (Tertiary)	Pliocene	5.3–2.6	Yorktown Formation (aka Duplin Formation)	Fine to medium grained shelly, clayey sand, bluish-gray in color. Sand, shell, sandy limestone. Well-indurated limestone cored 21-25 m (69 – 82 ft) below surface of Shackleford Banks. Top is confined by beds of silt and clayey sand. Medium to coarse sand at bottom. Beneath Core Banks, unconformity above Early Pliocene (6 million years missing).	Yorktown Aquifer: fresh water lens floating on saline water. Top of aquifer is 18 m (60 ft) below MSL (Cape Lookout) to 41 m (135 ft) below MSL (Ocracoke).
Neogene (Tertiary)	Miocene	23–5.3	Pungo River Formation	Clay, silty clay, and clayey sand. Confining bed thickens from west to east.	
Paleogene (Tertiary)	Oligocene/ Eocene	34–23	Castle Hayne Formation	Medium- to coarse-grained limestone. 104 m (340 ft) below MSL (Cape Lookout) to 183 m (600 ft) below MSL (Ocracoke). Dips northeastward.	Castle Hayne Confining Unit at top. Castle Hayne Aquifer: fresh water
Paleogene (Tertiary)	Paleocene	66–56	Beaufort Formation	Beaufort Aquifer is confined by glauconitic clay and silt beds. 1200 ft below the surface at Shackleford; 1700 ft deep below Core Banks. Glauconitic sand and sandy limestone beds.	Beaufort Confining Unit at top. Beaufort Aquifer: saline water
Cretaceous	Upper	101–66	Peedee Formation	Peedee Aquifer is confined by clay and silt beds. Peedee Aquifer has alternating beds of fine to coarse grained fossiliferous sand (3-6 m [10-20 ft] thick) alternating with dark brown clay. Slopes eastward; 366 m (1200) ft below western Shackleford Banks and more than 549 m (1800 ft) below northern Core Banks.	Peedee Confining Unit at top. Peedee Aquifer: saline water

*Age is in millions of years before present (MYA) and indicates the time spanned by the associated epoch or period. Rock/sediment units obtained in drill cores correspond to various epochs and periods, but do not encompass the entire age range, as indicated in the age column.

**MSL = mean sea level.

Column is based on interpretations by Moslow and Heron (1978), Moslow and Heron (1979), Susman and Heron (1979), Moslow and Heron (1981), Lautier (2009), Winner (1978), and NCDENR (2015). Colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps.

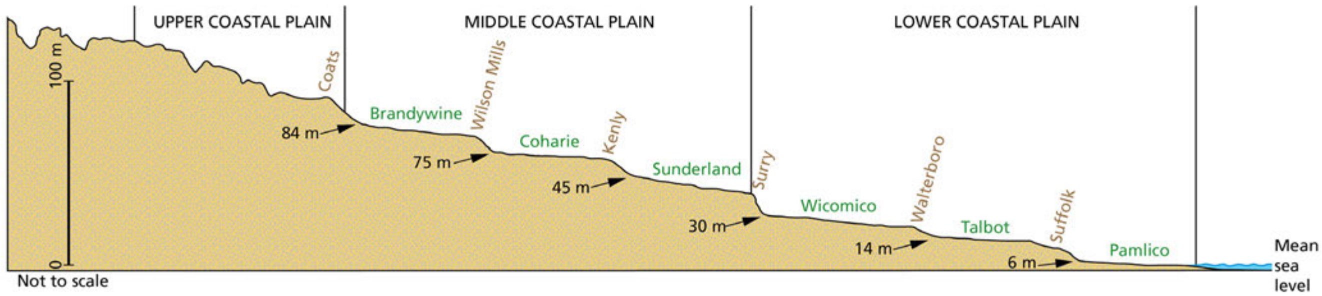


Figure 1. Cross-sectional topographic view of the marine terraces (green text) and paleoshorelines (brown text) of the North Carolina Coastal Plain. Graphic by Trista Thornberry-Ehrlich, modified after figure 3 in Daniels et al. (1984).

which can only be reached by boat. Depending on ferry service and storms, visitation varies from 480,000 to 860,000 people annually. Visitors come for beach-based recreation, fishing, historical tourism, and viewing wildlife including shorebirds and the legislatively protected free-roaming horses. Off-road vehicle use and beach driving provide access to these activities for many users. The main user groups at the park are campers, anglers, and day-use beach-goers (NPS 2016).

Geologic Setting

The Outer Banks lie along the Atlantic passive continental margin, which has experienced little tectonic activity since widespread rifting during the Mesozoic Era (252 to 66 million years ago) formed the Atlantic Ocean Basin (table 1). As rifting progressed, extensive marine, coastal, and riverine deposits filled the western edge of the Atlantic Basin forming the Atlantic Coastal Plain (table 2).

The Atlantic Coastal Plain is characterized by a series of former shorelines and terraces that formed during the Pliocene and Pleistocene Epochs in response to sea level changes (fig. 1). The terraces decrease in elevation and age toward the sea (Wells and Kim 1989; Farrell et al. 2003; Tweet et al. 2009). Seven river systems dissect the coastal plain (Colquhoun 1966).

The park barrier islands are perched on the flank of the Carteret Headland and have a narrow and shallow fringing back barrier estuarine system comprising Core Sound, Back Sound, and associated embayments (Riggs et al. 2015) (fig. 2). Drainages from this headland are small stream valleys that began to flood 3,000 to 2,000 years ago with rising sea levels. The shallow estuarine shoals landward of the park are known collectively as Core Flats; the flats reach a maximum water depth of 2 m (6 ft) and may be exposed during low tide. The combined processes of storm overwash and inlet flood-tides created these shoals and the barrier islands (Riggs et al. 2015). The shoreface slopes steeply until it reaches 8 to 23 m (25 to 75 ft) below sea level, where it flattens out onto the inner continental shelf (Riggs et al. 2008b).

Cape Lookout Shoal extends 16 km (10 mi) offshore and is the approximate location of the Cape Lookout High (fig. 2), a limestone ridge that divides the North Carolina coastal system into two distinct zones. The geologic differences of the two zones, described below, lead to differences in the geometries, processes, wave and current dynamics, and storm impacts along each zone (table 3) (Heron et al. 1984; Inman and Dolan 1989; York and Wehmiller 1992; McNinch and Wells 1999; Riggs and Ames 2003; Riggs et al. 2008b).

The Southern Coastal Zone, from Cape Lookout to the Cape Fear River, overlies the Carolina Platform—a structural high in the underlying crystalline basement rocks (Riggs and Belknap 1988) (fig. 2; table 3). The Carolina Platform consists of shallow (<1 km [0.6 mi]) Paleozoic crystalline basement rock, and extends from approximately Cape Romain, South Carolina to Cape Lookout, North Carolina (Riggs and Belknap 1988). South of the Cape Lookout High, the coastal zone is dominated by Tertiary and Cretaceous age rocks (Riggs et al. 1995).

The Southern Coastal Zone, which includes Shackleford Banks, has a relatively steep slope (average of 0.57 m/km) with short, stubby barrier islands and narrow estuaries (Riggs et al. 2008b), higher astronomical tidal ranges, extensive saltwater exchange and high salinities (Riggs and Ames 2003). The cuspate embayment known as the Onslow Bay compartment faces south to southeast, and so experiences offshore winds and waves during northeasters, onshore waves

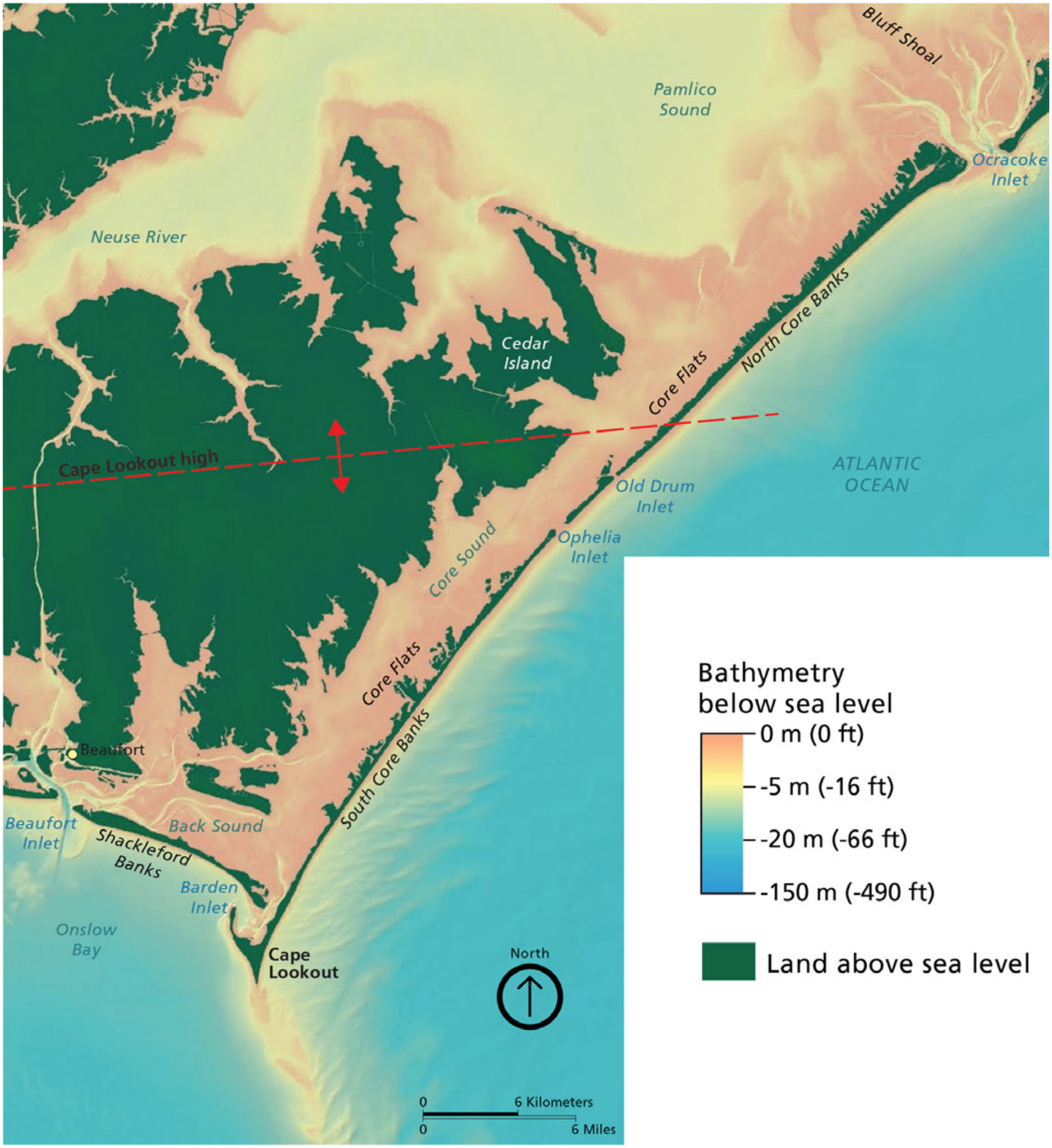


Figure 2. A bathymetric map for the Pamlico Sound region showing the approximate location of the Cape Lookout High axis (Snyder et al. 1982), using NOAA NOS Bathymetry (http://maps.ngdc.noaa.gov/viewers/bathymetry/). Graphic by Trista Thornberry-Ehrlich (Colorado State University).

from the southwesterly summer winds, and more frequent direct hits from hurricanes (Riggs et al. 2008b).

The Northern Coastal Zone, which includes Core Banks, is set within the Albemarle Embayment, a Cenozoic depositional basin that is bounded to the north by the Norfolk Arch (Foyle and Oertel 1997) and to the south by the Cape Lookout High (Horton et al. 2009). The Albemarle Embayment is slowly

Table 3. Comparison of geometries and processes of southern and northern coastal zones of North Carolina.

Geometry or Process	Southern Coastal Zone	Northern Coastal Zone
Geologic Framework and Control	Cretaceous-Miocene geologic framework: Dominantly rock control	Pliocene-Quaternary geologic framework: Dominantly Sediment Control
Slope	Steep land slopes (~ 57 cm/km)	Gentle land slopes (~ 4 cm/km)
Rivers	Coastal Plain-draining rivers (Many) Black-water rivers Low sediment input Low freshwater input	Piedmont-Draining Rivers (4) Brown-water rivers High sediment input High freshwater input
Islands and Inlets	Short barrier islands and many inlets (18) Maximum astronomical tides and currents Maximum salt water exchange	Long barrier islands and few inlets (5) Minimal astronomical tides Minimal salt water exchange
Results	Narrow back-barrier estuaries Regularly flooded Astronomical tide-dominated High brackish salinities	Deeply embayed estuaries irregularly flooded Wind, tide-, and wave-dominated Highly variable salinities

Source: Table 1 from Riggs et al. (2008b).

subsiding from Cape Lookout to the Virginia state line (Riggs et al. 2011). It contains a Quaternary sediment sequence that is 50–70 m (164–230 ft) thick (Riggs et al. 1995). The East-Central Coastal Plain that extends between Albemarle Sound and Onslow Bay is a gently southeastward dipping and southeastward thickening wedge of sediments and sedimentary rock ranging in age from Recent through Cretaceous (possibly Triassic), which rests on an underlying basement complex of Paleozoic age rocks (Lautier 2009). The sediment wedge was deposited during alternating transgressions and regressions of the Atlantic Ocean. Beneath the park, the basement surface is at a depth of up to 3,000 m (10,000 ft) below sea level (Lautier 2009).

The Northern Zone has long barrier islands and broad drowned-river estuaries that form the large Albemarle-Pamlico estuarine system (Riggs et al. 2008b). The land slope is shallow—an average of only 0.04 m/km along northern Core Banks (Riggs and Ames 2003). Deposits of estuarine peat and clay crop out in the surf zone of Core Banks; the peat layer is believed to be continuous from just below low-tide level on the ocean beach into the present-day back-barrier marsh (Pierce and Colquhoun 1970). The cuspate embayment known as Raleigh Bay faces southeast and so is somewhat sheltered from northeaster storms approaching the coast, but receives more direct landings of tropical storms (Riggs et al. 2008b).

A discussion of soil is beyond the scope of this report. A soil resources inventory was completed for the park (see NPS 2005).

Proposed Wilderness Area

The National Park Service submitted a wilderness recommendation to Congress in August 1985 for the entire emergent area of Shackleford Banks (1,210 ha [2,990 ac]), following a 1974 wilderness study conducted for the park that proposed designating approximately 16% as wilderness, in accordance with the Wilderness Act (PL 88-577) and directed by PL 93-477. However, no formal designation has been made to date (NPS 2012). The NPS is required to manage the wild horses (Public Law 105-202, Public Law 109-117, amended Public Law 89-366), which threaten the untrammeled wilderness character (NPS 2012).

Geologic Significance and Connections

The history of the park includes whaling, fishing and shipping industries, which are represented by multiple structures and sites in the Portsmouth Village National Register Historic District at the northern end of Core Banks (plate 1, in pocket). Chartered in 1753, the village served as a lightering port for heavily loaded ships that could not navigate the shallow sounds. There were about 500 Portsmouth Island residents in the 1850s, but the population declined around the time of the Civil War, and the last year-round residents moved off the island in the early 1970s (Burk et al. 1981).

Diamond City, on the east end of Shackleford Banks, was a whaling village in the late 1800s and was well known in the 19th century for shipping its salted mullet. Whale spotters used the high dunes there to 'look out' for whales. The Great Hurricane of 1899 damaged the community beyond recovery by flooding drinking wells and gardens with salt water, drowning livestock, and destroying the forests and dune vegetation (Pilkey and Young 2011, North Carolina Folklife Institute 2016). There are some remnants of an old village on the cape where the US Coast Guard Station now stands and a military base and gun mounts can also be found near the shore (Pat Kenney, Cape Lookout National Seashore, superintendent, conference call, 16 June 2015).

The park's historical and archeological legacy is associated with survival at the edge of the sea, and with navigation and life-saving. Traces of this history include prehistoric occupation sites (back to 2500 BCE) on Shackleford Banks, and sunken ships and cargoes from colonial exploration and from losses associated with German submarine attacks during the first months of World War II. Most documented archeological sites are deteriorating, but are listed as Other Important Resources and Values in the park's Foundation Document (NPS 2012). The iconic Cape Lookout Lighthouse was completed in 1859 to mark the headland and to aid in navigating the shoals and channels (NPS 2012). It was the first of the four tall tower lighthouses built on the North Carolina coast and was listed on the National Register of Historic Places in 1972. The 1917 U.S. Coast Guard Station (including the keepers' quarters and associated structures), the 1812 lighthouse site, and the 1886 U.S. Life-Saving Station also mark the area's nautical history (NPS 2012). Cape Lookout Village National Historic District is one of the park's Fundamental Resources and Values (NPS 2012).

Geologic and Environmental Features and Processes

These features and processes are significant to the park's landscape and history.

During the 2000 scoping meeting (see NPS 2000) and 2015 conference call, participants (see Appendix A) identified the following significant geologic features, processes, and topics at the park:

- Simple and Complex Barrier Island Model
- Geologic Framework and Barrier Evolution
- Sediment Transport Processes
- Oceanographic Conditions
- Inlets
- Estuaries
- Estuarine Sediments
- Groundwater
- Paleontological Resources

Significant features within Cape Lookout National Seashore mentioned in this text are listed in table 4 and mapped on plate 1 (park map; in pocket).

Coastal natural resources are located in a transition zone between terrestrial and marine environments, and include characteristics of both. Coastal environments—shaped by waves, tides, wind, and geology—may include tidal flats, estuaries, river deltas, wetlands, dunes, beaches, barrier islands, bluffs, headlands, and rocky tidepools. The National Park Service manages 85 ocean, coastal, and Great Lakes parks with more than 18,000 km (11,200 mi) of shoreline (Curdts 2011). Of that total, 552 km (343 mi) are within Cape Lookout National Seashore (Curdts 2011).

More than 120 parks, including Cape Lookout National Seashore, are close to the coast, even though some do not manage a shoreline, and are vulnerable to coastal hazards, including sea level rise, lower lake levels, salt water intrusion, and inundation during coastal storms (Beavers et al. 2016; see "Resource Management Issues" chapter). The NPS Geologic Resources Division Coastal Geology website, http://go.nps.gov/grd_coastal, provides additional information.

Coastal change in the Cape Lookout region is a product of geologic and oceanographic factors in combination with human modifications and climate-driven changes.

Simple and Complex Barrier Island Model

Riggs and Ames (2006) developed a model of Outer Banks barrier island evolution by integrating aerial photographs (1932–2003), topographic data (1852–2003), and field studies. The model describes two basic types of barrier islands in the area of Cape Lookout, (fig. 3): simple and complex.

Simple Barrier Islands

Simple barrier islands constitute about 70% of North Carolina's ocean shoreline (Riggs et al. 2011), including Core Banks. This type of barrier island is sediment poor and narrow, with low elevations and a surface morphology that has generally developed within the last 500 years. These islands have developed in response to recent environmental conditions and processes (Riggs and Ames 2006). They are migrating upward and landward in response to storm surges in which much of the sand is incorporated into overwash fans. Island width is built by the opening and closing of shallow, migratory inlets, with sand incorporated into flood tidal deltas (Riggs and Ames 2006).

Three primary features compose a simple barrier island: beach, overwash plain (upper, middle, and lower overwash ramps), and sound features (fig. 3) (Ames and Riggs 2006j). The morphology of each simple barrier island varies due to differences in storm patterns, sand supplies, coastal erosion rates, underlying geologic structure, and human activity.

The ocean and estuarine shorelines of a simple barrier island erode with rising sea level if sediment supply is low. Eventually the island becomes so narrow that a major storm overwashes it or forms a new inlet and tidal deltas. These processes deposit sediment, building island elevation and width. Where human constructions impede inlet formation and overwash, new sediment does not reinforce the island's height and width, and the island continues to narrow.

When a vegetated island is overwashed, the plant cover interrupts the flow of water and causes the rapid dumping of overwash sediment, building elevation on the ocean side of the island (fig. 4). Over time, this process steepens the upper overwash ramp and minimizes the middle overwash ramp. As the ocean

Table 4. Significant features at Cape Lookout National Seashore discussed in this report, listed in geographic order from north to south. Refer to Figure 1 (in pocket) for location. Table continues on next page.

Feature	Type of Feature	Notes
Pamlico Sound	Estuary	Supports diverse plant and animal communities. Threatened by increased nutrient loading in some portions.
Bluff Shoal	Estuarine shoal	Extends across Pamlico Sound, from the west bank of the Pamlico River to Ocracoke Inlet. Topography is controlled by the interstream divide between Pamlico Creek and Tar River.
Ocracoke Inlet	Inlet	One of only three inlets within the Pamlico Sound region of the northern Outer Banks. Southern boundary of Cape Hatteras National Seashore and northern boundary of Cape Lookout National Seashore. It is the oldest and most stable of the inlets north of Cape Lookout, and is sometimes dredged.
Core Sound	Estuary	High salinity due to presence of numerous inlets. Low fetch and shallow water minimize back-barrier erosion.
Portsmouth Island	Portion of Island	This refers to the northern portion of Core Banks (Ocracoke Inlet to Swash Inlet) and is the site of a historical village and landing strip that is now closed.
Core Banks	Island	Ephemeral and migrating inlets divide this long and narrow barrier island into portions referred to as Portsmouth Island and North, South, and Middle Core Banks.
Core Flats	Estuarine shoals	Shallow estuarine shoals landward of Core Banks, which range from intertidal to a maximum water depth of 2 m (6.6ft). They were created by storm-driven overwash and inlet flood tidal delta formations.
Long Point	Portion of island	A channel and basin allow ferry access to this portion of North Core Banks; the rustic cabins maintained here are frequently impacted by storm surges.
Old Drum Inlet	Inlet	Old Drum Inlet separates North Core Banks from South Core Banks. It closed naturally in 1971 and then reopened during Hurricane Dennis in 1999. Shoreline fluctuations are high adjacent to the inlet.
New Drum Inlet	Inlet	USACE created New Drum Inlet in 1971 about 4 km (2.5 mi) southwest of Old Drum Inlet and dredged the inlet through 1998. It closed in 2010, but the area continues to overwash during large storms.
Ophelia Inlet	Inlet	In 2005 Hurricane Ophelia opened this inlet, the largest of the three inlets that currently exist on Core Banks.
Great Island	Portion of island	A vehicle ferry runs between the mainland and Great Island, which has visitor facilities including rustic cabins, on South Core Banks.
Raleigh Bay	Ocean embayment	Regional embayment of the Atlantic Ocean along Core Banks
Cape Lookout	Cape	The southern end of Core Banks separates Onslow Bay from Raleigh Bay. Approximate location of the Cape Lookout High, a limestone ridge that divides the North Carolina coastal system into two distinct zones with different geologic framework and paleogeographic history, leading to differences in the two zones' geometries, processes, wave and current dynamics, and storm impacts.
Cape Lookout Shoal	Cape-associated shoals	Cape Lookout Shoal extends 16 km (10 mi) offshore of Cape Lookout. It has persistent morphology and location, and is approximately 3.5 km (2.2 mi) wide and 4 m (13 ft) deep. It limits sediment exchange between Core Banks and Shackleford Banks.
Power Squadron Spit	Cape-associated spit	The hook forms a partially enclosed embayment at the mouth of Barden Inlet. The prograding spit is extending to the north and widening to the west. Accretion accelerated after the 1914 construction of a 1.4 km (0.9 mi) long jetty, causing erosion on the Shackleford Banks beach.
Barden Inlet	Inlet	Barden Inlet separates Cape Lookout from Shackleford Banks. It was open from about 1770 to about 1860; its closure joined South Core Banks to Shackleford Banks. It reopened in the hurricane of 1933 and has been maintained through dredging since then.
Shackleford Banks	Island	Island oriented perpendicularly to Core Banks. Has dunes reaching up to 10.7 meters (35 ft).

Table 4, continued. Significant features at Cape Lookout National Seashore discussed in this report, listed in geographic order from north to south. Refer to Figure 1 (in pocket) for location.

Feature	Type of Feature	Notes
Onslow Bay	Ocean embayment	Regional embayment of the Atlantic Ocean along Shackleford Banks
Back Sound	Estuary	Narrow, shallow estuary is landward of Shackleford Banks.
Harkers Island	Island	The park's headquarters is on the east end of this older barrier island on the confluence of Core and Back sounds.
Beaufort Inlet	Inlet	The western edge of Shackleford Banks forms the park's boundary. The inlet has been substantially deepened and is maintained for the Morehead shipping port with a major dredging program that impacts the western portion of the park.

shoreline continues to recede, the island narrows and steepens, with the upper ramp totally eliminating the middle ramp and eventually burying the platform marshes that form the lower overwash ramp. The upper overwash ramp becomes a sediment bank shoreline covered with scrub shrub along the estuary (fig. 3) (Riggs and Ames 2006).

Complex Barrier Islands

Complex barrier islands constitute about 25% of North Carolina's ocean shoreline (Riggs et al. 2011), including the eastern end of Shackleford Banks. This type of barrier island is often older, more sediment rich, and wider and higher than simple barrier islands. Complex islands are generally composed of beach ridges and troughs (swales), with extensive dune fields (fig. 3). Older portions of these islands represent multiple stages of formation dating back to 3,000 years before present and a previous set of climatic and environmental conditions. A narrow, simple overwash-dominated barrier segment is often welded onto the oceanfront, resulting in an abnormally high and wide barrier island (Riggs and Ames 2006). These islands have little potential for the formation of new inlets or occurrence of small-scale overwash, other than along the front side of the barrier (Riggs et al. 2009).

The estuarine shorelines associated with complex barrier islands are generally scarped, with wave-cut cliffs and terraces in older upland sediment units or along the thicker peat deposits of the platform marshes (Riggs and Ames 2006). The upper 15 to 30 cm (6 to 12 in) of the peat layer contains a dense living root mass, below which the peat is soft and erodible (Riggs et al. 2008a). At low tide, waves erode the softer peat, causing the overhanging peat layer to fall (Riggs et al. 2008a). Strandplain beaches form in front of the erosional scarps if sand is available from the eroding shoreline, adjacent shallow estuarine waters, or as windblown sand from the dune fields (fig. 5) (Riggs and Ames 2006).

Poorly developed complex barrier islands form during storms that infrequently deliver a new supply of sand to the region. They are generally sand limited, with moderate widths and elevations and a few simple sets of low beach ridges separated by wide, wetland swales (Riggs and Ames 2006). Much of the older segment of such an island is buried by marsh expansion as sea level rises.

Shackleford Banks formed as a complex barrier island in several stages defined by changing rates of sea level rise, storm patterns, and sediment supply (Riggs et al. 2015).

Geologic Framework and Barrier Evolution

The underlying geology of North Carolina influences coastal evolution, morphology of the inner shelf, and formation of barrier islands (Thieler et al. 2014). The sediment available for the North Carolina barrier islands is influenced by stratigraphic units occurring beneath and seaward of the shoreface. The age, origin, and composition of these units interacts with coastal processes to determine the shoreface morphology, composition and texture of beach sediments, and shoreline recession rates (Riggs et al. 1995; Honeycutt and Krantz 2003). Pre-modern substrates that are exposed in the surf zone correlate with shoreline change hotspots, or areas with highly variable shoreline position (McNinch 2004, Browder and McNinch 2006, Miselis and McNinch 2006, Schupp et al. 2006).

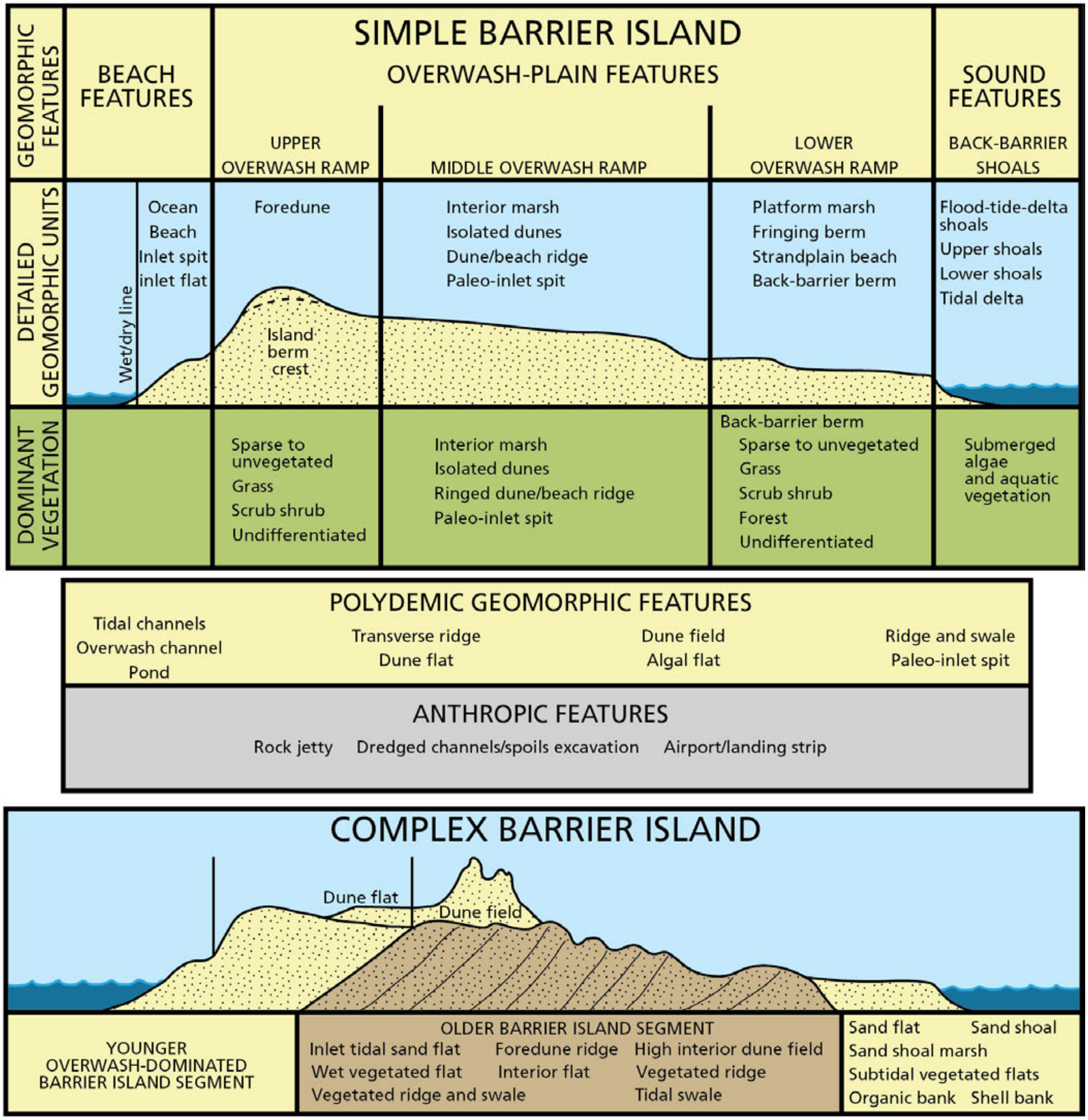


Figure 3. Diagram showing cross-section profiles and dominant vegetation of the model forming the basic framework of the geomorphic mapping developed by East Carolina University for this report. (Top) Simple barrier islands such as Core Banks are young, with active barrier components dominated by inlet and overwash processes, and are generally transgressive, with landward migration. (Bottom) Complex barrier islands, such as western Shackleford Banks, form when a simple barrier island migrates into and accretes onto an older island segment. When sand supply is locally abundant, a complex barrier island can form through the construction of beach ridges and back-barrier dune fields, resulting in the seaward progradation of the barrier segment. The older, complex segment of the barrier island is shaded brown, and the welded, younger, overwash-dominated portion of the barrier island is tan. Graphic redrafted by Trista Thornberry-Ehrlich (Colorado State University) after figure 28 from Riggs and Ames (2006).

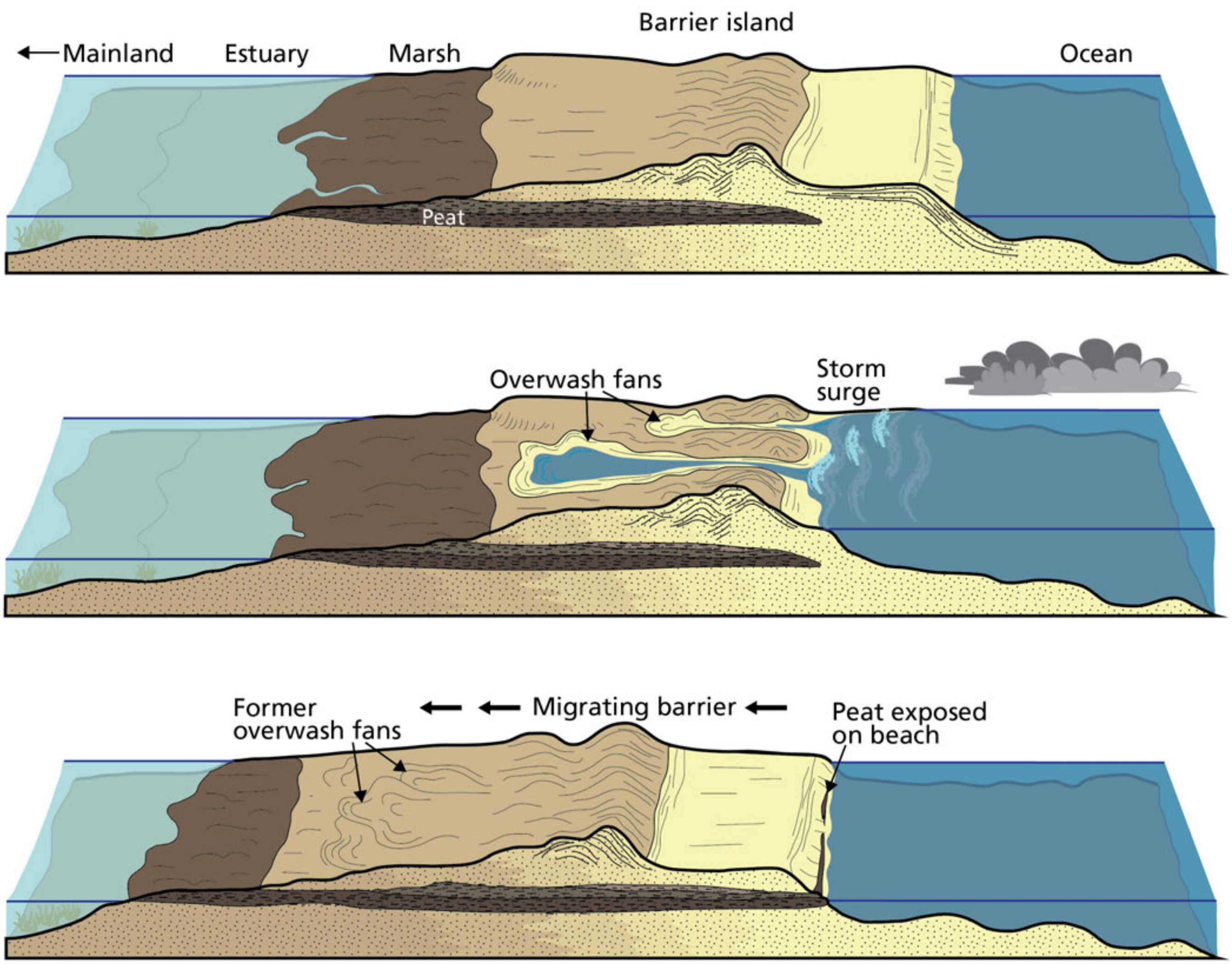


Figure 4. Schematic illustration of overwash fan development. When small storm surges carry sand across the beach, sediment is deposited as small overwash fans on the ocean side of the barrier. Large storm events can drive water across the island, resulting in large overwash ramps that bury the back-barrier platform marshes and may even build shallow shoals in the estuary. Graphic by Trista Thornberry-Ehrlich (Colorado State University) based on an online figure by NPS and University of Maryland Center for Environmental Science (2012).

Cape Lookout

Cape Lookout occurs on the south flank of the Cape Lookout High (fig. 2), a broad ridge composed of Tertiary (Oligocene through Pliocene) limestone and shaped by differential erosion (Snyder et al. 1982; Popenoe 1985; Ward and Strickland 1985; Popenoe 1990, as cited in Mallinson et al. 2010a; Snyder et al. 1990; Riggs et al. 1995). The ridge has an east-northeast trend along the Carteret Peninsula and passes under the mid-section of Core Banks.

The Holocene sediments of Cape Lookout are separated from the underlying Pleistocene sediments by a sharp contact that was created by shoreface erosion throughout the recent transgression (McNinch and Wells 1999). The underlying Late Wisconsin Pleistocene layers are dark gray, shelly, silty sand and clay called the Diamond City Clay (Susman and Heron 1979).

Cape Lookout Point (fig. 6) is composed of sands that become coarser moving upward through shoreface into barrier island sediments. This results from the growth of spits that extend seaward over shoreface deposits as they accumulate sediment (Moslow and Heron 1981). The unconsolidated Holocene sand is up to 20 m (66 ft) thick along the axis of the shoal, thinning to 1 m (3 ft) along the shoal margin (Heron et al. 1984).

Cape Lookout Point has changed position over time (fig. 7), and its treacherous shoals earned it the name

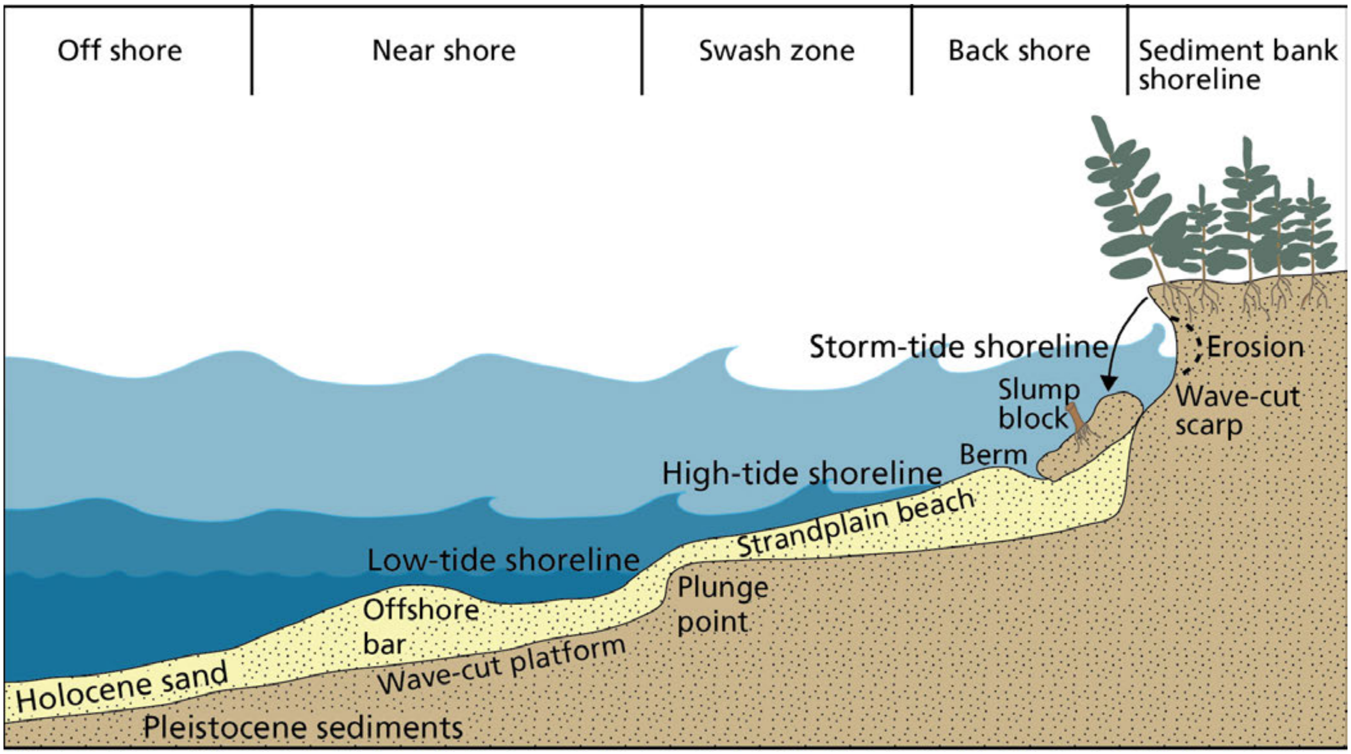
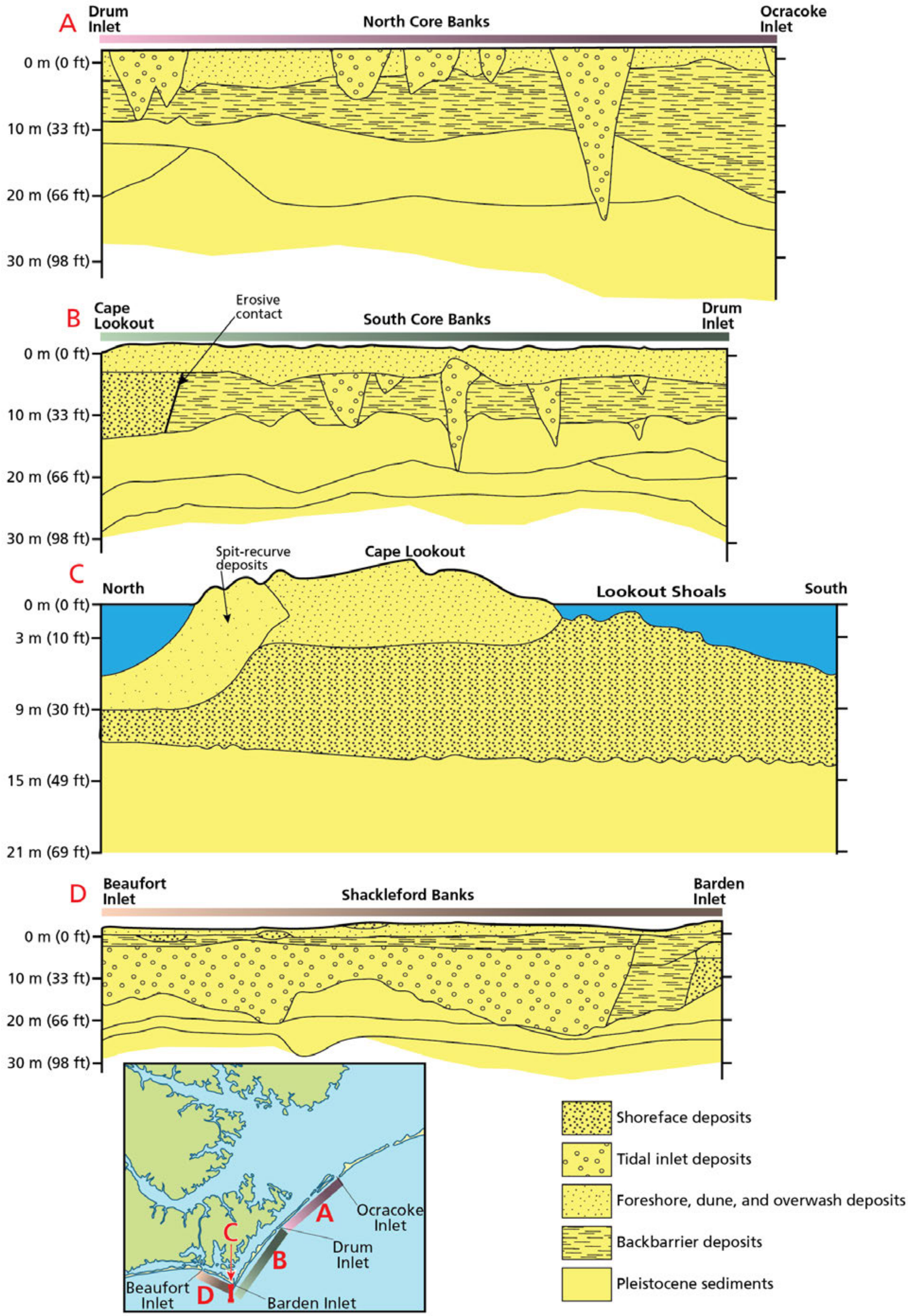


Figure 5. Schematic cross section of a strandplain beach. Strandplain beaches are common shoreline types on the estuarine sides of complex barrier islands. Coastal erosion occurs by direct wave attack during high astronomical, wind, and storm tides and provides a major source of sand sediment for an adjacent strandplain beach. As the sediment banks are undercut, slump blocks collapse onto the beach, where they are reworked by wave energy. Graphic redrafted by Trista Thornberry-Ehrlich (Colorado State University) after figure 4-2-1 in Riggs and Ames (2003).

promontorium tremendum (horrible headland) on a 1590 map of Cape Lookout (White and de Bry 1590). Between 1866 and 1955, the shoal grew by an average of 410,000 m^3/yr (536,000 yd^3/yr) (Pierce 1969), close to the USACE estimate of southerly longshore transport along Core Banks (J.T. Jarrett as cited in McNinch and Wells 1999). Sediment moves both onshore and offshore along the shoal (fig. 8).

Cape Lookout Shoal, as defined by the 10-m (33 ft) isobath where a distinct break in slope occurs, is 16 km (9.9 mi) long and approximately 3.5 km (2.2 mi) wide. It extends from the exposed portion of Cape Lookout (McNinch and Wells 1999). The surrounding shelf is 18 to 25 m (59 to 82 ft) deep. The shoal is persistent in its location; the prominent highs across the shoal tend to erode during the fall and winter, and then accrete

Figure 6 (facing page). Cross-sections showing Holocene and Pleistocene sediments below the park. Figure 10 displays cross-sections of the shallower sediments. (A) North Core Banks. Shore-parallel cross-section of North Core Banks including the Portsmouth segment on the northern end. Cross-section depicts the portion of the island extending from Drum Inlet (southwest) to Ocracoke Inlet (northeast). Note the extremely thick Holocene inlet-fill sequence at northern end of cross-section. The thick back-barrier sequence adjacent to Ocracoke Inlet is primarily a sequence of flood-tidal delta and lagoonal sediments. (B) South Core Banks. Shore parallel cross-section of the Holocene stratigraphy of South Core Banks from Cape Lookout to Drum Inlet. An erosive contact marks the facies change from the back-barrier silty sands beneath the Core Banks barrier to the shoreface deposits underlying Cape Lookout. The greatest volume of sediment is a transgressive sequence of foreshore and overwash overlying back-barrier facies, which is a sequence typical for most of the higher-energy barrier portion. (C) Cape Lookout. Cross-section of the Holocene and Pleistocene of Cape Lookout. The section is dominated by a regressive sequence of barrier washover sands overlying shoreface silts and sands, produced as the cape prograded seaward. (D) Shackleford Banks. Shore-parallel cross-section from Beaufort Inlet to Barden Inlet. Graphics by Trista L. Thornberry-Ehrlich (Colorado State University) based on figure 7 from Moslow and Heron (1981), figure 2.24 from Moslow and Heron (1994), and figures 9, 11, and 13 from Heron et al. (1984).



A
Drum Inlet
North Core Banks
Ocracoke Inlet
0 m (0 ft)
10 m (33 ft)
20 m (66 ft)
30 m (98 ft)
B
Cape Lookout
Erosive contact
South Core Banks
Drum Inlet
0 m (0 ft)
10 m (33 ft)
20 m (66 ft)
30 m (98 ft)
C
Spit-recurve deposits
Cape Lookout
North
Lookout Shoals
South
0 m (0 ft)
3 m (10 ft)
9 m (30 ft)
15 m (49 ft)
21 m (69 ft)
D
Beaufort Inlet
Shackleford Banks
Barden Inlet
0 m (0 ft)
10 m (33 ft)
20 m (66 ft)
30 m (98 ft)
Ocracoke Inlet
Drum Inlet
Beaufort Inlet
Barden Inlet
Shoreface deposits
Tidal inlet deposits
Foreshore, dune, and overwash deposits
Backbarrier deposits
Pleistocene sediments

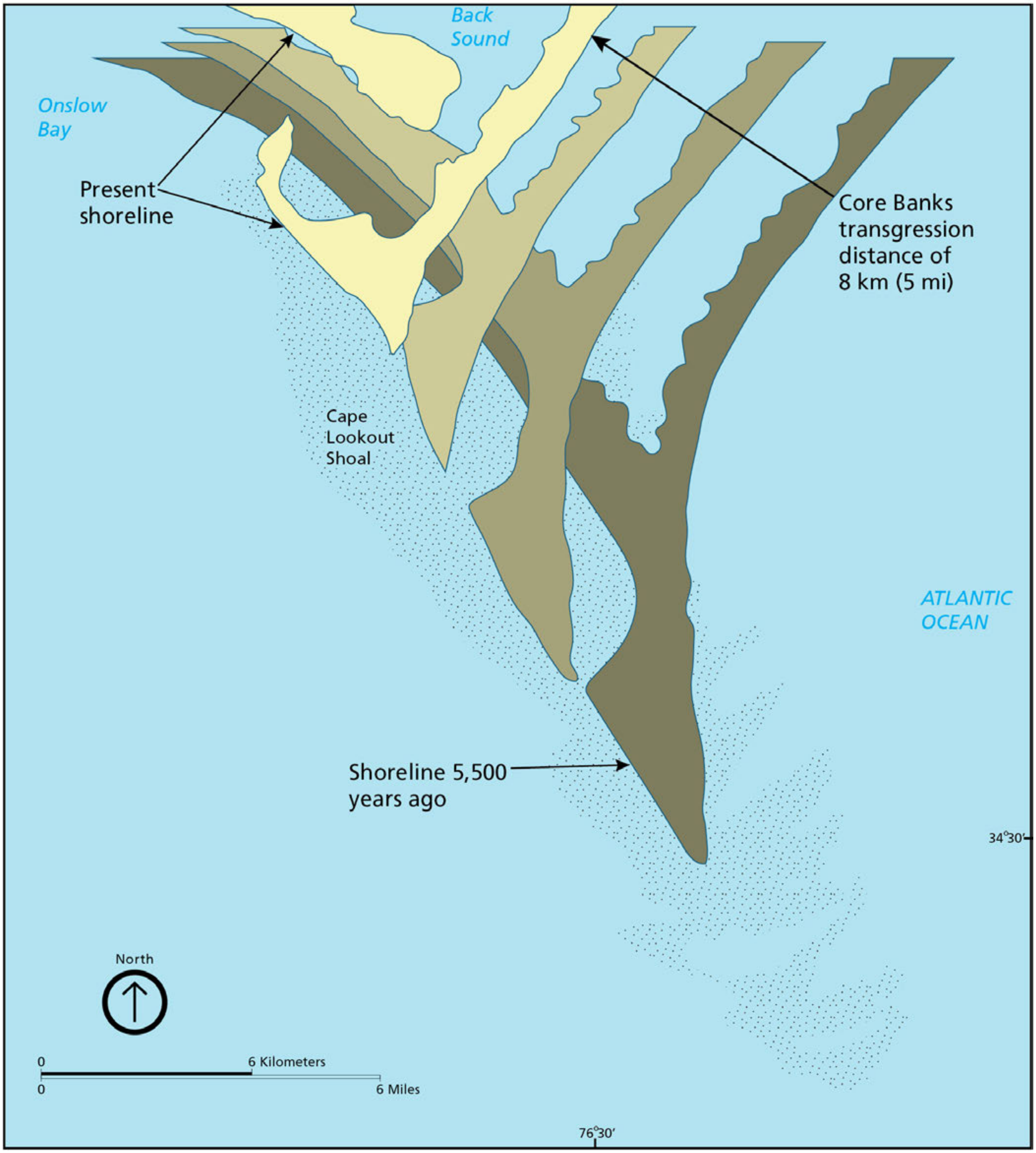


Figure 7. Likely transgression path of Cape Lookout Point over the past 5,500 years. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) based on figure 10 from McNinch and Wells (1999).

during the summer (McNinch and Wells 1999). The primary source of sediment to the shoal is longshore drift from Core Banks (fig. 8; McNinch and Wells 1999).

The modern Cape Lookout Shoal developed in the late Holocene (McNinch and Wells 1999). Many studies have proposed that the locations of Cape Lookout and the other Carolina capes (Capes Hatteras, Fear, and

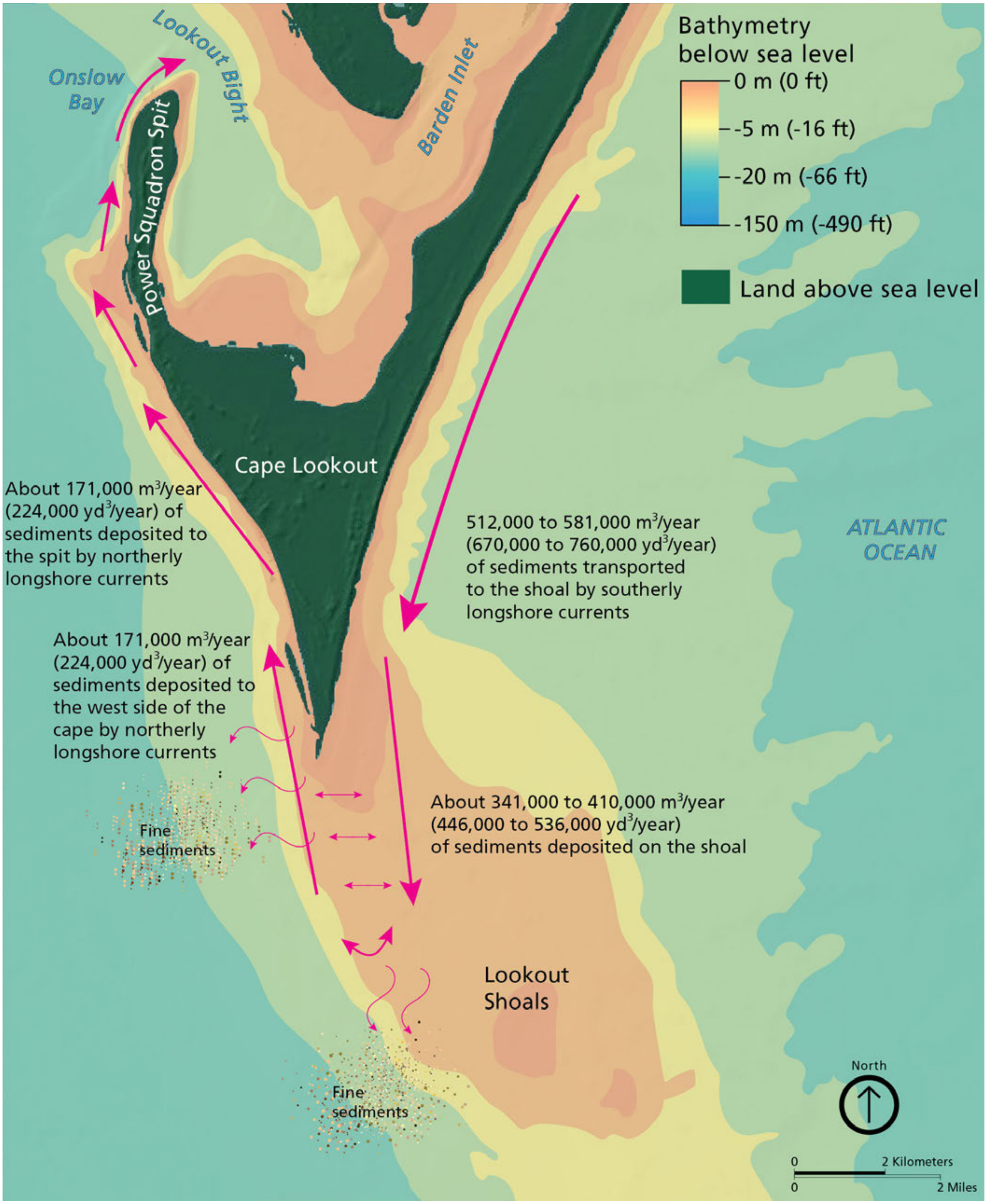


Figure 8. Longshore sediment transport rates and directions on Cape Lookout and Cape Lookout Shoal. Fine sediments are deposited where currents are slower. Data from figure 10 in Park and Wells (2005). Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Romain) are controlled by the underlying geologic framework (Swift et al. 1972; Moslow and Heron 1981; Popenoe 1985). Recent studies propose that the Carolina capes are dynamic, self-organized features that continue to evolve as the shoreline responds to waves that approach the coast at a large angle (Thieler and Ashton 2011) and to the coupling of tidal and wave-driven currents (McNinch 1997) that supply sediment to the shoal from the up-drift shoreline (McNinch and Wells 1999).

The shoal limits sediment exchange between Core Banks and Shackleford Banks (McNinch and Wells 1999). The effect is evidenced by the differences in sediment in Raleigh and Onslow bays. Raleigh Bay, to the northeast, has sand with a high percentage of iron-stained shell (Inman and Dolan 1989) and a higher percentage of coarse shell hash along the Cape Lookout Shoal (McNinch and Wells 1999), while Onslow Bay, to the southwest, has light gray, finer sands with higher carbonate and phosphate contents (Blackwelder et al. 1982) and no coarse shell along the Cape Lookout Shoal (McNinch and Wells 1999).

The shoal also influences the flow of water and distribution of sediment across the shelf, which in turn affects the following (McNinch and Wells 1999):

- shoreline migration,
- sediment budgets,
- coastal sewage outfalls,
- storm water discharge, and
- the fate of sediment placed along a cuspate foreland shoreline for nourishment purposes.

Power Squadron Spit

Power Squadron Spit has evolved over the last 60 years (Borrelli 2001; McNinch and Wells 1999) creating a hook-like shape at the end of Cape Lookout Point, and partially enclosing the embayment at the mouth of Barden Inlet (plate 1, in pocket). The prograding spit is extending to the north and widening to the west. Sediment transport to the spit is at a rate of approximately 180,000 m^3/yr (196,850 yd^3/yr) but occurs only when waves are from a southwest direction (Park and Wells 2007). The sediment is derived from the eastern side of the cape (Core Banks sediment bypassing around the shoal) and sometimes from the Cape Lookout Shoal before eventually being transported by the waves. The spit has accreted by an average 175,000 m^3/yr (191,382 yd^3/yr) over the last 25 years. Since 1976, multiple dune ridges have built up and become vegetated. There are stable curved beach ridges on the east side, and new ridges forming on the west side (Park and Wells 2007).

Construction in 1914 of a 1.5 km (0.9 mi) long jetty (plate 1, in pocket) created a shadow zone that enhanced sediment deposition and led to rapid spit growth of 35 m/yr. This has caused erosion on the Shackleford Banks beach to quadruple due to the growth of the spit, which has interrupted the westward sediment transport supply.

Core Banks

Core Banks is in a high energy environment with low sediment supply and fits into the simple barrier island model (fig. 9; table 5) (Moslow and Heron 1994). The stratigraphy of the island is described in this section; the geologic evolution of Core Banks is discussed in more detail in the "Geologic History" section.

The Holocene deposits of Core Banks are a mixture of 1) coarsening-upward, transgressive barrier island sequences; 2) isolated sequences of fining-upward inlet-fill; and 3) interbedded sequences of flood tidal delta, inlet-fill and, at the northern end, lagoon sediments (fig. 9, 10; table 5) (Heron et al. 1984).

Landward migration of Core Banks has produced a sequence of coarse overwash sands atop layers of silty sands deposited in back-barrier marshes and lagoons (fig. 11) (McNinch and Wells 1999). These Holocene sediments are about 10-12 m (33-39 ft) thick (fig. 6, 10). The barrier island proper consists of 2-3 m (6-10 ft) of linear overwash-foreshore sand (Heron et al. 1984). South Core Banks is generally located on top of the broad Cape Lookout High, whereas North Core Banks is located on the northern flank of the High where the underlying rocks dip towards the Albemarle Embayment. Both of these areas have low rates of long-term erosion due to their underlying geology (Riggs and Ames 2007).

Inlet-fill bodies (fig. 6, 9) underlie approximately 15% of Core Banks, and almost 40% of the northern end known as the Portsmouth Island segment. Inlet formation and migration rework previously deposited sediments in barrier islands, overwriting the stratigraphic record. Sediments deposited in an inlet are unlikely to be overwritten because they are

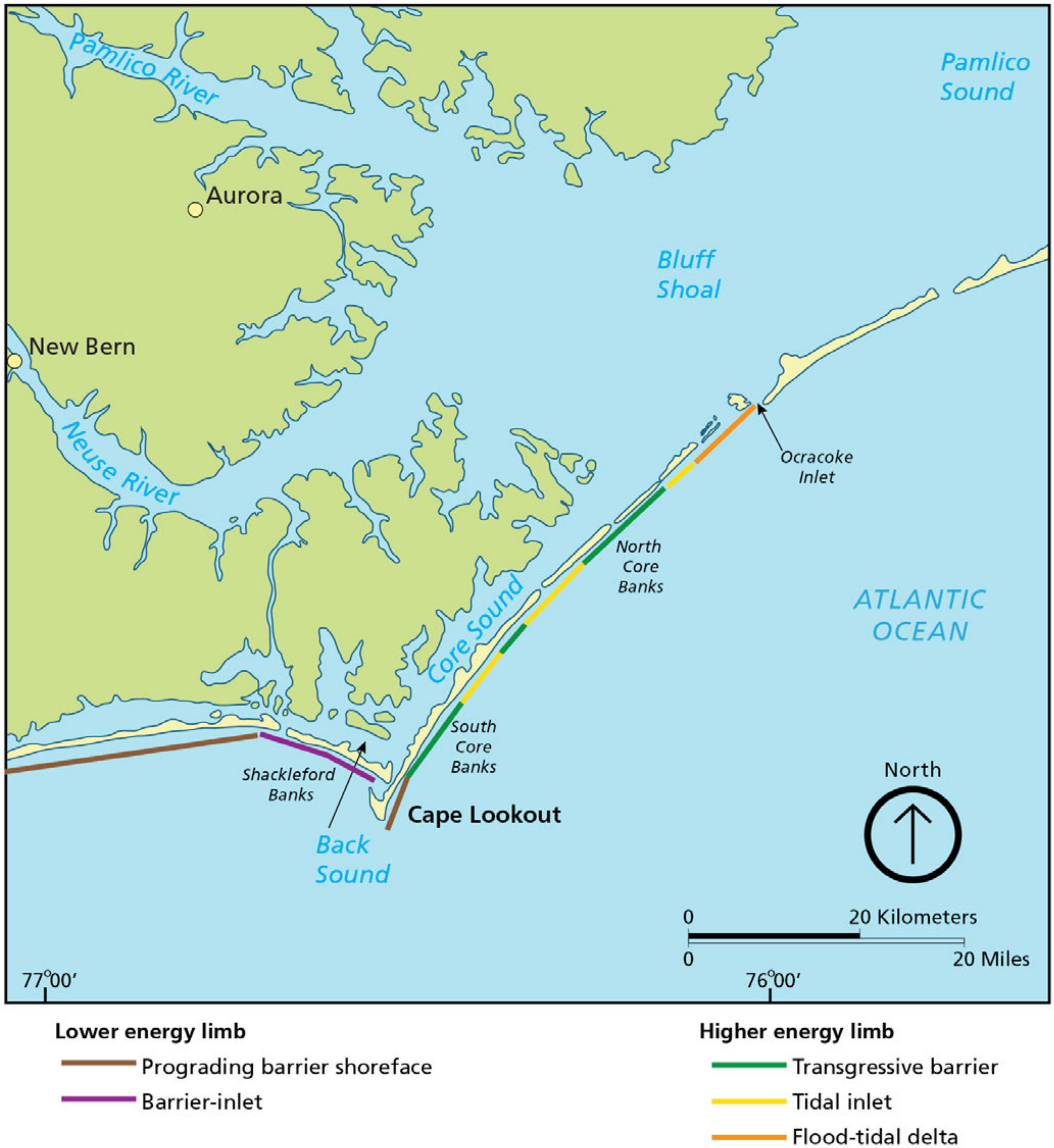
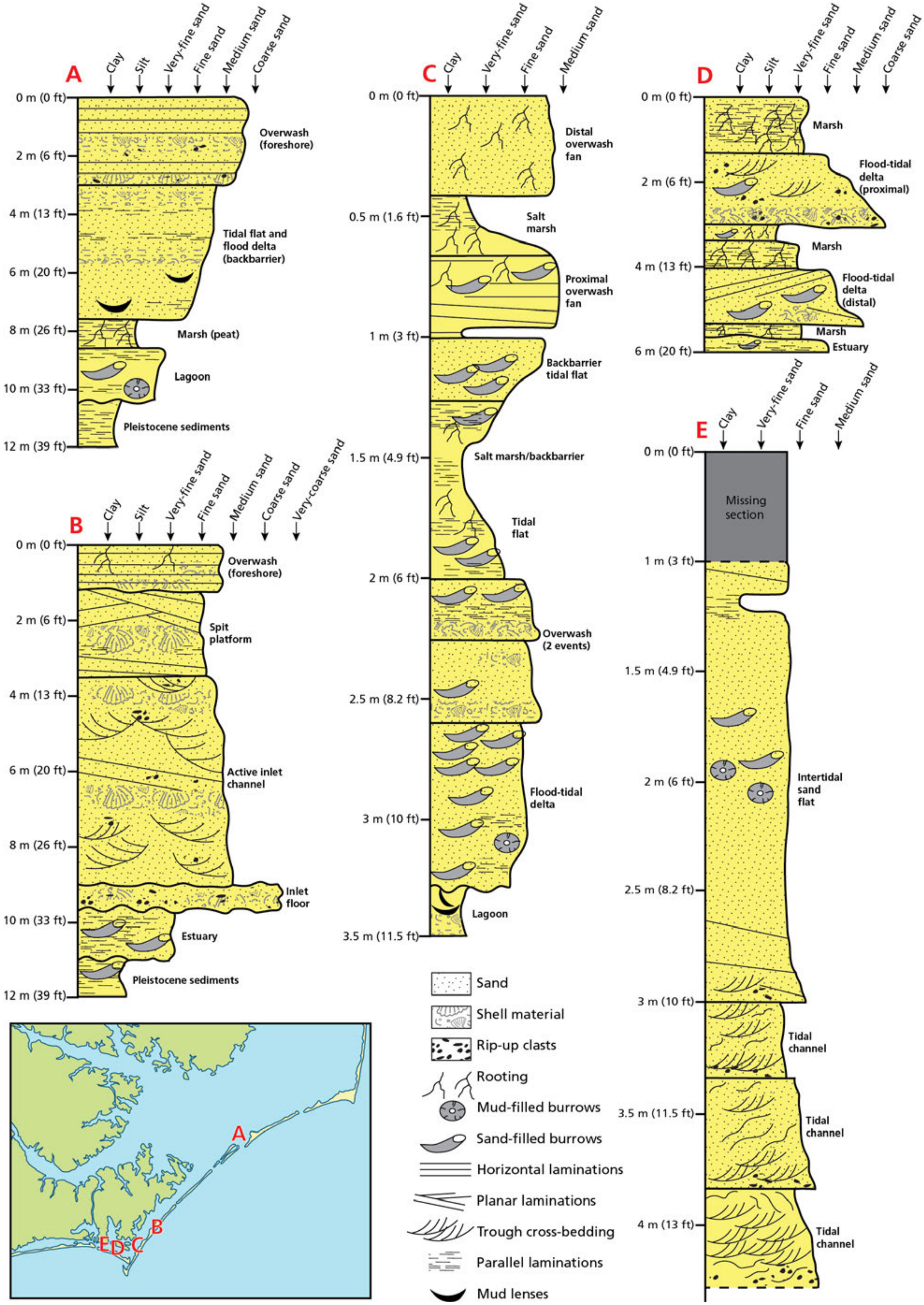


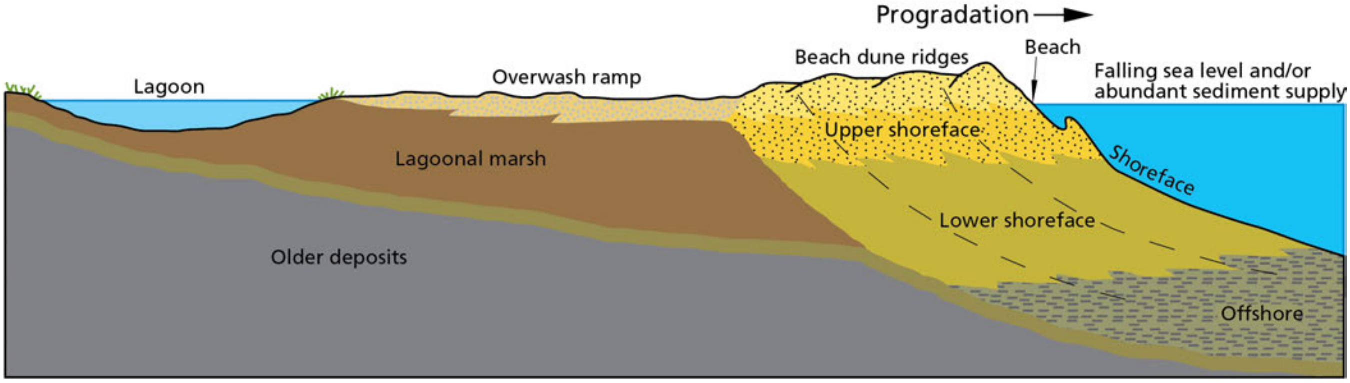
Figure 9. Variability in vertical sedimentary sequences along the park is related to depositional environment. The higher-energy transgressive barrier (North Core Banks and South Core Banks) has overwash, foreshore, shoreface, back-barrier, and migrating tidal inlet sequences. The lower-energy prograding barrier shoreface (Shackleford Banks and southern-most Cape Lookout) has shoreface, foreshore, flood tidal delta, and migrating tidal inlet sequences. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) based on figure 16 from Heron et al. (1984). See table 5 for more information.

Table 5. Characteristics of depositional environments. See figure 9 for map.

Depositional environment	Lithology	Shells and organics	Sedimentary structures	Large-scale features
Barrier: Overwash and foreshore	Clean, moderately sorted, fine to medium sand	Whole and abraded shells in layers, variable assemblage (low diversity)	Horizontal and planar laminations	Caps inlet and barrier sequences
Barrier: Shoreface	Well-sorted, fine to medium sand and silt	Abundance of sand-sized shell material *Gemma gemma*, *Arcopecten* sp., *Olivella* sp.	Cross-bedded (upper half) and burrowed (lower half) sequence	Coarsening-upward sequence, increase in mud content toward base
Backbarrier (lagoon, tidal flat, salt marsh)	Well-sorted, fine to medium silty sand and sandy clay	Organic rich, *Spartina* sp. and other plant material, *Ensis* sp., *Crassostrea* sp., *Crepidula* sp. (mollusks)	Burrowed, thin parallel clay laminations	Capped by salt marsh, increasing mud and organic content upwards
Flood-tidal delta	Moderately sorted, medium to coarse silty sand	Coarse shell fragments common, echinoderm fragments common	Gently dipping cross laminae, burrowed	Interbedded with backbarrier facies, cyclic fining-upward sequences
Migrating tidal inlet: Inlet margin	Clean, well-sorted, fine to medium sand	Mollusks rare, low diversity	Planar and horizontal laminations	Caps fining-upward inlet sequence
Migrating tidal inlet: Inlet channel	Moderately sorted, medium to coarse sand and shell, pebbly sand common	Mixed mollusk assemblage of shelf and backbarrier species, shells common and abraded	Cross-bedded (trough and planar?)	Thickest unit of inlet sequence, fines upward
Migrating tidal inlet: Inlet floor	Poorly sorted, coarse to pebbly sand and shell	Large, worn and abraded shell fragments common	Rip-up clasts, graded bedding	Basal scour lag

Figure 10 (facing page). Vertical sequences of shallow sediments below the park. See figure 6 for cross-sections of the underlying sediments. (A) Composite vertical sequence of Holocene and Pleistocene sediments for the Portsmouth area of North Core Banks (after figure 10 from Heron et al. 1984). (B) South Core Banks sedimentary sequence of Johnson Creek relict inlet fill is a fining-upward wave-dominated inlet sequence of cross-bedded sand and shell (after figure 2.16 from Moslow and Heron 1994). (C) Stratigraphy from back-barrier margin of South Core Banks. The basal unit is a burrowed and ripple-laminated silty sand to silty clay of back-barrier origin. It has an abrupt erosional contact with fine grained sand from an overlying flood-tidal delta. Overlying this is several interbedded units of proximal and distal overwash and back-barrier salt marsh and tidal flat deposits (after figure 2.15 from Moslow and Heron 1994). (D) The Back Sound back-barrier sequence from "Middle Marsh" has two stacked, fining-upward flood tidal delta sequences, interbedded and overlain by thin layers of salt-marsh muds (after figure 2.18 from Moslow and Heron 1994). (E) Stratigraphy of intertidal sand flat in Back Sound (after figure 2.19 from Moslow and Heron 1994). All graphics by Trista L. Thornberry-Ehrlich (Colorado State University) based on figures cited in caption.


A
Clay
Silt
Very-fine sand
Fine sand
Medium sand
Coarse sand
0 m (0 ft)
2 m (6 ft)
4 m (13 ft)
6 m (20 ft)
8 m (26 ft)
10 m (33 ft)
12 m (39 ft)
Overwash (foreshore)
Tidal flat and flood delta (backbarrier)
Marsh (peat)
Lagoon
Pleistocene sediments
B
Very-coarse sand
Overwash (foreshore)
Spit platform
Active inlet channel
Inlet floor
Estuary
Pleistocene sediments
C
0.5 m (1.6 ft)
1 m (3 ft)
1.5 m (4.9 ft)
2 m (6 ft)
2.5 m (8.2 ft)
3 m (10 ft)
3.5 m (11.5 ft)
Distal overwash fan
Salt marsh
Proximal overwash fan
Backbarrier tidal flat
Salt marsh/backbarrier
Tidal flat
Overwash (2 events)
Flood-tidal delta
Lagoon
D
Marsh
Flood-tidal delta (proximal)
Marsh
Flood-tidal delta (distal)
Marsh
Estuary
E
Missing section
Intertidal sand flat
Tidal channel
Tidal channel
Tidal channel
3.5 m (11.5 ft)
4 m (13 ft)
A
B
E D C
Sand
Shell material
Rip-up clasts
Rooting
Mud-filled burrows
Sand-filled burrows
Horizontal laminations
Planar laminations
Trough cross-bedding
Parallel laminations
Mud lenses



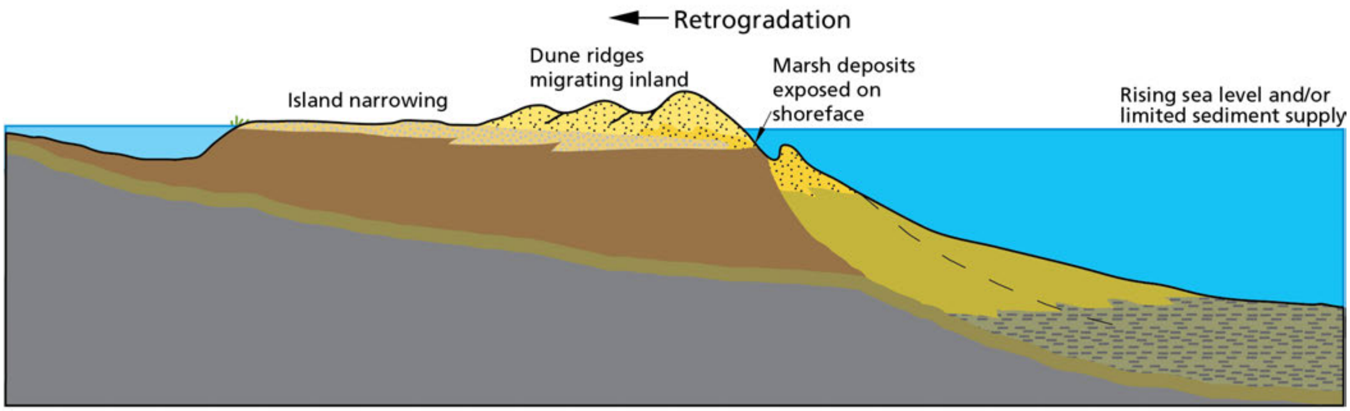


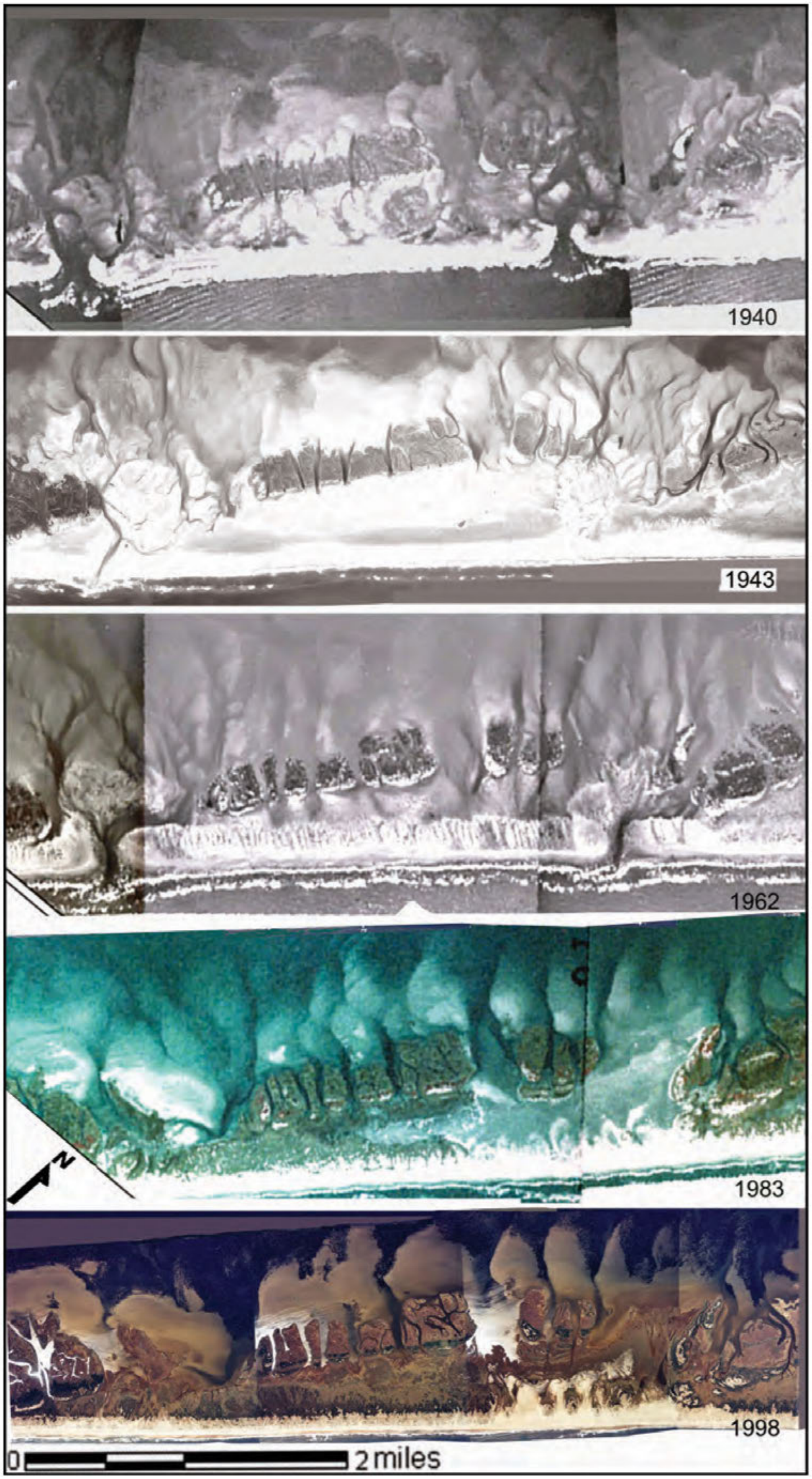
Figure 11. Schematic cross section showing a prograding shoreface during a regression (sea level fall and/or abundant sediment supply) and a retrograding shoreline during a transgression (sea level rise and/or low sediment supply). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after information provided by Kathleen Farrell (North Carolina Geological Survey, senior geologist, written communication, 13 August 2010) and Stanley Riggs (Department of Geologic Sciences, East Carolina University, professor, written communication, 30 December 2013).

deposited at depth, and are unlikely to be reworked by other processes. The size of the inlet fill bodies are comparable to modern inlets, with sequences that range from 2.8 m to 16.8 m (9 to 55 ft) thick, and widths of 0.72 to 2.1 km (0.45 to 1.3 mi). The inlet fill bodies are distinguished by three depositional patterns (fig. 6, 16) (Moslow and Heron 1978):

- a thin layer of coarse shell and pebble gravel, deposited on the inlet floor;
- a thick sequence of medium to coarse pebbly quartz and shell material deposited in the inlet channel; and
- an intermediate layer of very fine to medium grained clean sands deposited at the margin or spit platform.

Modern Core Banks is a simple barrier island with typical elevations of 1.5 to 3 m (5 to 10 ft), and an average width of 0.8 km (0.5 mi). During severe storms, much of the island is under water. Storm surges have opened at least nine inlets between Ocracoke and Barden Inlets since 1585, leaving large flood tidal deltas along the estuarine shoreline (Moslow and Heron 1978).

Figure 12 (facing page). A sequence of five georeferenced aerial photographs of the area of North Core Banks between Swash Inlet (left) and Whalebone Inlet (right). Vegetation in 1940, 1943, and 1962 is limited to back-barrier platform marshes and submerged sand bodies. The 1983 and 1998 aerial photographs show increasing amounts of subaerial, inter-tidal, and submerged aquatic vegetation with diminishing amounts of bare sand as overwash initially increased island elevation, which in turn decreased overwash and allowed vegetative cover to increase. Figure 26 from Riggs and Ames (2007).


1940
1943
1962
1983
N
1998
0
2 miles

Beginning in the 1970s, major storms created extensive overwash deposits on Core Banks, increasing its elevation and width and fostering increased vegetation growth (fig. 12) (Riggs and Ames 2007). In the absence of frequent overwash, the submerged fan-delta lobes became stabilized by aquatic vegetation and algae, and the intertidal portion of the fan-deltas evolved into low marshes. The post-1963 overwash plains formed stair-stepped ramps: the lower zone evolved into high marshes, the intermediate zone developed shrub-scrub communities, and the upper, oceanward part of the overwash ramp fostered scattered dune fields (Riggs and Ames 2007). As a result of this barrier evolution, the back-barrier environments of Core Banks have experienced a substantial increase in marsh wetlands and growth of submerged aquatic vegetation over the past four decades, in contrast to the majority of wetland-dominated marshes in North Carolina, which are experiencing severe erosion and wetland loss. This elevation-building was made possible by the generally undeveloped nature of Core Banks; constructed dune ridges and structures would have prevented such elevation building over much of Core Banks (Riggs and Ames 2007).

Shackleford Banks

Shackleford Banks is underlain primarily by tidal inlet-fill sequences up to 25 m (82 ft) thick (fig. 9; table 5). Those sediments overlie Pleistocene and late Tertiary shoreface sediment (fig. 6) (McNinch and Wells 1999); the Pleistocene Core Creek Sand is found from 17 m (55 ft) below MSL and up to 4.6 m (15 ft) above MSL.

Holocene sediments in the shallow bays and estuaries behind the barriers are 5 to 8 m (16 to 26 ft) thick, with fining-upward sequences of interbedded burrowed, rooted and laminated flood-tidal delta, salt marsh, and

Figure 13. The geomorphologic features on the western and eastern portions of Shackleford Banks are different due to the ages and processes during which they formed. The western half of the island has large dunes up to 9 m (30 ft) high and a maritime forest; the eastern half is lower, relatively flat, and is covered with grass and shrubs. Figure 6 from Riggs et al. (2015).

fine-to-medium overwash sediment (fig. 10) (Moslow and Heron 1994). The entire sequence of sediments in the area represents several episodes of changing sea level that occurred during the Pleistocene and Holocene (Susman and Heron 1979). Onslow Bay and the inner continental shelf to the south have very thin or absent Quaternary sediment cover (Mixon and Pilkey 1976; Meisburger 1979; Blackwelder et al. 1982; Hine and Snyder 1985) compared to the preserved Quaternary stratigraphic record to the north-northeast of Cape Lookout (York and Wehmiller 1992). The Yorktown Formation, a Pliocene limestone, is also present 21-25 m (69-82 ft) below the surface of Shackleford Banks (Susman and Heron 1979).

The geomorphologic features on the western portion of Shackleford are extremely different from the features on the eastern portions of the island (fig. 13). The western half of the island has large dunes up to 9 m (30 ft) high (Riggs et al. 2015) and a maritime forest; the eastern half is low and relatively flat, and is covered with grass and shrubs (Godfrey and Godfrey 1976). The evolutionary history illuminated by recent archeological datasets is described in the "Geologic History" chapter of this report.

Sediment Transport Processes

The geologic framework of the North Carolina inner shelf influences the sources, composition, transport, and sinks of sediment (Thieler et al. 2014). Sediment to the barrier islands comes from three main sources in the nearshore and inner continental shelf: ancient river channels, the Cape Lookout shoal complex, and sand-rich Pleistocene deposits (Riggs et al. 2009). Most modern riverine sediments are deposited in the bays and sounds; only fine sand and silt are carried to the ocean via inlets (Inman and Dolan 1989). In the nearshore between Cape Hatteras and Cape Lookout, fine to coarse iron-stained sand and shells are the most common sediment, with more shells occurring further from the shoreline (Inman and Dolan 1989). The percentage of yellow-red stained sand generally increases offshore. Iron staining is likely due to chemical weathering when the source sediments were exposed during low sea levels (Newton et al. 1971, as cited in Inman and Dolan 1989).

The foreshore (lower beach) of Core Banks, Cape Lookout, and Shackleford Banks have similar mean grain sizes, ranging from fine to medium sands (Pierce 1964, McNinch and Wells 1999). Gross longshore sediment transport westward along Shackleford Banks is around 40,000 m^3/yr (52,000 yd^3/yr) (Hine 1980). In comparison, along Core Banks, southerly sediment transport is estimated to be between 400,000 m^3/yr (523,000 yd^3/yr) (McNinch and Wells 1999) and 581,000 m^3/yr (760,000 yd^3/yr) (Park and Wells 2005).

Sediment transport along Cape Lookout and the shoals varies (fig. 8). Sediment moves southward along the eastside of the shoal, and northward along the west side of the shoal due to the high angle of wave approach from south and southwest waves. On the west side of the cape, northerly transport rates throughout the year were predominant (Park and Wells 2005).

An ample supply of sediment results in high and wide barrier island segments. Barrier island segments lacking significant sediment supply are typically simple overwash and inlet-dominated barrier islands (Riggs et al. 2009).

Eolian Transport

Isolated dunes are scattered along Core Banks. The rate of dune growth is controlled by the rate of sediment supply to the dunes. Dune size is controlled primarily by the distance from the shoreline that vegetation can grow and trap the sediment (Moore et al. 2015). The highest dunes are 7 m (23 ft) and occur as isolated mounds just south of Ocracoke Inlet.

Shackleford Banks faces the prevailing winds, which blow sand into the dunes, increasing their height to up to 10 m (33 ft) at the western end of the island (USACE 2013).

Wave Transport

Despite the high rate of longshore sediment transport, some areas of the shoreface and inner shelf are devoid of sand. Near the shore, there is commonly a thin layer of beach sand overlying older fluvial and estuarine sediments (muddy sands, mud, and sometimes rock that are remnants of pre-existing landforms). In some cases, the older underlying sediments are uncovered within 5 km (3.1 mi) of the shore in the region extending from Wilmington to Nags Head (Pearson 1979; Snyder 1993; Riggs et al. 1995; Miselis and McNinch 2006).

Raleigh Bay, the inner shelf area between Cape Hatteras and Cape Lookout, has both coarse and fine sediments (fig. 14). As sediment availability increases, such as on

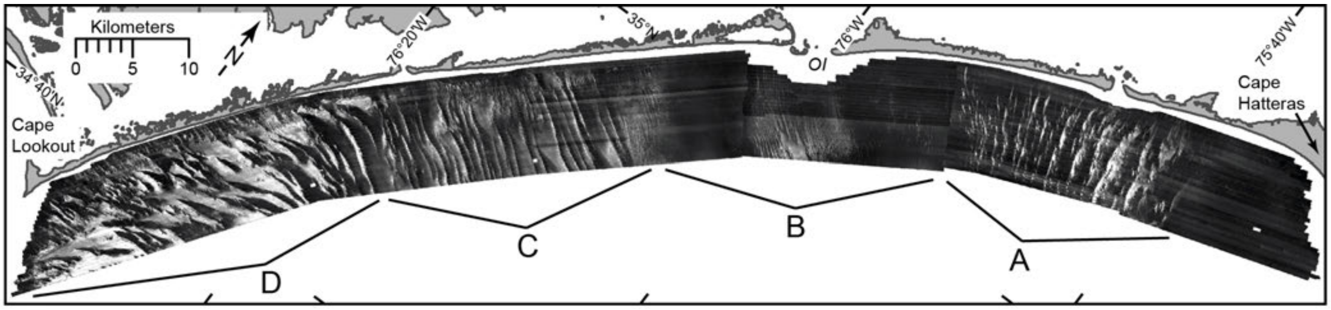


Figure 14. Map showing bathymetry including shoreface-attached ridges indicated by sidescan sonar mosaic of Raleigh Bay, between Capes Hatteras and Lookout. Dark tones indicate fine-grained sediments (low acoustic backscatter); light tones correspond to coarse-grained sediments (high acoustic backscatter). Shoreface-attached ridges occur where sediment availability increases, such as on the north side of Lookout Shoals (Region C). Southern Raleigh Bay (region D) has less continuous sorted bedform crests and troughs, in comparison with northern Raleigh Bay (Region A), and the seafloor in Region D has widespread coarse sediment, particularly in bedform troughs and on northeast-facing flanks of the ridges. Deposition of fine-grained sediment on the sea floor on either side of Ocracoke Inlet (Region B) results from inlet processes. OI=Ocracoke Inlet. Figure 13 from Thieler et al. (2014).

the north side of Cape Lookout Shoals, the inner shelf morphology is characterized by shoreface-attached ridges (Thieler et al. 2014).

Southern Raleigh Bay (region D in fig. 14) has fewer ridges than northern Raleigh Bay, and they are oriented oblique to shoreline. The seafloor has widespread coarse sediment, particularly in the troughs and on northeast-facing flanks of the ridges. Fine sediment covers ridge crests and all southwest-facing flanks (Thieler et al. 2014).

Examination of these sorted bedforms and their orientations in four regions of Raleigh Bay (fig. 14) indicate that waves and sediment transport move in two directions (Ashton and Murray 2006), towards both capes with a nodal zone in the middle (Region B). Sediment transport in Regions C and D is towards Lookout Shoals (Park and Wells 2005, Thieler et al. 2014). There is fine-grained sediment on the sea floor on either side of Ocracoke Inlet, which may represent sedimentation resulting from long-term, inlet-related processes since 1585; fine grained sediment on the ebb-tidal delta may indicate the lack of a preferential inner shelf sediment transport direction at this location (Thieler et al. 2014).

Nearshore water depth also interacts with waves, and currents to develop rip currents, which are common along the park shoreline and pose a safety concern for visitors. Waves break more strongly in some locations than in others, a pattern seen most often along beaches with nearshore bars separated by channels. A rip current forms as the narrow, fast-moving section of water travels in an offshore direction, usually through a break between the nearshore shore-parallel bar (NWS 2004).

Overwash and Landward Migration

Storm overwash is an important process in building island elevation, expanding marsh platforms, and creating and maintaining early-succession habitat. Overwash deposition maintains narrow marshes that would otherwise disappear without that sediment input (Walters et al. 2014) or rapid organic (peat) creation. Because vegetation, along with sediment supply, determines the size of coastal foredunes, plants play an active role in determining the vulnerability of barrier islands to erosion caused by storm-induced overwash (Moore et al. 2015).

When small storm surges produce waves that overtop the island berm and erode the dune ridge, sediment is deposited in small overwash fans along the beach or in the interior of the barrier island. Large storms can drive meters of water across the island berm, resulting in large, arcuate overwash ramps that bury the back-barrier platform marshes and may even build shallow shoals in the estuary (fig. 4) (Riggs et al. 2009). By moving sediment on top of and across the island, overwash builds island elevation and width. The change in elevation subsequently controls the locations of post-storm habitats and revegetation (e.g., scrub shrub, high and low marsh) (Riggs and Ames 2006).

When a major storm erodes the shoreface sand, flattens

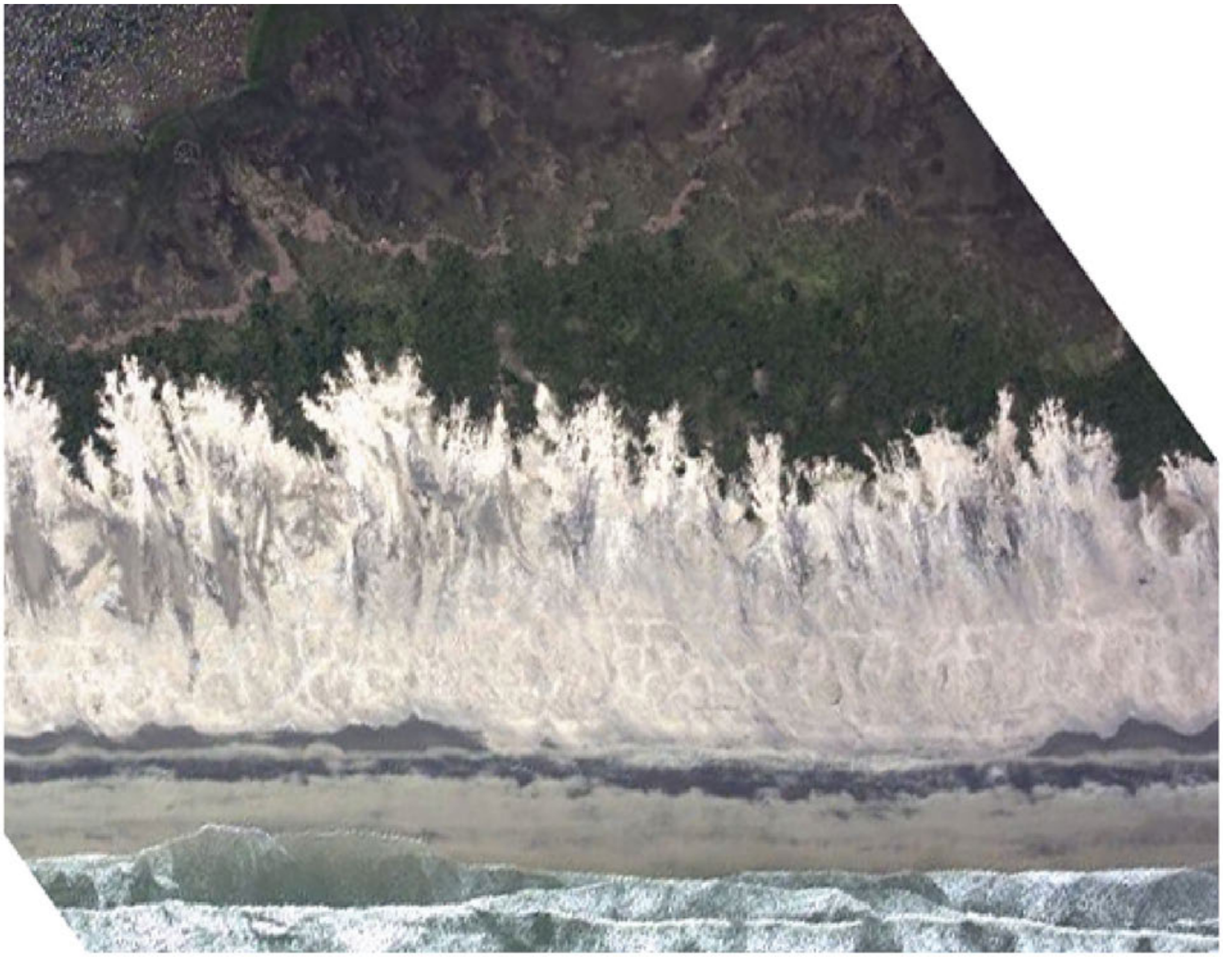


Figure 15. Aerial imagery of overwash. When a major storm erodes the shoreface sand, flattens island topography, and buries vegetation across the island, a low and wide island area results. (Top) This portion of Core Banks is dominated by a new overwash plain that formed during Hurricane Irene (2011). Notice that the broad plain of newly deposited sand was built by a vast network of individual fans that have added substantial elevation to the island and a portion of the back-barrier platform marsh. (Bottom) An aerial photograph of Portsmouth Island after the 1962 Ash Wednesday storm when peak storm surge flowed completely across the overwash ramp and through the tidal channels and deposited vast shoal system into Pamlico Sound (top of the image). As the storm waned, the decreasing storm surge produced the smaller-scale berm crest and overwash fans along the oceanfront. Notice that this newly deposited sand sheet has no vegetation as occurs on the older portion where Portsmouth Village is located. Top image from NOAA Emergency Response Imagery (http://storms.ngs.noaa.gov/storms/irene/index.php). Bottom is figure 3 from Riggs and Ames (2007).

island topography, and buries vegetation across the island, a low and wide island area results. On islands without fixed features, such as forested berms or houses, the resulting overwash plain will form broad overwash ramps that diminish gradually into the back-barrier and estuarine habitats (fig. 15, top). On islands with fixed features, a more irregular geometry of arcuate back-barrier shoals and associated tidal channels will form, and the overwashed sediments will evolve into the classic "molar-tooth" structure (fig. 16b). In this formation, the lower overwash ramp is dominated by platform marshes in the intertidal zone, with back-barrier shoals in the subtidal and submarine zones. The platform marshes are separated by active tidal channels that move water and sediment onto and off of the supratidal portion of the middle overwash ramp, which is often dominated by interior marsh or algal flats (Riggs and Ames 2006).

The first vegetation to recolonize the island is salt tolerant, particularly on the middle and lower overwash ramps, with the early development of salt marsh grasses in the intertidal zone and high salt marsh grasses and microbial mats above the tideline. With time, the middle and upper portions of the overwash ramp will revegetate with grasses such as Spartina patens and dune grasses. Early-succession plants can generally tolerate subsequent overwash events and are important in stabilizing sediment on the back side of the island. Wrack, dead plant material from the marsh and aquatic vegetation, forms a series of fringing berms around the platform marshes and absorbs much of the wave energy coming onto the marsh during small storm tides (Riggs and Ames 2006).

The rate at which an island migrates landward through overwash processes is controlled by the following factors:

- an increase in the volume of sand on the back-barrier region leads to a decrease in landward migration rates of the barrier island (Walters et al. 2014);
- relative rate of sea level rise (Walters et al. 2014)
- underlying geology and stratigraphy (Belknap and Kraft 1985; Riggs et al. 1995; Masetti et al. 2008; Moore et al. 2010);
- sediment grain size (Storms et al. 2002; Masetti et al. 2008);
- substrate slope (Storms et al. 2002; Wolinsky and Murray 2009; Moore et al. 2010; Walters et al. 2014); and
- substrate erodibility (Moore et al. 2010).

The barrier island and marsh systems are coupled (Walters et al. 2014). Under rising sea level, a back-barrier marsh will lose areal extent equal to the rate at which the barrier island rolls over the marsh platform, unless the marsh progrades into the sound as it is flooded by the rising sea level. Sediment deposited on the marsh by overwash may maintain marsh elevation relative to rising sea level, complementing or negating the need for fine-grained sediment deposition through flooding.

Model results suggest that the width of back-barrier marshes are constantly adjusting by narrowing or widening, until either the estuarine basin becomes completely filled or the marsh has completely eroded away (Walters et al. 2014). Tidal salt marsh accretion rates depend on fine-grained sediment input, which primarily occurs when sediment-laden water floods the marsh (Kirwan et al. 2011; Mudd 2011; Gunnell et al. 2013) and increases in the growth rate and subsequent organic deposition of marsh vegetation (e.g., Spartina alterniflora) in response to high tide levels (Cahoon and Reed 1995; Morris et al. 2002; Mudd et al. 2010; Kirwan et al. 2011). This maintains the elevation of the marsh platform relative to sea level and keeps marsh plants within the elevation range to which they are adapted (French 1993).

The longshore presence or absence of back-barrier marshes is also correlated to barrier island migration rates (Walters et al. 2014). Where back-barrier marshes are present, the island will migrate onto the top of the marsh as relative sea level rises. The island can maintain its offshore position without significant sand input from the shoreface or longshore sand transport. The presence of a marsh platform reduces the space, behind the island that would need to be filled with sediment in order to reach sea level. Such a situation would reduce the landward migration rate of the island (Walters et al. 2014). When relative sea level rise rates become too high, and the input of fine-grained sediments becomes too low, marshes can transition to become tidal flats, which is a different stable state (Fagherazzi et al. 2006; Mariotti et al. 2010).

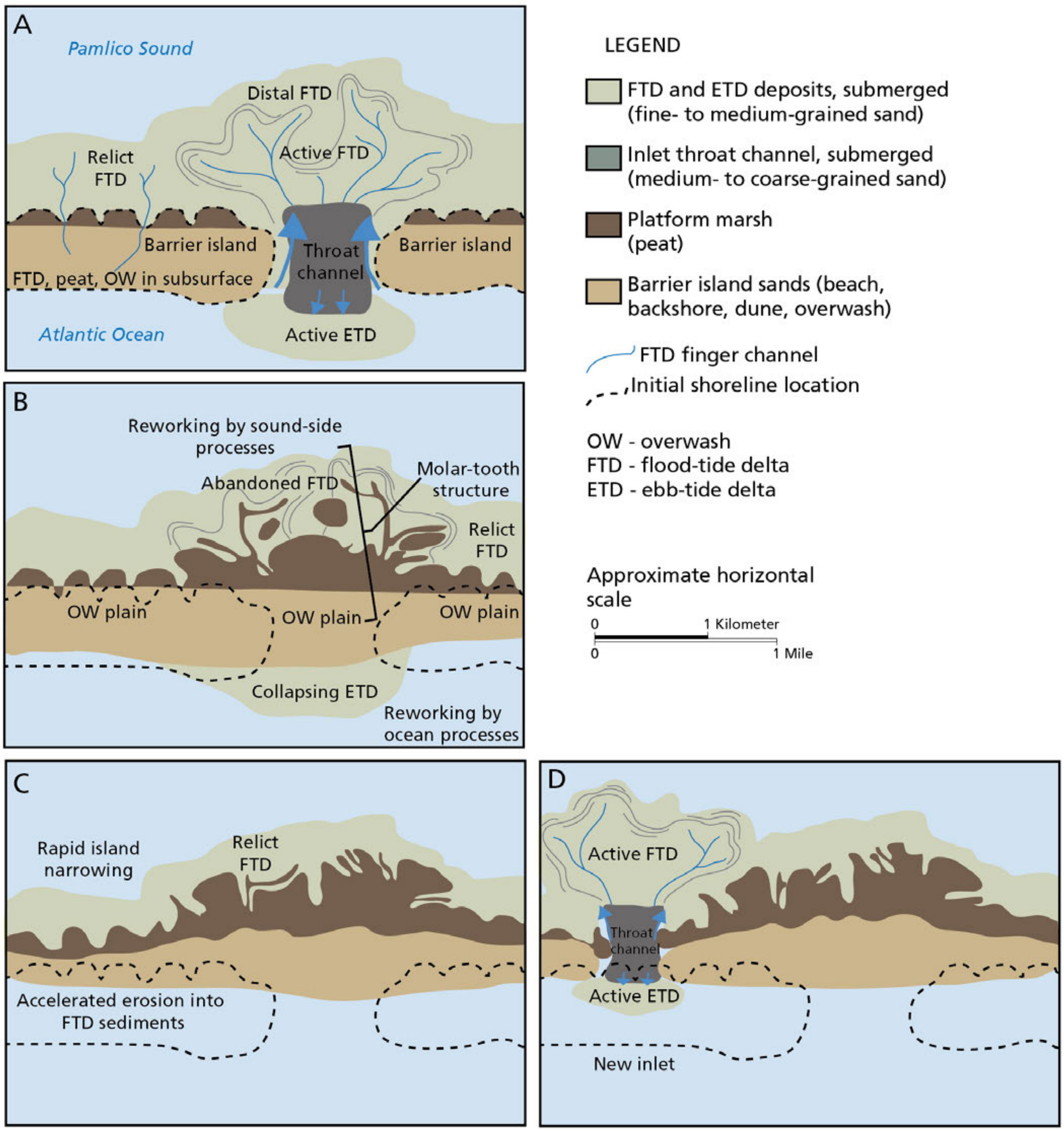


Figure 16. Schematic illustrations of inlet formation. Inlet formation and shoreline recession are important components of barrier island evolution. (A) Active flood and ebb tidal deltas (FTDs and ETDs, respectively) form in association with an inlet. (B) As the inlet closes, the ETD collapses, causing temporary and localized shoreline accretion, while adjacent areas continue to erode. A molar-tooth platform marsh and marsh islands develop on FTD shoals, increasing island width. (C) Continued coastal erosion narrows the island more rapidly in areas underlain by fine FTD sediments, while slower erosion occurs where coarse sands are associated with the inlet throat channel. (D) The narrow portion of the island breaches during a storm and cross-island flow and downcutting create a new inlet. Erosion accelerates in adjacent areas underlain by fine FTD sediment, continuing the evolutionary succession. Graphic redrafted by Trista Thornberry-Ehrlich (Colorado State University) after figure 3 and text from Mallinson et al. (2008b). OW = overwash.

Frequent overwash of Core Banks during stormy periods (1960-1962 and 1971-2005) increased island width and added elevation to the barrier islands (Riggs and Ames 2007). The islands with higher elevation had a reduced frequency and extent of overwash events. Without overwash in those segments, the ocean shoreline slowly recedes, narrowing the island and moving the island berm farther inland, ultimately eliminating the middle overwash zone. As the island narrows, overwash is re-established once again, re-building the back barrier and marsh platforms (Riggs and Ames 2006).

Oceanographic Conditions

The Gulf Stream along North Carolina is located seaward of the continental shelf-slope break. It flows northward and drives the predominantly counterclockwise circulation in Raleigh Bay through frictional forcing (Mallin et al. 2006).

Core Banks receives triple the wave energy of Shackleford Banks. The mean tidal range along Core Banks and Portsmouth Banks is 0.47 m (1.5 ft) (Heron et al.1984), half of the 1 m (3 ft) range found along Bogue and Shackleford Banks (Klavans 1983); this difference is at least partly responsible for many of the variations in morphology and sedimentation observed between the northern and southern zones (Heron et al.1984). Mean annual wave height is 1.58 m (5.18 ft) with wave heights exceeding 2.0 m (6.6 ft) approximately 26% of the year (McNinch and Wells 1999); these values are among the highest for the U.S. East Coast (Heron et al. 1984). Summer waves arrive primarily from the southeast; in the other seasons, wave direction is primarily from the east. The longest average wave period is from the east at 10.7 s, followed by 9.7 s from the southeast (McNinch and Wells 1999). Fall and winter winds are primarily from the northeast to northwest (McNinch and Wells 1999). Spring and summer winds are primarily from the southwest, but wave height is fetch-limited and wind events are less energetic than the northeasterly winter storms (McNinch and Wells 1999).

Cuspate coastlines such as that of Cape Lookout are controlled by the interactions of coastline shape, underlying geology, and gradients in longshore sediment flux (Ashton et al. 2001), and are sensitive to small changes in the long-term wave climate (Moore et al. 2013). In fact, the Cape Lookout area has become increasingly asymmetric since 1975, changing shape in response to a pattern of increasing erosion along the northeastern flank (Core Banks) and increasing accretion on the southwestern flank (Shackleford Banks) of the cape (Moore et al. 2013).

Inlets

An inlet through a barrier island is created when storm-driven surges flow across an island and excavate a channel from either the ocean or estuarine side (FitzGerald and Hayes 1980). The inlet widens by erosion and collapse of the adjacent bank, and deepens as flow scours the channel (Wamsley et al. 2009).

Tidal currents construct a flood tidal delta on the estuarine side of the barrier island and an ebb tidal delta on the ocean side. These tidal deltas are created where sediment is deposited as the swiftly moving tide dissipates into larger water bodies (fig. 16a) (Riggs et al. 2009). Tidal delta shoals are important components of both the coastal sediment budget and long-term evolution of the barrier islands. Ebb tidal deltas store sand and episodically release it to nearby beaches and coastal systems. Waves and currents rework the ebb-tidal delta sand into shoals, which migrate alongshore and merge with the beach downdrift of the inlet (Mallinson et al. 2008b).

Shoals along the inlet margins are often formed after a storm, when the water flow returns to normal. Sufficient depth of scour in the inlet allows the interchange of lagoon water and ocean water after the storm has subsided, and tidal flow continues to widen and deepen the channel. The exchange of water through new inlets also moves nutrients, organisms, and sediment out of and into back-barrier sounds (Dolan and Lins 1986; Ames and Riggs 2006j).

If the inlet flow is strong enough to flush sediments faster than they are introduced, the inlet is maintained (Wamsley et al. 2009). However, many inlets are temporary features produced by elevated storm water levels and last only a few days (Dolan and Lins 1986). Ephemeral inlets can open and close on a time scale of months to years (Mallinson et al. 2010b). If the inlet closes, the shallow flood-tidal delta shoals become the base of back-barrier marshes (fig. 16b) (Dolan and Lins 1986), which are necessary for island migration as sea level rises (Riggs et al. 2009; Mallinson et al. 2010b).

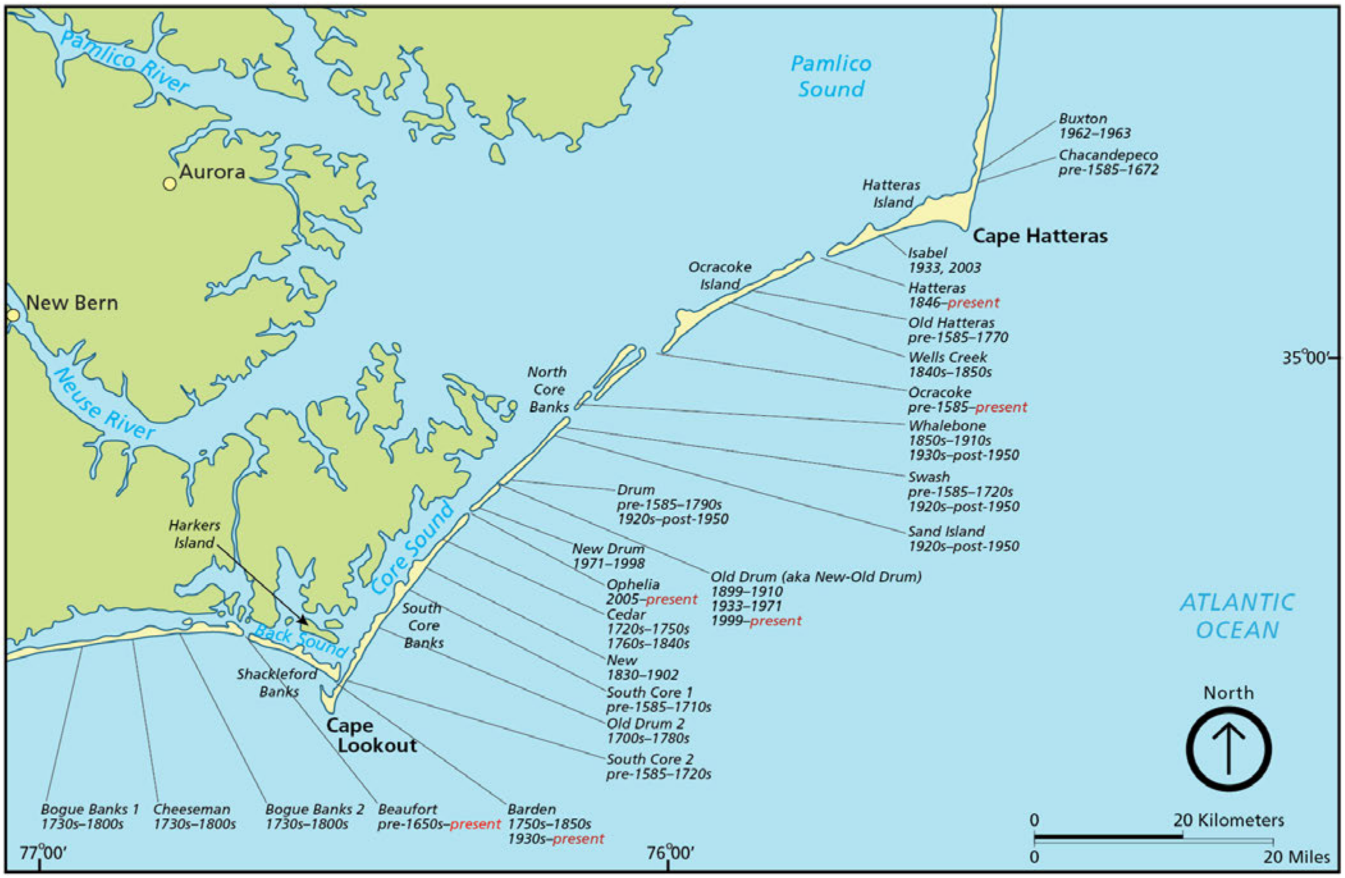


Figure 17. Location and duration of historical and modern inlets along the Outer Banks. Graphic by Trista Thornberry-Ehrlich (Colorado State University), created with information from Fisher (1962), Dolan and Lins (1986), and Mallinson et al. (2010b). Table 6 also lists the inlets and their duration.

Coastal erosion narrows the island more rapidly in areas underlain by fine flood-tidal delta sediments, while slower erosion occurs where coarse sands are associated with the inlet throat channel (fig. 16c). As overwash buries the marsh, the ephemeral inlet channels are filled with sand. The barrier island migrates over the former marsh, which often crops out on the beach and upper shoreface during storms. As storm surge flows over the narrow portions of a barrier island, the exposed marsh peat surface resists erosion while the adjacent sand-filled tidal channels and narrow portions of the island are more easily eroded, producing new inlet channels (fig. 16d) (Mallinson et al. 2008b; Riggs et al. 2009).

Historic Inlets

As many as 30 inlets have opened and closed between Cape Hatteras and Bogue Banks since the first European presence in this area 400 years ago (fig. 17; table 6) (Dolan and Lins 1986), and approximately 70% to 85% of the Outer Banks have had one or more inlets in the past 500 years (Riggs et al. 2009).

Ocracoke Inlet, the northern boundary of Cape Lookout National Seashore, appears on maps as far back as 1590 and has historically been relatively stable, likely because it occurs within the ancient river valley of Pamlico Creek, which drained the Pamlico Sound basin during the Last Glacial Maximum (Riggs and Ames 2003; Mallinson et al. 2008, 2010a). It is now irregularly dredged; see the “Inlet Maintenance” section of the “Geologic Resource Management Issues” chapter for additional information.

Old Drum Inlet separated northern Core Banks from southern Core Banks from 1899 until 1910, when it closed naturally (fig. 18) (Riggs and Ames 2007). During a 1933 hurricane, storm surge returning from the bay into the ocean re-opened the inlet, then built a flood-tidal delta over time (Riggs and Ames 2007). The inlet was dredged for several decades, but continued to narrow and migrate southwestward, closing naturally in

Table 6. Location and duration of historical and modern inlets along the Outer Banks. Inlets are listed North to South and then East to West. See figure 17 for map.

Location/Island	Inlet Name	Duration
Hatteras Island	Buxton	1962–1963
Hatteras Island	Chacandepeco	pre-1585–1672
Hatteras Island	Isabel	1933, 2003
Between Hatteras and Okracoke Islands	Hatteras	1846–**present**
Ocracoke Island	Old Hatteras	pre-1585–1770
Ocracoke Island	Wells Creek	1840s–1850s
Between Ocracoke Island and North Core Banks	Ocracoke	pre-1585–**present**
North Core Banks	Whalebone	1850s–1910s 1930s–post-1950
North Core Banks	Swash	pre-1585–1720s 1920s–post-1950
North Core Banks	Sand Island	1920s–post-1950
North Core Banks	Drum	pre-1585–1790s 1920s–post-1950
North Core Banks	Old Drum (aka New-Old Drum)	1899–1910 1933–1971 1999–**present**
North Core Banks	New Drum	1971–1998
Between North and South Core Banks	Ophelia	2005–**present**
South Core Banks	Cedar	1720s–1750s 1760s–1840s
South Core Banks	New	1830–1902
South Core Banks	South Core 1	pre-1585–1710s
South Core Banks	Old Drum 2	1700s–1780s
South Core Banks	South Core 2	pre-1585–1720s
Between South Core and Shackleford Banks	Barden	1750s–1850s 1930s–**present**
Between Shackleford and Bogue Banks	Beaufort	pre-1650s–**present**
Bogue Banks	Bogue Banks 2	1730s–1800s
Bogue Banks	Cheeseman	1730s–1800s
Bogue Banks	Bogue Banks 1	1730s–1800s

Sources: Fisher (1962), Dolan and Lins (1986), and Mallinson et al. (2010b)

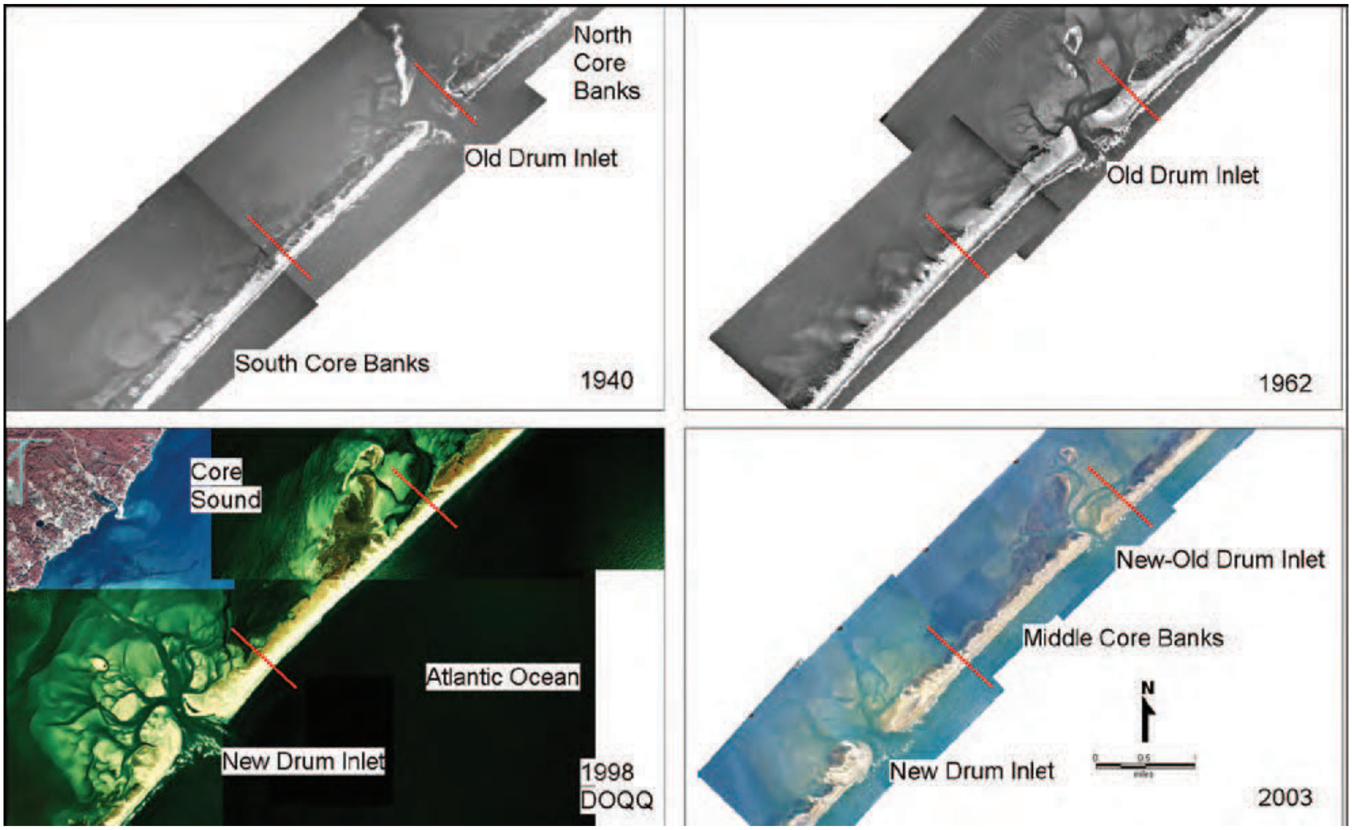


Figure 18. A four-part, georeferenced aerial photograph time series (A, 1940; B, 1962; C, 1998; and D, 2003) showing the evolution of Old Drum Inlet, New Drum Inlet, and New-Old Drum Inlet. The red reference lines represent two fixed positions and show the changing relative locations of the inlets through time. Figure 2 from Riggs and Ames (2007).

January 1971; marsh grew on the flood-tidal delta (Riggs and Ames 2007). Hurricane Dennis reopened Old Drum Inlet in 1999.

In December 1971, New Drum Inlet was dredged 4 km (2.5 mi) south of Old Drum Inlet, but experienced rapid shoaling (Mallinson et al. 2008b). The USACE dredged it until 1998. It closed in 2010, but its former location continues to overwash during large storms (Jon Altman, biologist, Cape Lookout National Seashore, email, 19 January 2017).

In 2005, Hurricane Ophelia opened a new inlet (Ophelia Inlet) 0.25 mi southwest of New Drum Inlet; it is a wide inlet and has been migrating southward (Jon Altman, biologist, Cape Lookout National Seashore, email, 19 January 2017).

The maintenance history of Ocracoke, Drum, Barden, and Beaufort Inlets are described in the “Inlet Modifications” section of the “Geologic Resource Management Issues” chapter.

Estuaries

Core and Back sounds are the narrow shallow-water estuaries behind Cape Lookout National Seashore. The sounds are at the southern end of the Albemarle-Pamlico estuary system, which is the second largest estuary in the United States and which drains a watershed of approximately 77,700 square km (30,000 square mi) with five major river basins (Chowan, Roanoke, Pasquotank, Tar-Pamlico, and Neuse).

Tide range within the Albemarle-Pamlico estuarine system is low in most areas (10 cm [3.9 in] or less) (Wells and Kim 1989), but is higher in Core and Back sounds, where there is little direct input from rivers. The tidal ranges are increased by the presence of the inlets. Pamlico Sound receives freshwater from five major watersheds and has a surface area of 435,000 ha (110,000 ac) (Giese et al. 1985), with an annual turnover of 1.7 years (Burkholder et al. 2004, as cited in Mallin et al. 2006). This long residence time is the result of the sound’s limited connection with the Atlantic Ocean, which occurs primarily through three narrow inlets

(Paerl et al. 2006). Circulation is controlled by wind-driven currents. Average currents in Pamlico Sound are 10 to 26 cm (3.9 to 10.2 in)/s, with a high speed of 69 cm (27 in)/s recorded during a squall and a low speed of 0.5 cm (0.2 in)/s (Wells and Kim 1989). The winds driving the currents also presumably influence the bottom sediments through processes of wave resuspension (Wells and Kim 1989).

Increased surface water temperatures associated with climate change may increase the frequency and severity of hypoxic (oxygen deprivation) events in the sounds (Diaz and Rosenberg 2008), which are already problematic (Stanley and Nixon 1992; Paerl et al. 2001) and may exacerbate other ecological concerns in the sounds (NPS 2016). The inlets around the park increase water exchange with the ocean and would reduce the risk of hypoxia in Core and Back Sounds in comparison to the inner portions of Pamlico Sound.

Core Sound is very saline (25-36 ppt in Summer 2004) due to the presence of three inlets and limited freshwater input (Pruitt et al. 2010). Core Sound experiences both astronomical tides and wind tides; the latter have a major influence on water levels due to the fetch and relatively uniform depth of the large sounds to the north (Riggs 2002). Wind-driven water level can be as a high as 3 m (10 ft) during storm events (Pilkey et al. 2002). As a result of the low fetch and shallow water in portions of Core Sound, the estuarine shorelines have low erosion rates, and are actually accreting in places where overwash occurs (Riggs and Ames 2006).

Back Sound is very shallow in most areas adjacent to the park, averaging less than 1 m (1 to 2 ft) deep at low tide (USACE 2016). High tidal flushing occurs around Beaufort Inlet because it is more than 6 m (20 ft) deep; tidal currents can reach speeds up to 2.1 m (6.7 ft)/s (NOAA 2005).

Estuarine Sediments

Wells and Kim (1989) thoroughly described the sediments in the Albemarle-Pamlico Sound System. These sediments are derived from four major sources: rivers, coastal erosion, the continental shelf, and fauna and flora (e.g., shell fragments). Minor contributions are derived from silt and sand transported from the barrier islands by storms and from unvegetated agricultural fields on the mainland. Input from rivers is mostly silt and clay with high organic content. Shell fragments (fig. 19) represent less than 2% of bottom sediments throughout much of Pamlico Sound, but more than 16% of sediments at Ocracoke Inlet, where fragments are transported from adjacent Outer Banks beach environments. High concentrations of shell fragments (8% to 16%) in the central basin and seaward of the Pamlico and Neuse rivers may be related to preferential growth of oysters in these regions.

Wells and Kim (1989) also described sediment transport into the sound. Coastal erosion by direct wave attack provides the major source of coarse sediment, mainly from high banks and bluffs that are undercut during storms and then collapse onto the beach (fig. 5). Erosion rates of 1 to 3 m/yr (3.3 to 10 ft/yr) are sufficient to supply sediment to beaches along the estuarine shorelines. Most of the sands in Core Sound are barrier island sand carried by overwash and offshore sediments carried through inlets, as evidenced by the similarity in texture and mineral composition between sound and barrier-island sediments. Flood tidal deltas, including the one formed by Ocracoke Inlet, account for approximately half of the medium-grained sand in the Albemarle-Pamlico estuarine system. The estuarine shoals support vast beds of aquatic grass and associated benthic ecosystems.

Groundwater

The marine sediments that underlie the park form eight significant aquifers and confining units: the surficial unconfined aquifer, Yorktown, Castle Hayne, Beaufort, Peedee, Black Creek, Upper and Lower Cape Fear aquifers (Lautier 2001). A confined aquifer is bounded above and below, and contains confined groundwater. An unconfined aquifer contains water that is not under pressure beneath a confining bed The surficial sand aquifer, Yorktown aquifer, and Castle-Hayne Aquifer have fresh groundwater (table 2, fig. 20) (Winner 1978).

The surficial unconfined aquifer extends from the land surface down to the first beds of silt and clay (a maximum of 30 m [100 ft]); it is composed of modern barrier island sands and is subject to periodic salt water overwash (fig. 20). The aquifer is recharged by rainfall and discharges into the ocean and sound. The water level of the aquifer has been decreasing gradually, according to daily measurements collected since 1986 (NPS 2011b). Fresh water in this aquifer is a lens-shaped mass floating in and above denser salt water. Development of a freshwater lens is limited by

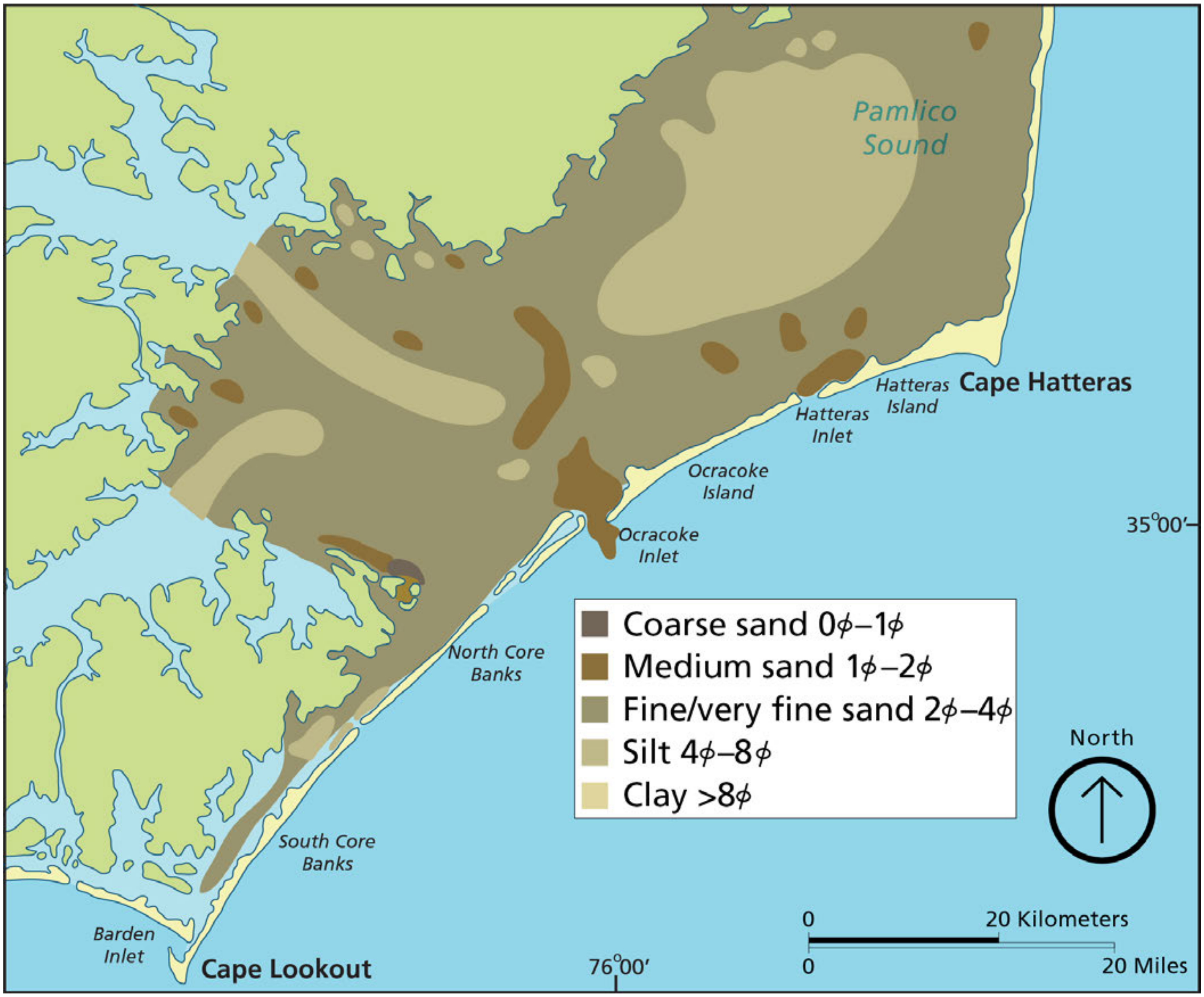


Figure 19. Sediment size distribution in Pamlico Sound, following the Wentworth classification. Figure redrafted by Trista Thornberry-Ehrlich (Colorado State University) after figure 7 in Wells and Kim (1989).

the presence of confining beds, the effects of tides, and periodic storm overwash (Winner 1978). Dunes at Cape Lookout and on Shackleford Banks prevent most storm overwash from inundating the freshwater lens (Winner 1978). When overwash does occur, it can take weeks to months for the saltwater to be flushed from the aquifer and for the freshwater lens to be restored, depending on the amount of saltwater overwash infiltration and the amount of subsequent rainfall.

Several freshwater ponds are present on northern Core Banks (Mallin et al. 2004). These ponds vary widely in size, vegetation composition, and pH (Schwartz 1982, as cited in Heron et al. 1984). Additional, ephemeral ponds form in or near marsh areas and are highly dependent on rainfall, but are not entirely freshwater (Rasmussen et al. 2009). Groundwater withdrawals may reduce the freshwater recharge to surficial ponds (Mallin et al. 2004). A number of freshwater ponds are also found on Shackleford Banks, principally on the west end (Mallin et al. 2004). The unconfined surficial aquifer provides the only source of freshwater for the horses on Shackleford Banks.

The upper confined aquifer is part of the early Pliocene Yorktown Formation (fig. 20) and is composed of sand, partially consolidated shell beds, and sandy limestone. It occurs at depths of 18-41 m (60-135 ft) (fig. 20). Some of the sand and shell beds at the top of the aquifer may be of Quaternary age. The aquifer is recharged by

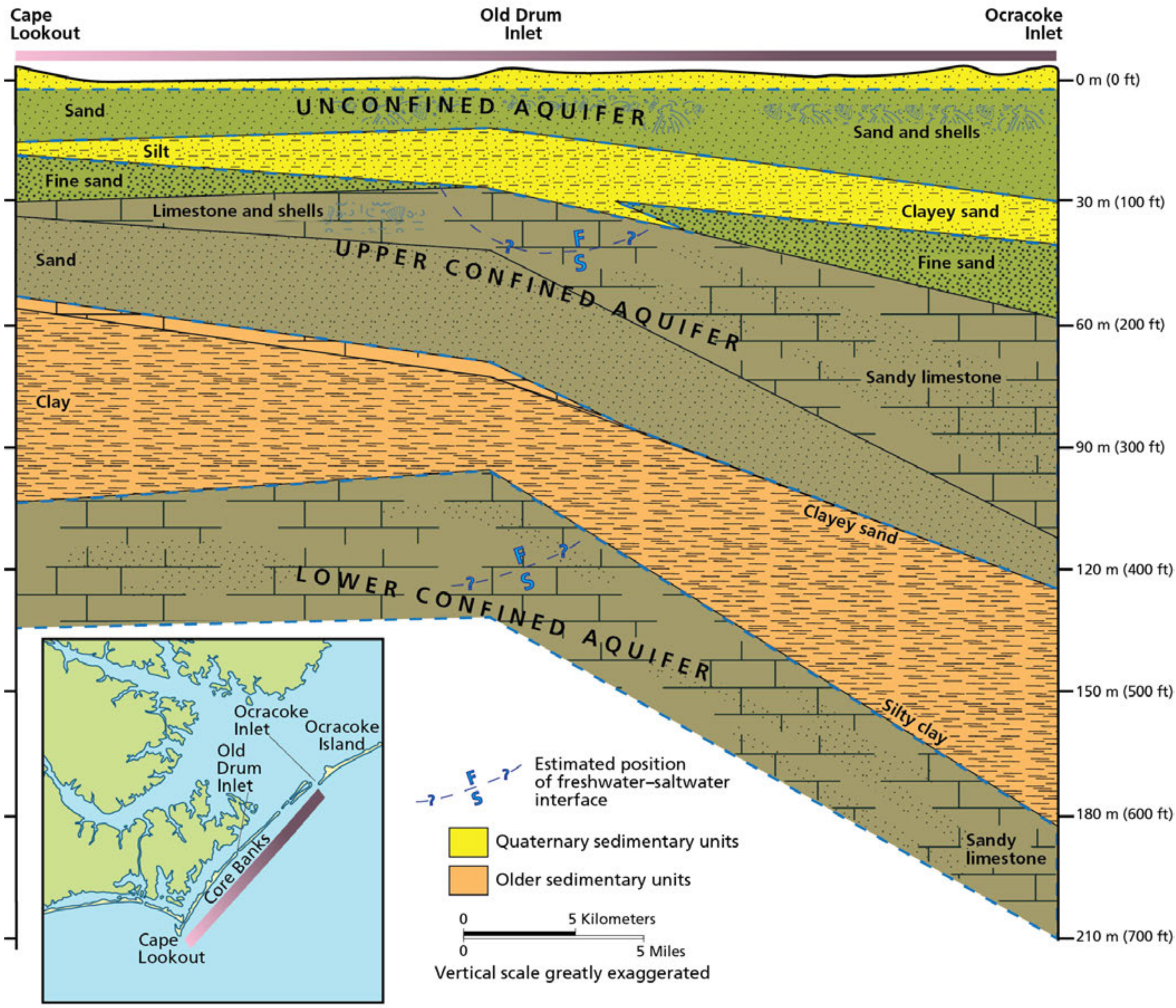


Figure 20. Hydrogeologic cross-section from Cape Lookout to Ocracoke Inlet. A confined aquifer is bounded above and below by confining beds, and contains confined groundwater. Groundwater in the unconfined surficial aquifer is affected by tides and storm overwash, which cause saltwater infiltration, and by rising sea level, which drives saltwater intrusion and water-table height. Graphics by Trista L. Thornberry-Ehrlich (Colorado State University) based on Figure 3 from Winner (1978).

freshwater moving from areas where the aquifer crops out on the mainland. Studies in the Drum Inlet area indicate that freshwater may also be leaking upward from the lower confined aquifer (Winner 1978).

The lower confined aquifer, known as the Castle Hayne aquifer, consists of Oligocene-age medium to coarse-grained limestone that is over 61 m (200 ft) thick; it occurs at depths of 104-183 m (340-600 ft) and contains freshwater (fig. 6, 20). The lower aquifer is confined by an overlying layer of clay, silty clay, and clayey sand that is part of the Pungo River Formation of early and middle Miocene age (Winner 1978). It is the highest-yielding aquifer in the North Carolina coastal plain (Lautier 2009). Annual measurements indicate a gradual decline in water level since 2003 (NPS 2011b).

Climate change may influence groundwater by driving salt water intrusion, raising water tables, and changing soil moisture. Groundwater dynamics in surficial aquifers are affected directly by rising sea levels and indirectly by the associated morphological changes in the barrier islands. An increase in sea level changes the groundwater discharge to surface water such as ponds and wetlands, affecting aquifer salinity and the volume of the freshwater lens. Models show that a sea level rise of 20 cm (0.7 ft) would lead to substantial changes in the depth of the water table and the extent and depth of saltwater intrusion, both of which strongly influence the establishment, distribution and succession of barrier island vegetation and habitat, particularly in the marsh and shrub thicket zones (Masterson et al. 2013). The increased water-table height in areas where the water occurs near the surface resulted in inundation of the land and a thinning of the freshwater lens. Groundwater response was shown to have a strong interdependence with island morphology (Masterson et al. 2013).

Paleontological Resources

Paleontological resources (fossils) are any evidence of life preserved in a geologic context (Santucci et al. 2009). All fossils are non-renewable. Body fossils are any remains of an actual organism such as bones, teeth, shells, or leaves. Trace fossils are evidence of biological activity; examples include burrows, tracks, or coprolites (fossil dung). Park fossils present opportunities for education, interpretation, and continued or future scientific research in the park. NPS allows collecting of modern (not fossil) shells if the shell does not contain a live animal; the Superintendent's Compendium establishes personal daily limits (5 gallons per day) (Pat Kenney, Cape Lookout National Seashore, superintendent, conference call, 20 October 2015). The NPS Fossils and Paleontology website, http://go.nps.gov/fossils_and_paleo, provides more information about fossils servicewide. The fossils of Cape Lookout National Seashore and other parks in the NPS Southeast Coast Network were summarized by Tweet et al. (2009).

Fossils in the park may wash up onshore, be exposed by erosion, or be sampled by drilling. Pleistocene marine shell assemblages are abundant on North Carolina beaches, and it can be difficult to differentiate between fossils and recent remains. Stained shells are considered to be fossils (Riggs et al. 1995; Wehmiller et al. 2003). Black or brown stained shells may correspond to anoxic coastal swamps or estuarine deposits. Brown shells are generally younger (Pleistocene or Holocene) than black shells; however, in anoxic sediments, shells can become blackened in as little as three weeks (Pilkey et al. 1969). The common bivalve *Mercenaria* commonly changes from chalky white (modern) to yellow-orange (Holocene) to gray-black (Pleistocene). Boring by other invertebrates (Pilkey et al. 1969), abrasion, and trace element composition can also be used to distinguish modern from fossil shells (Wehmiller et al. 2003). Pleistocene and Holocene coastal sediments from the park may include crustacean burrows (from coastal settings); peat and tree stumps (from back-barrier forests and swamps); and shell fragments (from the base of inlet deposits). Middle Marsh and Back Sound, landward of the park, have estuarine mollusks (bivalves and gastropods) and echinoids dated from 2850 BCE to 380 CE (Berelson and Heron 1985).

Quaternary fossils eroded out from nearshore outcrops wash onto the park shoreline. A late Pleistocene terrace crops out in 9 to 12 m (30 to 40 ft) of water. Fossils from this unit include sponges, bryozoans, polychaete worm tubes, barnacles, echinoderms, and various mollusks (bivalves, gastropods, and scaphopods). Offshore ridges of coralline algae (a type of reef-forming algae), up to 26,250 years old, also contribute to the sediment that may wash up (Cleary and Thayer 1973). There is also the potential for vertebrate remains to wash onshore, as evidenced at Cape Hatteras to the north (Tweet et al. 2009).

The park has potential buried fossil resources that may be sampled by shallow drilling (less than 30 m [100 ft] below sea level) (Tweet et al. 2009). Beneath Core Banks, the Holocene sediments extend down at least 6 m (20 ft) below sea level and include peat, plant fragments, bryozoans, bivalves and other mollusks, polychaete worm tubes, barnacles, and echinoderms. The Diamond City Clay, found 9 m (30 ft) to 22.2 m (73 ft) below mean sea level, contains corals (Susman and Heron 1979), bryozoans, mollusks, polychaete tubes, barnacles, decapods, and ostracods (small shelled crustaceans) (Tweet et al. 2009). The Atlantic Sand, present in some areas between the Diamond City Clay and Core Creek Sand, contains mollusks in shell hashes at the base, as well as bryozoans, barnacles, and echinoids. The Core Creek Sand (down to 30 m [98 ft]) includes corals, bryozoans, bivalves, polychaete tubes, barnacles, ostracods, and echinoderms. Fossils are rare under the Pliocene-age Yorktown (Duplin) Formation caprock in the South Core Banks, but if present, could be foraminifera (single-celled shelled animals), corals, bryozoans, barnacles, ostracods, echinoids, or various mollusks (bivalves, gastropods, scaphopods, and chitons) (Tweet et al. 2009).

Beneath Portsmouth Bank, there are mollusks present in a unit correlated with the James City Formation (1 MYA, lower Pleistocene), which is found at a depth of 27.7 to 28.7 m (90.9 to 94.2 ft) and 32.9 to 34.4 m (107.9 to 112.9 ft).

The Canepatch Formation (200,000 years ago) is found beneath Shackleford Banks; fossils in this formation include corals, echinoids, and mollusks (gastropods and bivalves) (Tweet et al. 2009).

Management of paleontological resources is discussed further in the "Geologic Resources Management Issues" chapter.

Geologic Resource Management Issues

Some geologic features, processes, or human activities may require management for human safety, protection of infrastructure, and preservation of natural and cultural resources. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

During the 2000 GRI scoping meeting (see NPS 2000), a 2013 stakeholder meeting (Bagstad et al. 2015), and the 2015 GRI conference call (see Appendix A), following geologic resource management issues were identified:

- Coastal Resources Management and Planning
- Coastal Erosion
- Coastal Vulnerability and Sea Level Rise
- Hurricane Impacts and Human Responses
- Inlet Modifications
- Ferry Infrastructure and Use
- Coastal Engineering and Shoreline Armoring
- Grazing Horses on Shackleford Banks
- Recreational and Watershed Land Use
- Paleontological Resource Inventory and Protection
- Additional Information Needs
- Additional Planning Needs

Coastal Resources Management and Planning

NPS has developed a variety of databases and guidance for managing coastal resources and planning for the impacts of climate change. Refer to Appendix B for laws, regulations, and NPS policies pertaining to coastal resources.

The NPS *Coastal Adaptation Strategies Handbook* (Beavers et. al 2016) provides climate change adaptation guidance to coastal park managers in the 118 parks, including Cape Lookout National Seashore, that have been identified by their regional offices as potentially vulnerable to sea level change. Focus topics include NPS policies relevant to climate change, guidance on evaluating appropriate adaptation actions, and adaptation opportunities for planning, incident response, cultural resources, natural resources, facilities and assets, and infrastructure. The handbook also provides guidance on developing communication and education materials about climate change impacts, and it details case studies of the many ways that individual parks are implementing adaptation strategies for threatened resources.

Additional Reference Manuals that guide coastal resource management include NPS Reference Manual #39-1: *Ocean and Coastal Park Jurisdiction*, which can provide insight for parks with boundaries that may shift with changing shorelines (available at http://www.nps.gov/applications/npspolicy/DOrders.cfm); and NPS Reference Manual #39-2: *Beach Nourishment Guidance* (Dallas et al. 2012) for planning and managing nourishment projects.

The NPS *Cultural Resources Climate Change Strategy* (Rockman et al. 2016) connects climate science with historic preservation planning. It identifies and described seven climate change adaptation options for cultural resources and cultural landscapes:

- no active intervention;
- offset stress;
- improve resilience;
- manage change;
- relocate or facilitate movement;
- document and prepare for loss; and
- interpret the change.

The park's Natural Resource Condition Assessment (Burkholder et al. 2017) inventoried the park's natural resources, synthesized available information, identified knowledge gaps, and developed a set of indicators for natural resource conditions that can be tracked over time. The report addressed the following resources: surface water, groundwater, climate, air quality, surface sediments, geology and soils including sea level rise, erosion, and shoreline hardening.

The NPS Southeast Coast Network developed a Climate Science Strategy to prepare for and mitigate the adverse impacts of climate change on national parks along the southeast coast (DeVivo et al. 2011). Actions include enhancing monitoring of tides and salt marsh elevation, modifying ten monitoring protocols to provide data relevant to predicted consequences of climate change, and integrating data collection and management with partner networks.

Coastal Resources Datasets

Multiple efforts to develop data and models are producing useful datasets for this and other coastal parks. These efforts include sea level rise projections, coastal engineering inventories, asset vulnerability assessments, and long-term monitoring, as described below.

The NPS Geologic Resources Division (GRD) and Climate Change Response Program (CCRP) are developing sea level rise and storm surge data that parks can use for planning purposes over multiple time horizons. For Cape Lookout National Seashore, Caffrey (2013) projected the combined elevations of storms surge and sea level for planning horizons of 2030, 2050, and 2100. See "Coastal Vulnerability and Sea Level Rise" and "Hurricane Impacts and Human Response" sections for additional information on the study.

NPS has developed a Coastal Engineering Inventory Report for the park that provides a summary of the coastal engineering projects including coastal structures such as seawalls, dredge and fill projects (e.g., inlets), beach nourishment, and dune construction projects (Coburn et al. 2010). The report includes historical data, imagery, cost and a discussion of impacts (where available and appropriate), and accompanies a Geographic Information Systems (GIS) database.

Another recent NPS study (Peek et al. 2015) characterized park assets (e.g., historic structures, visitor facilities, buildings) based on their overall exposure to long-term (1 m [3 ft]) sea level rise and associated storm vulnerability; 100% of the 289 assets at Cape Lookout National Seashore were categorized as having high exposure to sea level rise impacts.

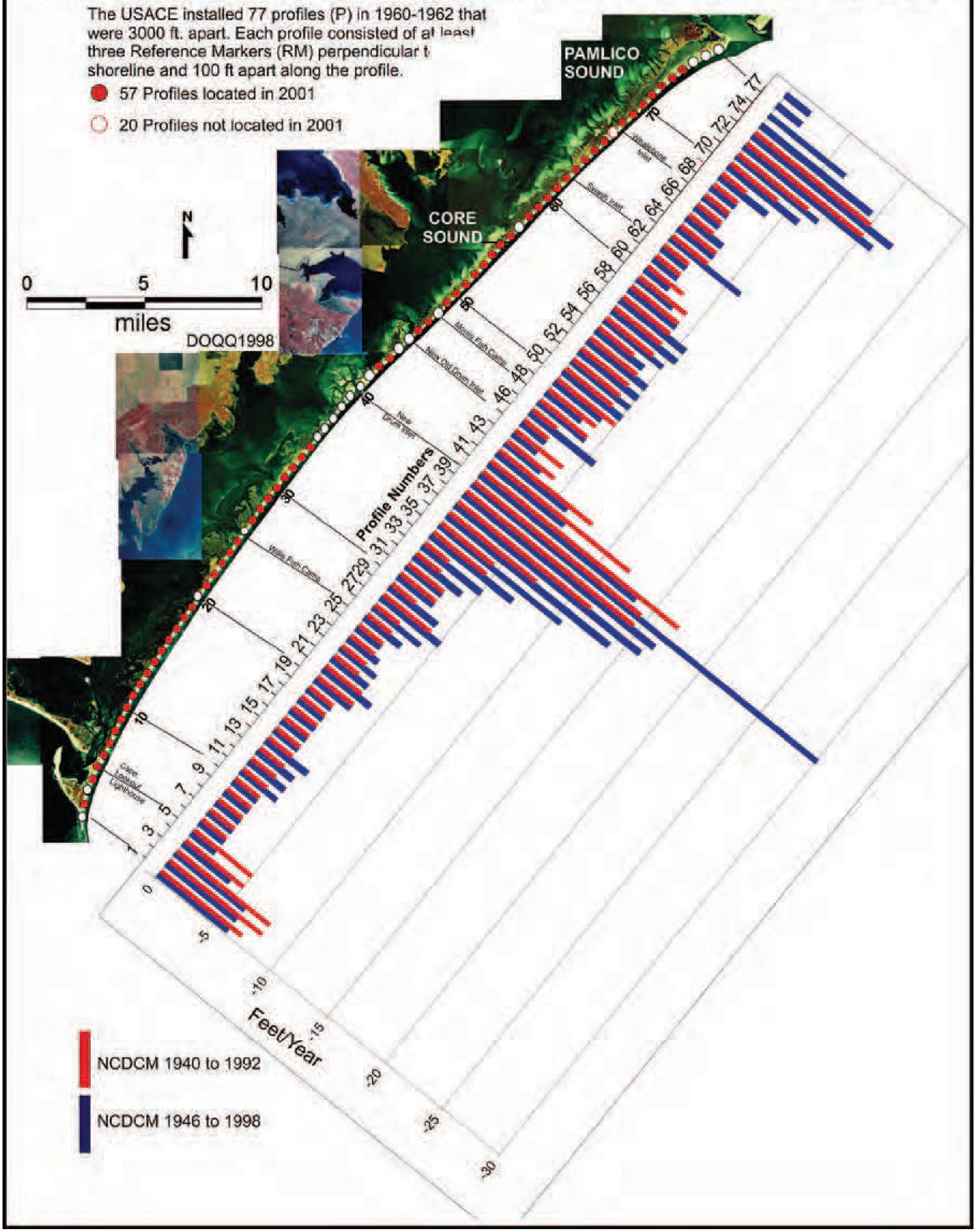
In Spring 2015, the NPS Southeast Coast Inventory & Monitoring Network (SECN) began measuring the park ocean shoreline position annually to semi-annually (see "Coastal Erosion" section of this report and http://go.nps.gov/secn_shoreline for additional information and reports as they are completed. SECN also collects salt marsh monitoring data on elevation, accretion, pore water salinity, and vegetation at a sentinel site on North Core Banks (see "Groundwater" section). Using a similar protocol, NOAA monitors salt marsh on South Core Banks. NPS and the Rachel Carson National Estuarine Research Reserve cooperate to monitor water quality in Back Sound at near the western end of Shackleford Banks and at Middle Marsh, approximately 1 mi north of Shackleford Banks (NCNERR 2009). Tidal data is also available from gauges in Morehead City (PSMSL station ID 719) and Beaufort (NOAA station ID 8656483) (see "Coastal Vulnerability and Sea Level Rise" section).

To develop additional monitoring protocols for coastal resources, such as topographic and bathymetric change, the park can work with SECN and can also consult suggested protocols such as the *Geological Monitoring* chapter about coastal features and processes defined in Bush and Young (2009), which described methods and vital signs for monitoring the following coastal features and processes: (1) coastal change, (2) coastal dune geomorphology, (3) coastal vegetation cover, (4) topography/elevation, (5) composition of beach material, (6) wetland position/acreage, and (7) coastal wetland accretion. Resource managers may also find the book Geological Monitoring (Young and Norby 2009; http://go.nps.gov/geomonitoring) useful for addressing these geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies.

The NPS Water Resources Division, Ocean and Coastal Resources Branch website(https://www.nps.gov/orgs/1439/ocrb.htm) has additional information

Figure 21 (facing page). Shoreline change varies along Core Banks. Shoreline retreat is lower where South Core Banks sits atop the Cape Lookout High and where North Core Banks is underlain by peat from former marshes. Erosion is high on North Core Banks at the southwestern end of the Portsmouth Overwash Plain and northeast of Whalebone Inlet. Shoreline variability is highest near Ocracoke Inlet and generally decreases southwestward to the lighthouse, then increases to intermediate levels towards Cape Lookout. Fluctuations are generally high adjacent to ephemeral inlets and along low and narrow island segments that frequently overwash. Shoreline change data is from the North Carolina Division of Coastal Management 1940–1992 and1946–1998 data sets. Data for the 1940–1992 period are from Benton et al. (1993) and the 1946–1998 period are from Benton et al. (1997). The straight line data at the -2 ft/yr level are based on the assumption that all shorelines are receding over the long term. This is the number used by NCDCM as the minimum rate of shoreline recession for their regulatory program. Figure 22 from Riggs and Ames (2007).

NORTH AND SOUTH CORE BANKS: LONG-TERM AVERAGE ANNUAL SHORELINE EROSION FACTORS BASED ON THE NCDCM 1946 TO 1998 AND 1940 TO 1992 STUDIES



about servicewide programs and the resources and management programs at the ocean, coastal, and Great Lakes parks. Shoreline maps of each park, along with shoreline and water acreage statistics from Curdts (2011), are available at http://go.nps.gov/shorelinemaps.

Coastal Erosion

Barrier islands recede when erosion exceeds the ability of the sediment supply to replenish the beach system. Variations in wave energy, sediment availability, sea level change, and human activities influence the balance between erosion and deposition (Dolan and Godfrey 1972).

Coastal erosion along Core Banks (fig. 21) is lower where South Core Banks sits atop the Cape Lookout High, a subsurface limestone ridge, and where North Core Banks is underlain by peat from former marshes (Riggs and Ames 2007). In contrast, the highest rates of erosion are on North Core Banks at the southwestern end of the Portsmouth Island overwash plain and northeast of Whalebone Inlet. Between 1960 and 2001, the shoreline change rate along North Core Banks was 2.4 m/yr (-8 ft/yr), and along South Core Banks was 0.9 m/yr (3 ft/yr) (Riggs and Ames 2007). Although the beach accretes after stormy periods, it rarely reaches its pre-storm location before the next storm causes new erosion (Riggs and Ames 2007). Shoreline variability (both erosion and accretion) is highest near Ocracoke Inlet and generally decreases southwestward to the lighthouse, then increases to intermediate levels towards Cape Lookout due to waves around the Cape and associated shoals. The low and narrow segments of Core Banks have periods of major erosion and accretion due to overwash and the opening or closing of ephemeral inlets (Riggs and Ames 2007); fluctuations are generally high adjacent to New Drum Inlet and Old Drum Inlet, in response to inlet dynamics.

The Shackleford Banks beach is also eroding (fig. 22). From 1943 to 1976, the ocean side of Shackleford Banks eroded approximately 15 m (49 ft), an average of 0.46 m/yr (1.5 ft/yr) (Dolan and Heywood 1977). Between 1974 and 2010, some sections along the ocean shoreline of Shackleford Banks eroded up to 150 m (500 ft), an average erosion rate of about 4.3 m/yr (14 ft/yr) (USACE 2016). There is a potential for accelerated erosion and local accretion on Shackleford Banks due to human activities, such as installation of a Cape Lookout Jetty and subsequent failure of the jetty; maintenance dredging of Barden and Beaufort Inlets; and maintenance of the Morehead City federal navigation channel (NPS 2012). These issues are discussed in the "Inlet Modifications" section of this chapter.

The coast along the park's headquarters area on Harkers Island has also experienced severe and persistent erosion due to wave action, occasional inundation at high tide, and boat wake. The erosion threatened structures and other park facilities along the shoreline, and was the incentive for a shoreline stabilization project (NPS 2006) discussed in the "Coastal Engineering and Shoreline Armoring" section of this chapter. The northeastern shoreline is approximately 518 m (1,700 ft) long, and extends from the coastal marsh at the northeast corner of the island, southward to the boat basin. The shoreline is an eroded upland bank with a steeply sloping face of 0.6 to 2.1

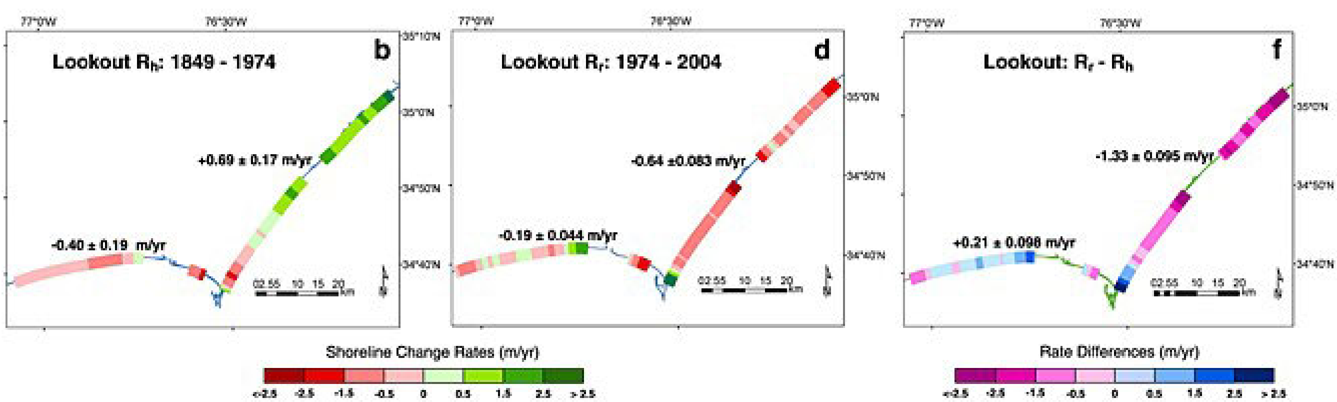


Figure 22. Historical (1849–1974) and recent (1974-2004) shoreline-change rates for the Cape Lookout area, and average rate differences. The Shackleford Banks beach continues to erode. Shorelines are plotted underneath the data to delineate general coastline trend. Figure 2 from Moore et al. (2013).

m (2 to 7 ft). At the toe of the eroded bank is firm peat interspersed with sandy beach areas and patchy marsh vegetation. Submerged aquatic vegetation (SAV) grows offshore of the coastal marsh but not along the eroding bank. The southeastern shoreline has been protected with timber bulkheads that are 0.6 – 1.8 m (4-6 ft) above MSL. SAV grows offshore of the northern segment of bulkhead. It includes a boat basin. The southern shoreline is 390 m (1,280 ft) long and includes a sandy beach area, an eroding upland bank that is 0.3 to 1 m (1 to 3 ft) high, and patchy emergent marsh vegetation, some large and contiguous. SAV grows along most of this shoreline. Erosion also threatens an asphalt parking area and picnic structures (NPS 2006).

Coastal erosion and storm events threaten historical and archeological resources, such as remnants of mid-19th century whaling community residences and prehistoric occupation sites on Shackleford Banks, and shipwrecks now buried within the islands (NPS 2012). Some American Indian middens have already been exposed by erosion along the estuarine shoreline; others are buried by younger geomorphic features on the north side of Shackleford Banks, or are sub-tidal in the shallow Back Sound and buried by thin deposits of modern estuarine sediments, and could be exposed by erosive events. Subtidal relict shell ridges with associated loose prehistoric pottery scatters also exist in the shallow southeastern portion of Back Sound. The oldest segment of Shackleford Banks, the eastern portion, has the greatest potential for containing additional undocumented archeological deposits buried beneath the younger overwash fans, interior flats, and low dune fields; those deposits will be exposed as the estuarine shoreline continues to erode (Riggs et al. 2015). On Cape Lookout, sound-side erosion and Barden Inlet migration during Hurricane Isabel in 2003 destroyed the Keepers' Quarters Coal Shed (NPS 2012). Inlet migration and coastal erosion continue, threatening the 1873 Keepers' Quarters, Summer Kitchen, the historic landscape, and the 1859 lighthouse (NPS 2012).

Shoreline change trends can be evaluated using data collected by the NPS SECN, which measures the park ocean shoreline position annually to semi-annually (Lisa Baron, SECN, coastal ecologist, written communication, 17 February 2016).

Coastal Vulnerability and Sea Level Rise

Sea level rise is caused by increased global temperatures in combination with regional and local effects of geologic, oceanographic, and atmospheric conditions (fig. 23) (Williams 2013). Global, or eustatic, sea level refers to the global ocean elevation. On a global scale, sea level varies with changes in the volumes of ocean basins and ocean water, caused by expansion due to heat and the addition of meltwater from ice sheets and glaciers. Local sea level rise refers to the combination of global rise with regional and local factors, such as sediment compaction, glacial isostatic adjustment, and changes in ocean circulation and wind patterns. Isostatic adjustment occurs when land that had been depressed under glacial weight rebounds in the glacier's absence. The park is located between the Carolina Platform area to the southwest that is experiencing slow uplift at 0.24 mm/yr ±0.15 mm (van de Plassche et al. 2014) and the Albemarle Embayment area to the northeast that is rapidly subsiding at 1.00 ± 0.10 mm/yr (Engelhart et al. 2009, 2011; Kemp et al. 2009, 2011). Analysis of data from the Beaufort tide gauge (1953-2013) indicates a vertical land movement of -1 mm/yr (NCCRC 2015). As a result of the different trends, Late Holocene relative sea level (since 2050 BCE) rose 0.82 ± 0.02 mm/yr in the park area (southern North Carolina), more slowly than in northern North Carolina (Horton et al. 2009). Relative local sea level rise is measured by tide gauge records, the growth of salt-marsh peat, and the submergence of human structures.

Historical Sea Level Rise

Sea level has fluctuated over the past millennia. During an interglacial (warm) period about 125,000 years ago, sea level was 5 to 6 m (16 to 20 ft) higher than present (Imbrie et al. 1984). About 20,000 years ago, during the last glacial period, sea level was about 130 m (425 ft) lower than present (Imbrie et al. 1984). As the glaciers melted, sea level rose, reaching about 91 m (300 ft) lower than present about 18,000 to 14,000 years ago. North Carolina's Atlantic coastline was farther offshore, about 100 km (60 mi) off Morehead City and Wilmington due to the shallow and wide rock floored shelf but only about 25 km (15 mi) off Cape Hatteras due to the very narrow shelf and steep slope (Riggs et al. 2011).

Over the last 12,000 years, after the ice age glaciers receded, relative sea level change along the North Carolina coast has varied as a function of latitude, with

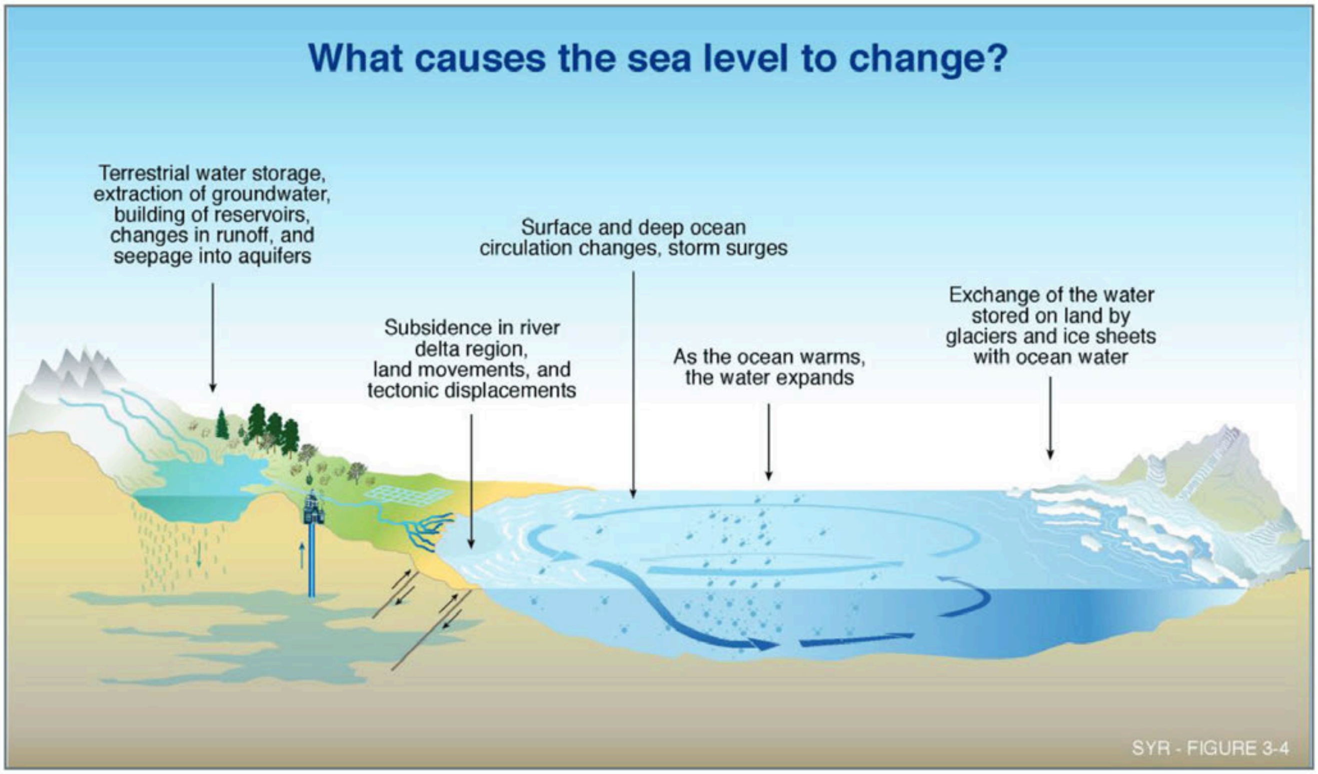


Figure 23. Schematic graphic illustrating causes of sea level rise. Sea level rise is caused by global climate warming in combination with regional and local effects of geologic, oceanographic, and atmospheric conditions, which vary spatially and temporally. Graphic from IPCC Third Assessment Report, Climate Change 2001 Synthesis Figure 3-4, available at https://toolkit.climate.gov/image/640.

higher rates of rise in the north and lesser rates of rise in the south. This pattern is a result of the local geology as well as subsidence and uplift (North Carolina Coastal Resources Commission [NCCRC] 2010). Relative sea level rose rapidly during the early and mid-Holocene from about 36 m (118 ft) to about 4 m (13 ft) below MSL (fig. 24, table 7).

In the past century, global sea level has risen approximately 0.18 m (0.6 ft), a rate of 1.8 mm (0.07 in) per year (Douglas 1997). A recent study (Sallenger et al. 2012) found that rates of relative sea level rise are increasing three to four times faster along parts of the US Atlantic coast than globally. Since about 1990, global sea level has risen 0.6 to 1.0 mm (0.02 to 0.04 in) per year.

In North Carolina, the NOAA (2014) tide gauge at Beaufort measured a local sea level rise from 1953–2014 (table 8, fig. 25) that is higher than the rate of sea level rise measured along a larger area of the North Carolina coast between 1900-2000 (fig. 26) (Kemp et al. 2011).

Future Sea Level Rise

Over the next century, differences in the rate of sea level rise between the two regions of North Carolina are likely to be overwhelmed by the much larger global rise in sea level (NCCRC 2010). New models and scenarios used by the Intergovernmental Panel on Climate Change (IPCC) predict that sea level will rise 0.26 to 0.98 m (0.85 to 3.2 ft) by 2100 (fig. 27) (Church et al. 2013). Many recent assessments have proposed a projected 1-m (3.3-ft) global average sea level rise by 2100 as a reasonable value to be used for planning purposes (Williams 2013). Some estimates include the possibility that sea level may rise as much as 2 m (6.6 ft) by 2100 along the mid-Atlantic coast (Rahmstorf 2007, Parris et al. 2012). Models that also consider accelerated melting of glaciers and the Greenland and West Antarctic ice sheet, along with the relationship between sea level and temperature, predict that sea level may rise by 0.9 to 1.2 m (2.9 to 3.9 ft) by the end of this century (Boesch 2008; Karl et al. 2009; The World Bank 2012). Current global emissions are at or above IPCC emissions scenario A2, which would lead to a projected

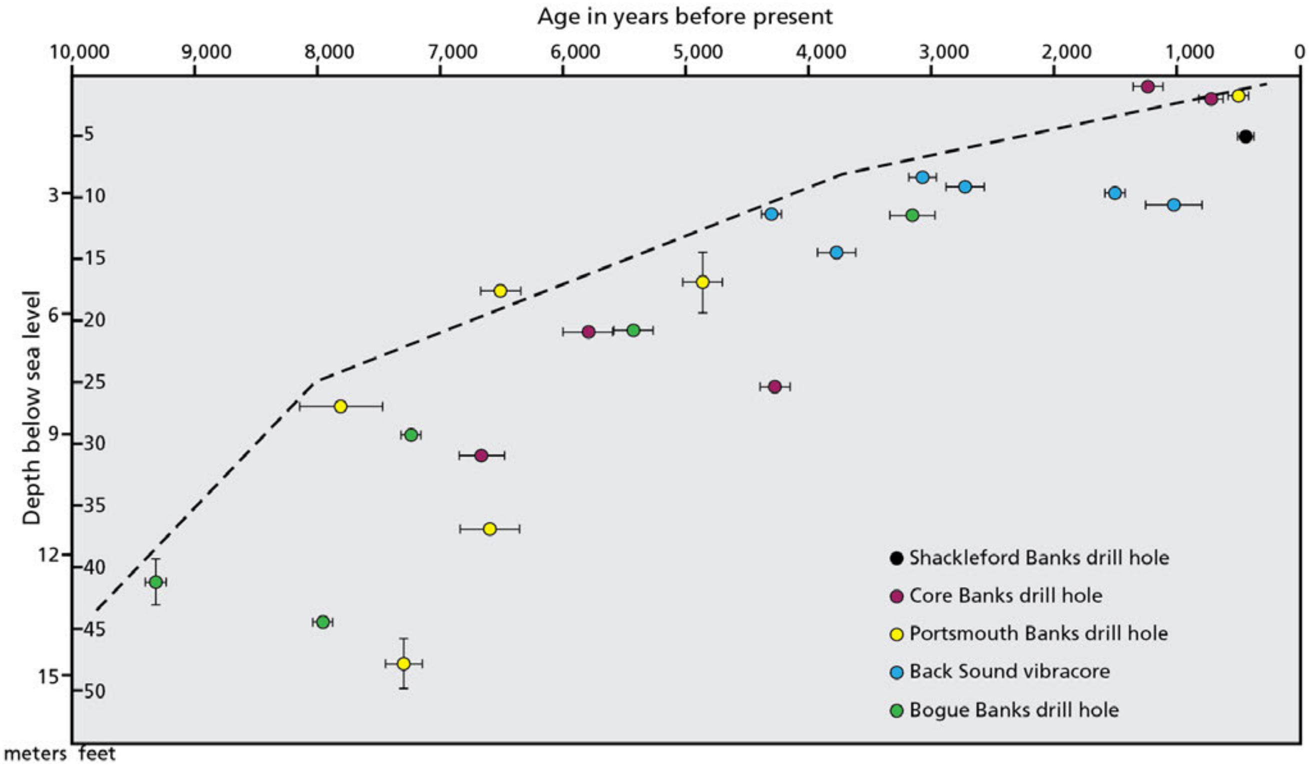


Figure 24. Holocene sea level curve determined for the Cape Lookout cuspate foreland. Sea level rise slowed about 4,000 years ago, as indicated by the break in the curve. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after figure 9 from Moslow and Heron (1981), which in turn was based on Berelson (1979) and Steele (1980).

Table 7. Holocene rates of sea level change along the North Carolina Coast. Sea level rose rapidly during the early and mid-Holocene.

Time period (years Before Common Era)	Sea level in meters (relative to modern MSL
9,112–8,626 BCE	-35.7 ± 1.1 m
2,290–1,642 BCE	-4.2 m ± 0.4 m
1,955–1,439 BCE	-3.4 ± 0.4 m

Data from Horton et al. (2009), converted from calibrated years before present (cal yr BP, or years before 1950) into years Before Common Era (BCE) for context. MSL = Mean Sea Level

1.24 m (4.07 ft) of global sea level rise by 2100 above its 1990 level (Vermeer and Rahmstorf 2009).

Along the North Carolina coast, sea level is likely to rise 0.4 to 1.4 m (1.25 to 4.6 ft) above the present level by 2100, but not necessarily in a linear fashion (NCCRC 2010). The North Carolina Coastal Resources Commission (2010) recommends that a 1-m (3.3-ft) rise is considered a good estimate for planning purposes because it is not located at the upper or lower extreme of valid projections. Additionally, that rate requires only that the linear relationship between temperature and sea level noted in the 20th century remains valid for the 21st century (Rahmstorf 2007). Sea level data downscaled to Beaufort, NC project a sea level rise rate that is higher than the global average rate (table 8, fig. 28) (Caffrey 2013).

Sea level trends can be evaluated using gauges in Morehead City (PSMSL station ID 719) and Beaufort (NOAA station ID 8656483) and correlated with other regional and global locations.

Coastal Impacts of Sea Level Rise

Different rates of sea level rise are tied to the formation of particular types of landforms. For example, global deltas formed approximately 8000 years ago when rates of sea level rise slowed to less than 10 mm (0.4 in)/year (Stanley and Warne 1994), and barrier islands and Atlantic wetlands formed when rates of sea level rise fell below 5 to 7 mm (0.2 to 0.3 in)/year (Shennan and Horton 2002; Horton et al. 2009). In the past, portions

Table 8. Climate change trends and projections for Cape Lookout National Seashore.

Metric	Mean	Standard Deviation	Unit of Measure
Historical			
Temperature 1901–2002 annual average	15.1	0.6	°C
Temperature 1901–2002 linear trend	0.3	0.02	°C/century
Precipitation 1901–2002 annual average	920	190	mm/year
Precipitation 1901–2002 linear trend	ca.0	<0.1	%/century
Sea level, North Carolina 1900–2000	2.1	n/a	mm/year
Sea level, Beaufort 1953–2010	2.61	0.4	mm/year
Projected: IPCC B1 scenario (lower emissions)			
Temperature 1990–2100	1.9	0.2	°C/century
Precipitation 1990–2100	+2	1	%/century
Sea level by 2100	104	n/a	cm above 1990
Projected: IPCC A1B scenario (medium emissions)			
Temperature 1990–2100	2.8	0.3	°C/century
Precipitation 1990–2100	+2	1	%/century
Sea level by 2100	124	n/a	cm above 1990
Projected: IPCC A2 scenario (higher emissions)			
Temperature 1990–2100	3.1	0.3	°C/century
Precipitation 1990–2100	+2	1	%/century
Sea level by 2100	124	n/a	cm above 1990

Table C.1 from NPS (2012). Note: Historical and projected climate (mean ± standard deviation (SD)) for the 50 km by 50 km (31 mi by 31 mi) square area that includes the seashore (Mitchell and Jones 2005, IPCC 2007, Gonzalez et al. 2010), North Carolina historical sea levels from Kemp et al. (2011), Beaufort mean sea levels calculated based on data from Morehead City tidal gauge data from PSMSL (Permanent Service for Mean Sea Level station ID 719; http://www.psmsl.org/data/obtaining/stations/396.php) and NOAA (station ID 8656483; http://tidesandcurrents.noaa.gov/sltrends/sltrends_update.shtml?stnid=8656483); projections of global mean sea level from Vermeer and Rahmstorf (2009).

of the North Carolina Outer Banks were segmented for periods of a few hundred years, and later reformed (Mallinson et al. 2005; Culver et al. 2008a). Riggs et al. (2012) and Mallinson et al. (2014) found that during slower sea level rise within the Albemarle-Pamlico coastal system, the barrier islands built up with few inlets and more restricted estuarine environments including organic-rich mud deposition. During times of rapid sea level rise, the barrier islands receded and were segmented by inlets due to increased storminess, resulting in marine sand deposition in the estuaries (as cited in Riggs et al. 2015).

As sea level rises, various processes modify coastal landforms, causing cumulative impacts at a range of

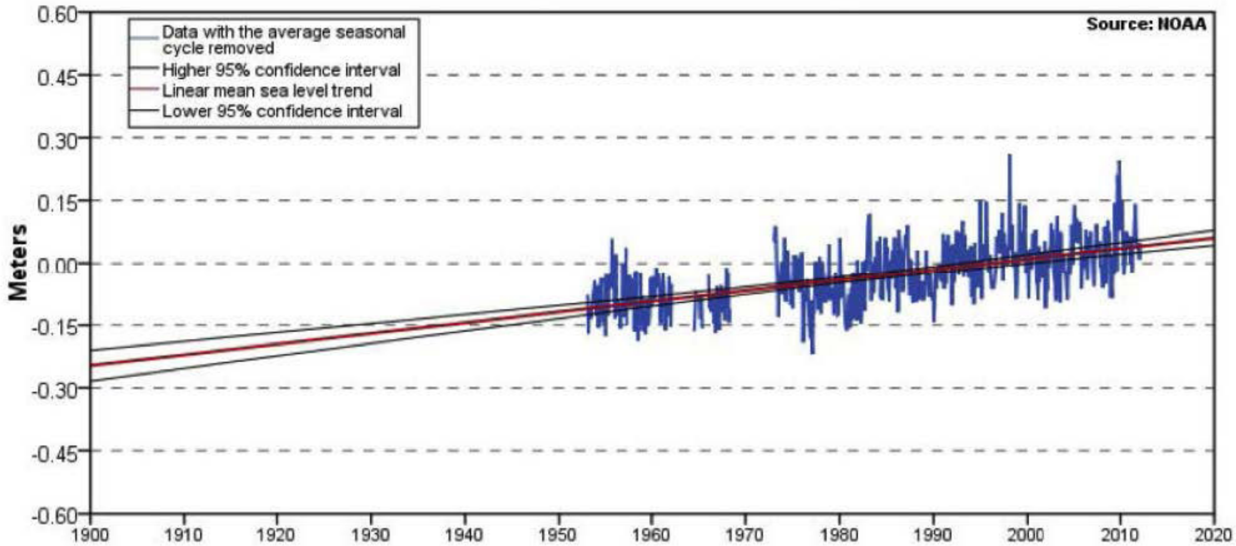


Figure 25. Recent sea level rise based on tide gauge data from Beaufort, NC 1953-2012. Mean sea levels were calculated based on data from Morehead City tidal gauge data from PSMSL (station ID 719; http://www.psmsl.org/data/obtaining/stations/396.php) and NOAA (station ID 8656483; http://tidesandcurrents.noaa.gov/sltrends/sltrends_update.shtml?stnid=8656483). Figure C.6 from NPS (2012).

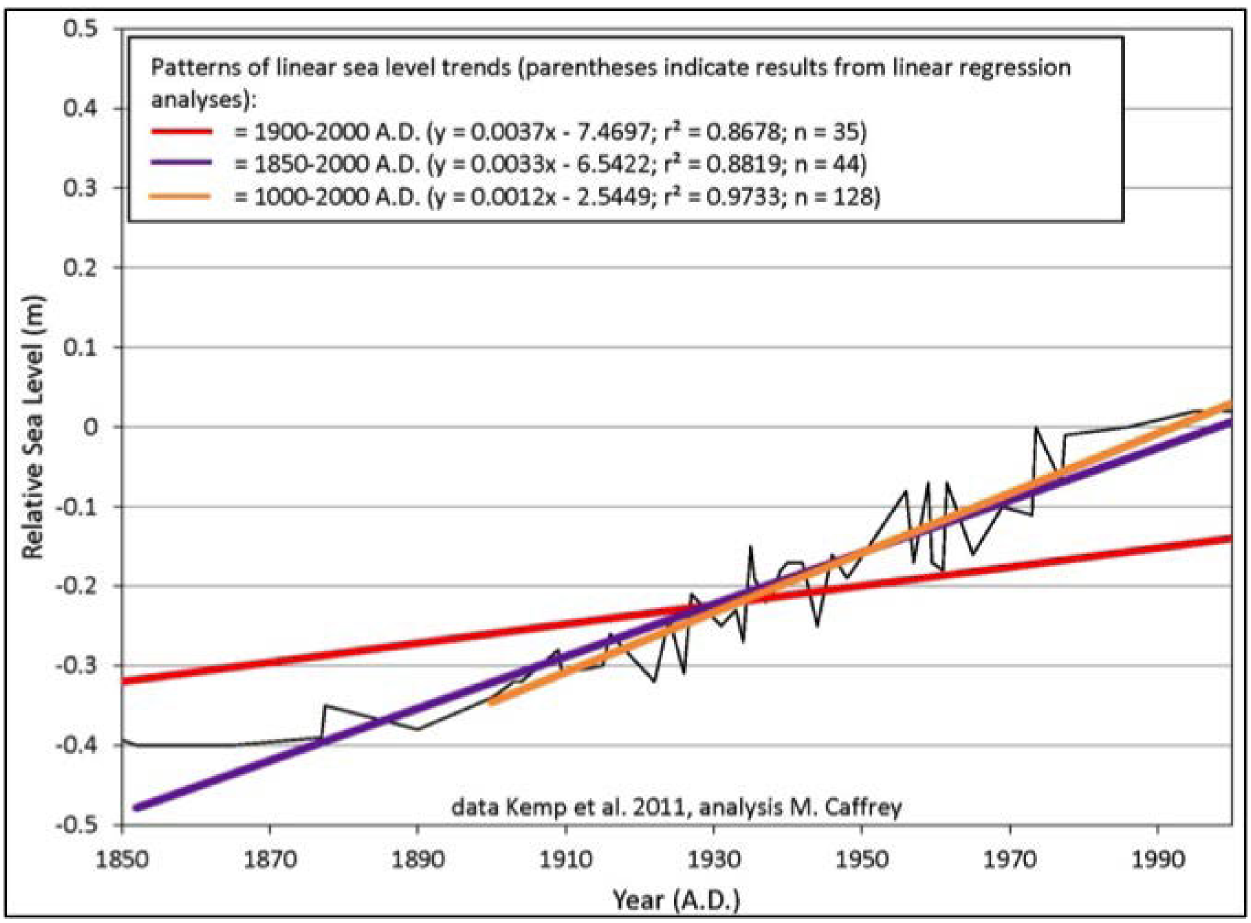


Figure 26. Historical sea level rise in North Carolina from 1850-2000. Figure C.5 from NPS (2012). Fossil data from coastal North Carolina from Kemp et al. (2011); trend analysis by Maria Caffrey (NPS Geologic Resources Division).

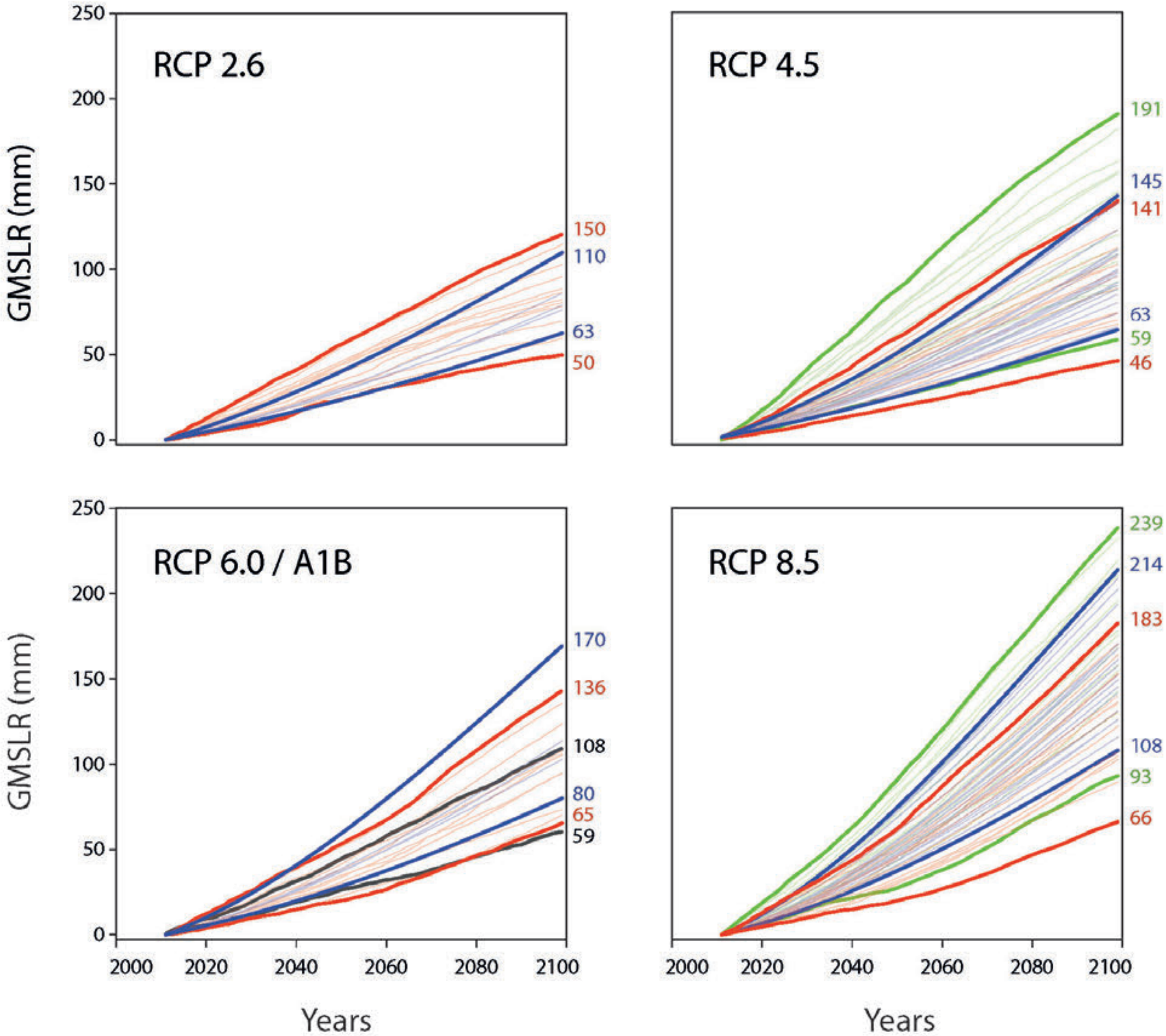


Figure 27. Projected global mean sea level rise (GMSLR) by 2100 (in millimeters). Over the next century, global sea level will rise, although the magnitude of projections under various modeling scenarios varies. Representative Concentration Pathways (RCPs) describe four different 21st century pathways of greenhouse gas emissions and atmospheric concentrations, air pollutant emissions and land use. The RCPs include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high GHG emissions (RCP8.5). Scenarios without additional efforts to constrain emissions ('baseline scenarios') lead to pathways ranging between RCP6.0 and RCP8.5. Figure 9 from Church et al. (2013).

spatial and temporal scales (Williams 2013). Coastal evolution in response to sea level rise and storms is influenced in large part by several conditions:

- geologic framework (underlying geology) and nearshore bathymetry (Riggs et al. 1995; Honeycutt and Krantz 2003; Browder and McNinch 2006; Miselis and McNinch 2006; Schupp et al. 2006; Wikel 2008);
- coastal and nearshore oceanographic processes (i.e., waves, currents, circulation) (Williams 2013);
- sediment supply and transport (Williams 2013);
- and human actions that alter sediment movement (e.g., jetties) (Williams 2013).

In the face of frequent storms, islands tend to be either extremely vulnerable or fairly stable in terms of storm recovery. On complex barrier islands such as western Shackleford Banks, where dune building is driven by vegetation trapping sand, islands tend to be well-developed with high ecosystem diversity. Such islands have minimal vulnerability to storms and tend

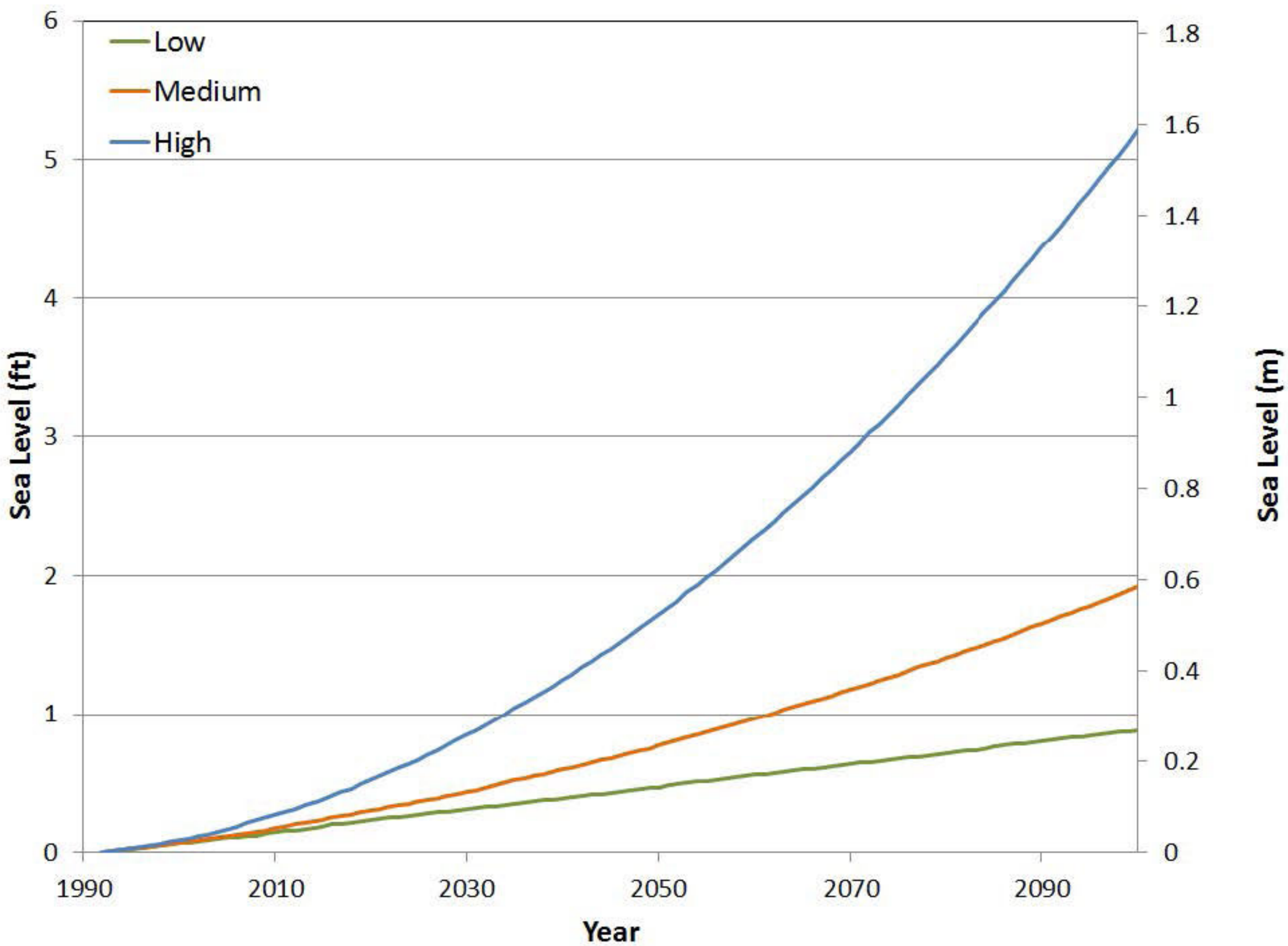


Figure 28. Projected rate of sea level rise for Beaufort, NC. Projections were calculated using the USACE Sea-Level Change Curve Calculator (USACE 2013), which uses variables modified from IPCC and NRC sea level rise scenarios (read more at http://www.corpsclimate.us/ccaceslcurves(superseded).cfm). The low scenario uses the historical rate of rise. Figure from Caffrey (2013).

to migrate slowly, if at all. In contrast, simple barrier islands are vulnerable even to mild storms. Those islands, such as middle Core Banks, have low elevation, a lack of dunes, frequent overwash, rapid migration, and low ecosystem diversity; sea level rise may lead to their disintegration (Moore et al. 2015). See the “Simple and Complex Barrier Island Model” section of the “Geologic and Environmental Features and Processes” chapter for a broader discussion of the island types.

Threshold Crossing

Barrier islands likely have thresholds of stability. When limits of sea level rise and storm activity are exceeded, or sediment supply rates decrease to an unstable level, the islands become unstable and prone to irreversible changes in form and position (Riggs and Ames 2003; FitzGerald et al. 2008; Gutierrez et al. 2009; Moore et al. 2010, 2011). These changes may result in increased landward migration, reduction in size or segmentation, or, in extreme cases, submergence (Williams 2013). Gutierrez et al. (2007) identified the following indicators that a barrier island may have reached threshold conditions:

- increased rate of landward migration of the barrier island;
- decreased barrier width and elevation of barrier island and sand dunes;
- increased frequency of storm overwash;
- increased frequency of barrier island breaching and inlet formation and widening; or
- barrier island segmentation.

Given the potential for future increases in sea level

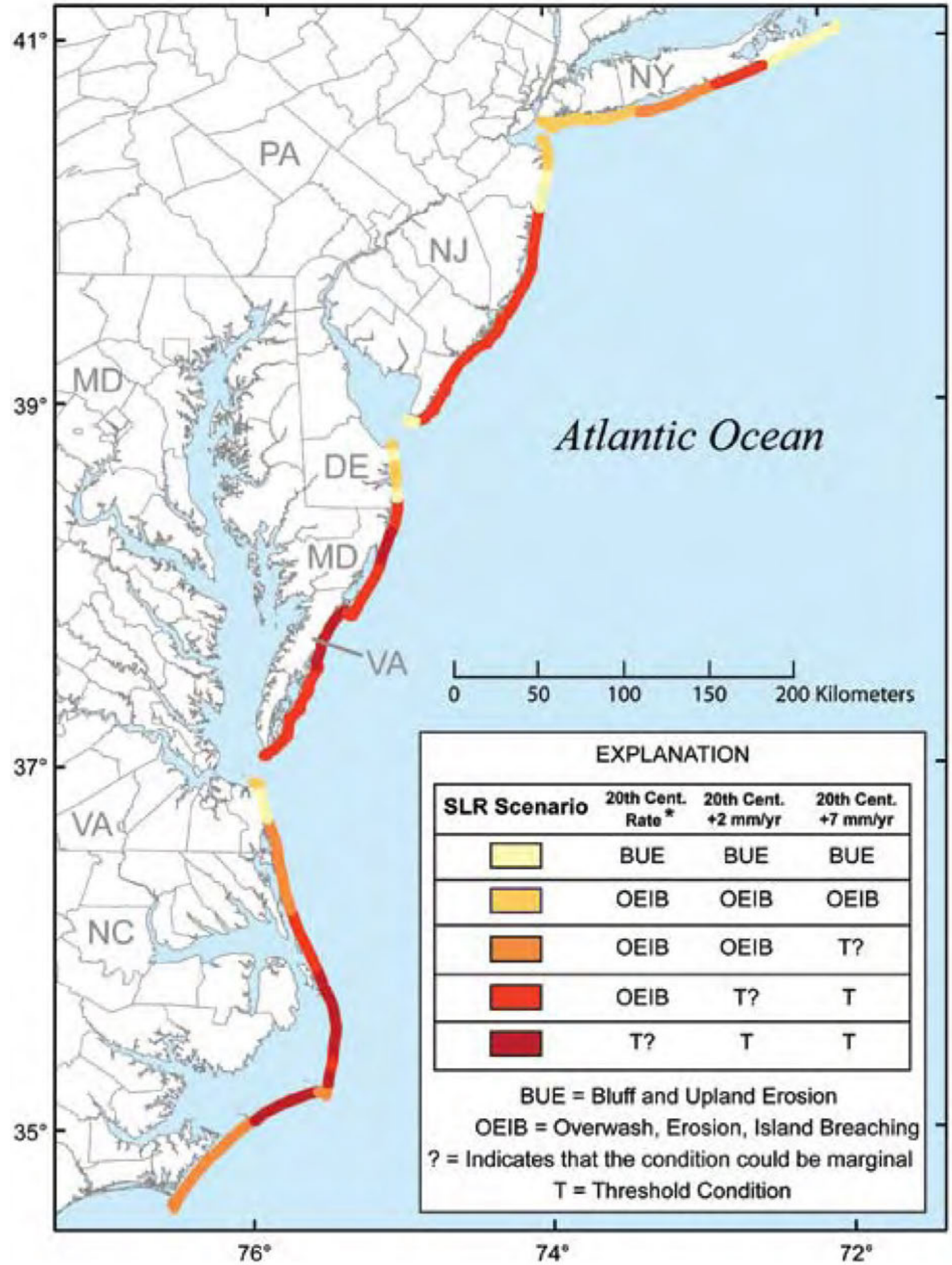


Figure 29. Map showing potential Atlantic coastal responses to three sea level rise scenarios. If mid-Atlantic sea level rise continues at the present rate, the majority of wave-dominated barrier islands along the mid-Atlantic coast will almost certainly continue to undergo morphological changes through erosion, overwash, and inlet formation. Additional changes will occur under higher rates of sea level rise. Figure 4 from Gutierrez et al. (2009).

and storm activity, threshold crossing may occur in the Outer Banks, and portions of these barrier islands could once again become segmented into submarine shoals. Gutierrez et al. (2009) postulated that if mid-Atlantic sea level rises 0.3 to 0.4 m (1 to 1.3 ft) by 2100, the majority of wave-dominated barrier islands along the mid-Atlantic coast will continue to experience erosion, overwash, and inlet formation, as they have over the last several centuries (fig. 29). Modeling of the Outer Banks north of Cape Hatteras suggest that a more rapid increase in sea level (up to 0.88 m [2.9 ft]) by 2100 would cause the Outer Banks to migrate 9.8 m/yr (32 ft/yr), about 2.5 times more rapidly than at present but within the range observed for rapidly migrating barrier islands elsewhere (e.g., in Louisiana) (Moore et al. 2007). When sea level rises more quickly than the shoreface can erode to provide sediment to the island, the island begins to disintegrate and a threshold crossing occurs (Moore et al. 2010). Human mitigation efforts, such as beach nourishment, have little effect on barrier island migration rates and vulnerability to collapse (Moore et al. 2007). Where marsh is present, islands migrate more slowly, so it is likely that islands migrate more quickly where human activities have reduced deposition by overwash (Moore et al. 2015).

Wetland Drowning

Mid-Atlantic wetlands are expected to keep pace with moderate rates of sea level rise, but higher rates (e.g., 1 m [3.3 ft] by 2100) may result in the conversion of most tidal wetlands to open water bays and lagoons (Williams 2013). In North Carolina, the rate of vertical accretion within marshes has largely kept pace with the rate of sea level rise (Feldman et al. 2009). A recent study of fringing marsh vegetation in Carteret County, which included two sites at the park, suggested that under the current rate of sea level rise (3 mm [0.12 in]/yr), fringing marshes will be able to maintain marsh biomass and surface elevation, assuming that the sediment supply does not decrease due to coastal structures or other changes (Currin et al. 2015). Wetland drowning may occur if rates of global sea level rise increase by 2 mm (0.08 in)/year and is likely if rates increase by 7 mm (0.28 in)/year (Feldman et al. 2009) (table 9). With a rise of 10 mm (0.4 in)/year, fringe wetlands of North Carolina's lower coastal plain would drown, and peat-

Table 9. The rate of sea level rise will determine the responses of coastal wetlands and their driving processes.

Scenario	Vertical Accretion of Wetland Surface	Coastal Erosion Rate	Sediment Supply
Non-drowning: historical exposure of wetlands (past hundreds to several thousand years) is predictive of future behavior. Vertical accretion will keep pace with rising sea level (about 2 to 4 mm [0.08 to 0.16 in] per year)	Keeps pace with rising sea level	Recent historical patterns are maintained	Low due to a lack of sources; vertical accretion mostly biogenic
Drowning: vertical accretion rates cannot accelerate to match rates of rising sea level; barrier islands remain intact	Wetlands undergo collapse and marshes break up from within	Rapid acceleration when erosion reaches collapsed regions	Local increases in organic and inorganic suspended sediments as wetlands erode
Barrier island breached: change to tidal regime throughout Pamlico Sound	Biogenic accretion replaced by inorganic sediment supply	Rapid erosion where high tides overtop wetland shorelines	Major increase in sediments and their redistribution; tidal creeks develop along antecedent drainages, mostly in former upland regions

Table 4.3 from Cahoon et al. (2009).

Table 10. Projected sea level rise will increase the vulnerability of park cultural resources.

Resource	Current Height Above MSL (m)	Height Above Projected Year 2100 MSL at Current SLR Rate of 0.31/100 yrs	Height Above Projected Year 2100 MSL at IPCC Low SLR Rate of 0.49 m/100 yrs	Height Above Projected Year 2100 MSL at IPCC High SLR Rate of 0.88 m/100 yrs
Portsmouth Life Saving Station	0.937	0.627	0.447	0.057
Portsmouth Village Church	1.150	0.840	0.660	0.270
Portsmouth Village P.O. and Store	0.927	0.617	0.437	0.047
1873 Keepers Quarters	2.096	1.786	1.606	1.216
Cape Lookout Coast Guard Station	3.476	3.166	2.986	2.596
Long Point Cabin Area	3.460	3.150	2.970	2.580
Great Island Cabin Area	2.450	2.140	1.960	1.570

Table from page 21 of CALO (2011) using park GPS data obtained June 2010, and Riggs et al. (2003). MSL: Mean Sea Level.

based wetlands would be unlikely to maintain elevation relative to sea level. The peat, root map, and vegetation would be killed by brackish water (Feldman et al. 2009). Creation of additional inlets due to sea level rise would increase tide range, salinity, and wave activity in the estuaries, which would in turn impact wetlands (Feldman et al. 2009). Sea level rise will also impact cultural resources at the park (Riggs et al. 2003) (table 10).

Coastal Vulnerability to Climate Change

Thieler and Hammar-Klose (1999) evaluated the coastal vulnerability of the U.S. Atlantic coast to sea level rise according to six variables:

- geomorphological type of shoreline, and its relative resistance to erosion;
- historical rate of accretion and erosion of the shoreline ;
- regional coastal slope, and its relative susceptibility to flooding;
- relative sea level change;
- mean significant wave height; and
- mean tidal range.

This study did not explicitly consider the types, frequencies, or intensities of storms and associated surge, which are also important variables affecting coastal vulnerability (Stanley Riggs, East Carolina University, professor, email, 12 December 2013). Thieler and Hammar-Klose (1999) found that in the Cape Lookout region, of the six equally ranked variables, the values for shoreline change, geomorphology, coastal slope, and significant wave height had the largest ranges, and therefore the strongest influence on the overall vulnerability score. Due to shoreline orientation and the sheltering effect of the shoals, there is a substantial difference in wave energy between the east-facing (high energy) and the south-facing (lower energy) flank of the cape (fig. 30).

Expected climate change impacts include significantly warmer temperatures and a more variable precipitation regime which may lead to both more frequent droughts and more severe flooding (Fisichelli 2013). The park has been experiencing extremely warm and wet conditions over the past 10 to 30 years) relative to its 1901–2012 historical range (fig. 31, 32) (Monahan and Fisichelli 2014a, 2014b). Anticipated impacts of sea level rise on groundwater are discussed in the “Groundwater” section of the “Geologic Setting and Significance” chapter.

The park has begun a Stakeholder Engagement Effort through which it will survey three specific stakeholder groups (historic preservation professionals, local community, and park visitors) to gauge their attitudes and beliefs about climate change and park cultural resources. This will support a Structured Decision-

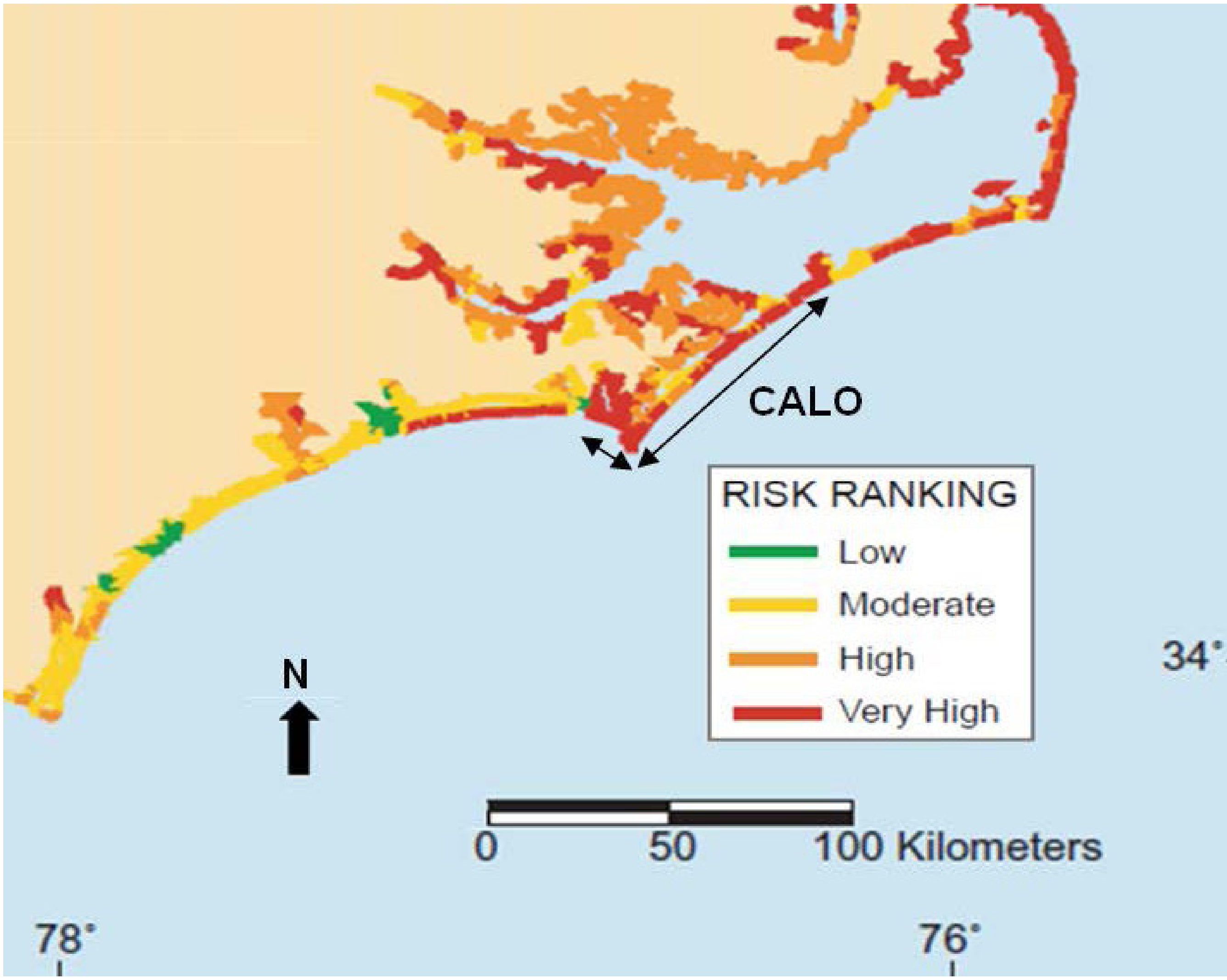


Figure 30. Preliminary analysis of the overall CVI for the park's vulnerability to sea level rise. The map indicates vulnerability of seashore areas to future inundation from a direct-hit hurricane as sea level rises over the 21st century. Most of Cape Lookout National Seashore has very high vulnerability. Figure 21 from Burkholder et al. (2017) as modified from Thieler and Hammar-Klose (1999).

Making Effort, led by USGS, which will integrate future sea level rise scenarios into developing potential adaptation options for Portsmouth Village and Lookout Village. In that effort, participants will rank adaptation options to understand the tradeoffs amongst various options. The results from the stakeholder assessment will inform the Structured Decision-Making process as to how different adaptation efforts are viewed. The project will also produce visualization tools and a cultural resources vulnerability index (Janet Cakir, NPS Southeast Regional Office, Climate Change, Socioeconomics, and Adaptation Coordinator, telephone, 10 June 2015).

The park is one of the sites included in the development of a new management instrument called the Coastal Recovery from Storms Tool (CReST) (Ruggiero 2014; Elko et al. 2016). This model will evaluate feedbacks between dune vegetation and sand transport to assess beach and dune evolution in both natural and managed systems in response to sea level rise and extreme storms. The results will estimate recovery and vulnerability to future storm events under a variety of sea level rise, storm change, and management scenarios. The project intends to convert the derived data into useable knowledge that addresses NPS questions and supports local management decisions aimed at reducing vulnerability of natural ecosystems under climate change (Ruggiero 2014).

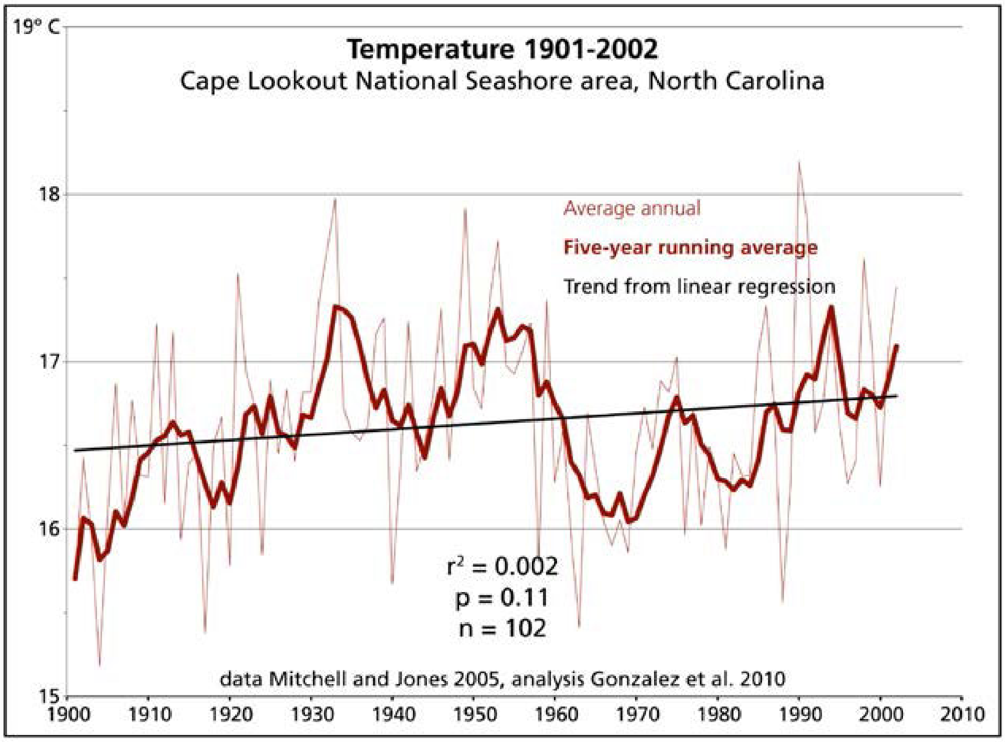


Figure 31. Historical temperature data from the park area. Figure C.2 from NPS (2012). Note: Historical and projected data for the 50 km by 50 km (31 mi by 31 mi) square area that includes the seashore is from Mitchell and Jones (2005); analysis is from Gonzalez et al. (2010).

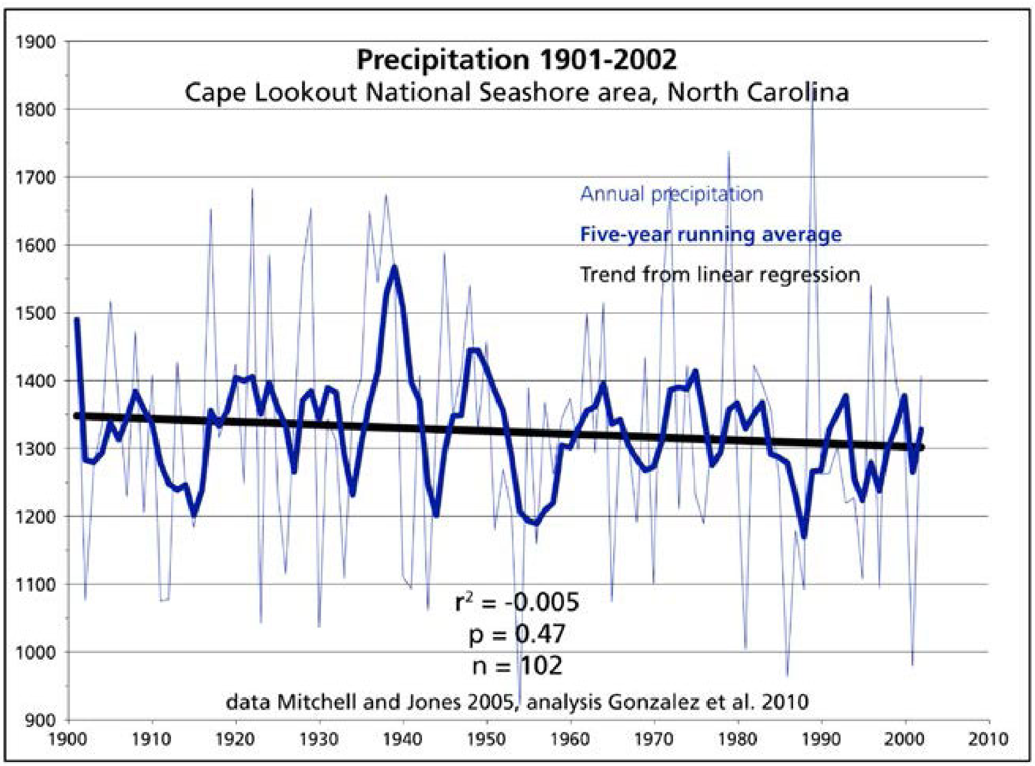


Figure 32. Historical precipitation data from the park area. Figure C.4 from NPS (2012). Note: Historical and projected data for the 50 km by 50 km (31 mi by 31 mi) square area that includes the seashore is from Mitchell and Jones (2005); analysis is from Gonzalez et al. (2010).

Hurricane Impacts and Human Responses

Hurricanes and other major storms are important agents of geomorphological change along the Outer Banks, as the winds, waves, and storm surge move sand across and off of the islands. The Saffir-Simpson scale describes a range of hurricane impacts (table 11). Maximum storm surge usually occurs to the right side of the hurricane's path, and decreases with distance away from the center of the storm. Under present conditions, storm surges are predicted to reach up to 5.2 m (17.1 ft) at the park visitor center if a category 5 storm struck at high tide (fig. 33, 34) (Caffrey 2013).

Between 1842 and 2011, 6 hurricanes moved directly across the park and another 12 hurricanes passed within 16 km (10 mi) (Caffrey 2013). Hurricane storm surges flooding Core Banks between 1900-1962 ranged from 0.9 to 3.2 m (3 to 10.6 ft) above MSL. These numbers did not include northeaster storms. There was a period of high storm activity 1940-1962, and a period of relative calm 1963-1970. The most active storm period in recorded North Carolina history occurred 1991-2005, a 14-year period with 13 hurricanes and several northeasters that directly impacted the North Carolina coast.

In September 1999, Hurricane Dennis reopened Drum Inlet, which had closed naturally in 1971. It is now called Old Drum Inlet by the park, and is sometimes referred to as New-Old Drum Inlet (Riggs and Ames 2007). In 2005, Hurricane Ophelia opened an inlet approximately a quarter mile south of New Drum Inlet; Ophelia Inlet is the largest of the three inlets that currently exist on Core Banks (Coburn et al. 2010).

The strongest storm path to move over the park belonged to Hurricane Isabel, which was a category 2 hurricane when it made landfall at North Core Banks on 18 September 2003. It brought a 1.8 to 3 m (6 to 10 ft) storm surge, overwashing the width of the island in many locations (Riggs and Ames 2007). Hurricane Irene made landfall at Cape Lookout on August 27, 2011, and overwashed several portions of the park. Comparison of Shackleford Banks spring shoreline and nearshore surveys from before and after the storm show an

Table 11. The Saffir-Simpson Hurricane Wind Scale is a 1 to 5 rating based on a hurricane's sustained wind speed.

Category	Sustained Winds	Types of Damage due to Hurricane Winds
1	74–95 mph 64–82 kt 119–153 km/h	**Very dangerous winds will produce some damage**: well-constructed frame homes may sustain damage to roofs, shingles, vinyl siding, and gutters. Large branches of trees will snap and shallowly rooted trees may be toppled. Extensive damage to power lines and poles likely will result in power outages that could last a few to several days.
2	96–110 mph 83–95 kt 154–177 km/h	**Extremely dangerous winds will cause extensive damage**: well-constructed frame homes could sustain major roof and siding damage. Many shallowly rooted trees will be snapped or uprooted and block numerous roads. Near-total power loss is expected, with outages that could last from several days to weeks.
3 (major)	111–129 mph 96–112 kt 178–208 km/h	**Devastating damage will occur**: well-built frame homes may incur major damage or removal of roof decking and gable ends. Many trees will be snapped or uprooted, blocking numerous roads. Electricity and water will be unavailable for several days to weeks after the storm passes.
4 (major)	130–156 mph 113–136 kt 209–251 km/h	**Catastrophic damage will occur**: well-built framed homes can sustain severe damage with loss of most of the roof structure and/or some exterior walls. Most trees will be snapped or uprooted and power poles downed. Fallen trees and power poles will isolate residential areas. Power outages will last weeks to possibly months. Most of the area will be uninhabitable for weeks or months.
5 (major)	≥157 mph ≥137 kt ≥252 km/h	**Catastrophic damage will occur**: a high percentage of framed homes will be destroyed, with total roof failure and wall collapse. Fallen trees and power poles will isolate residential areas. Power outages will last for weeks to possibly months. Most of the area will be uninhabitable for weeks or months.

This scale estimates potential property damage. Hurricanes reaching category 3 and higher are considered major because of the potential for significant loss of life and damage.

Information source: National Hurricane Center (2012), available online at: http://www.nhc.noaa.gov/aboutsshws.php (accessed 27 August 2014).

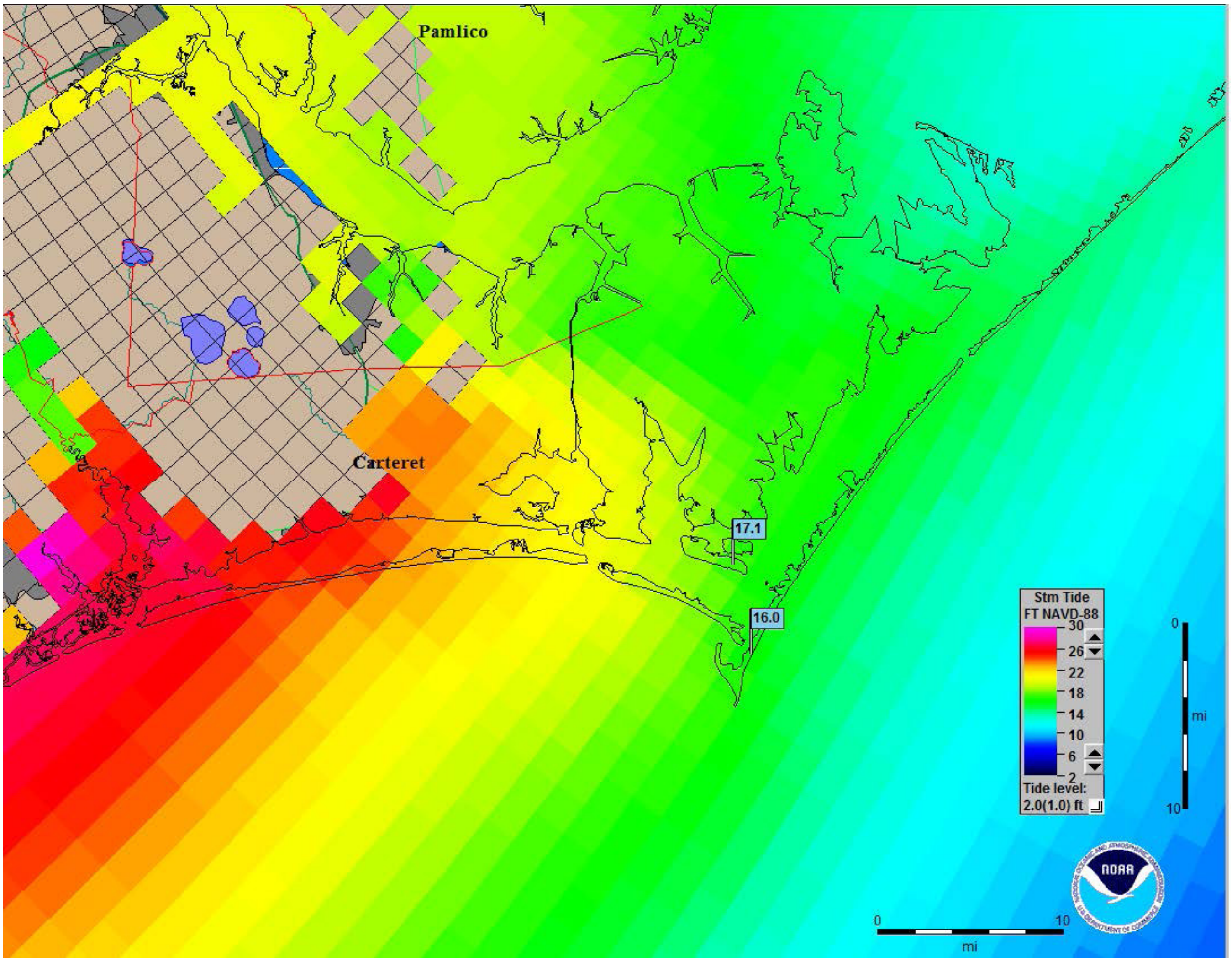


Figure 33. Storm surge (in feet) projected for a category 5 storm at high tide. Figure 3 from Caffrey (2013) using data from NOAA SLOSH model.

average shoreline change of -6.1 m (-20.1 ft), and loss of sediment along much of the frontal dune, the beachface, and down to the outer (Geodynamics 2012).

Impacts of Hurricanes on Facilities

In August 2011, Hurricane Irene created overwash deposits of sand up to 1 m (3 ft) thick beneath the raised cabins, shelters, and bath house in the Long Point cabins area. It eroded the dunes in front of the cabins, allowing waves to reach the cabins and to move large amounts of sand across the island and into the sound. Hurricane Irene also destroyed much of the below ground electrical, water, and wastewater systems for the cabins (Beavers 2011b). Additional overwash on September 7-8, 2011 deposited shells on the overwash fan created in the Long Point cabins area by Hurricane Irene. The park recognizes that the site would continue to be a management challenge for the park given the compromised nature of the infrastructure and its low elevation (Beavers 2011a).

Storm events, erosion, and Barden Inlet migration have impacted the historic landscape of the Cape Lookout lighthouse, which has not been stabilized (NPS 2012). Storms also threaten structures and gravestones in the Portsmouth Village historic district (NPS 2012). There are ongoing weathering and storm event impacts on the U.S. Life-Saving Station Complex, and the U.S. Coast Guard Station Complex (NPS 2012). Projected increases in storm surge increase the vulnerability of structures resources in coastal areas (Ingram et al. 2013) through coastal erosion, undermining, and inundation. Some historic buildings are highly vulnerable to damage from storm surge, such as the lighthouse keepers

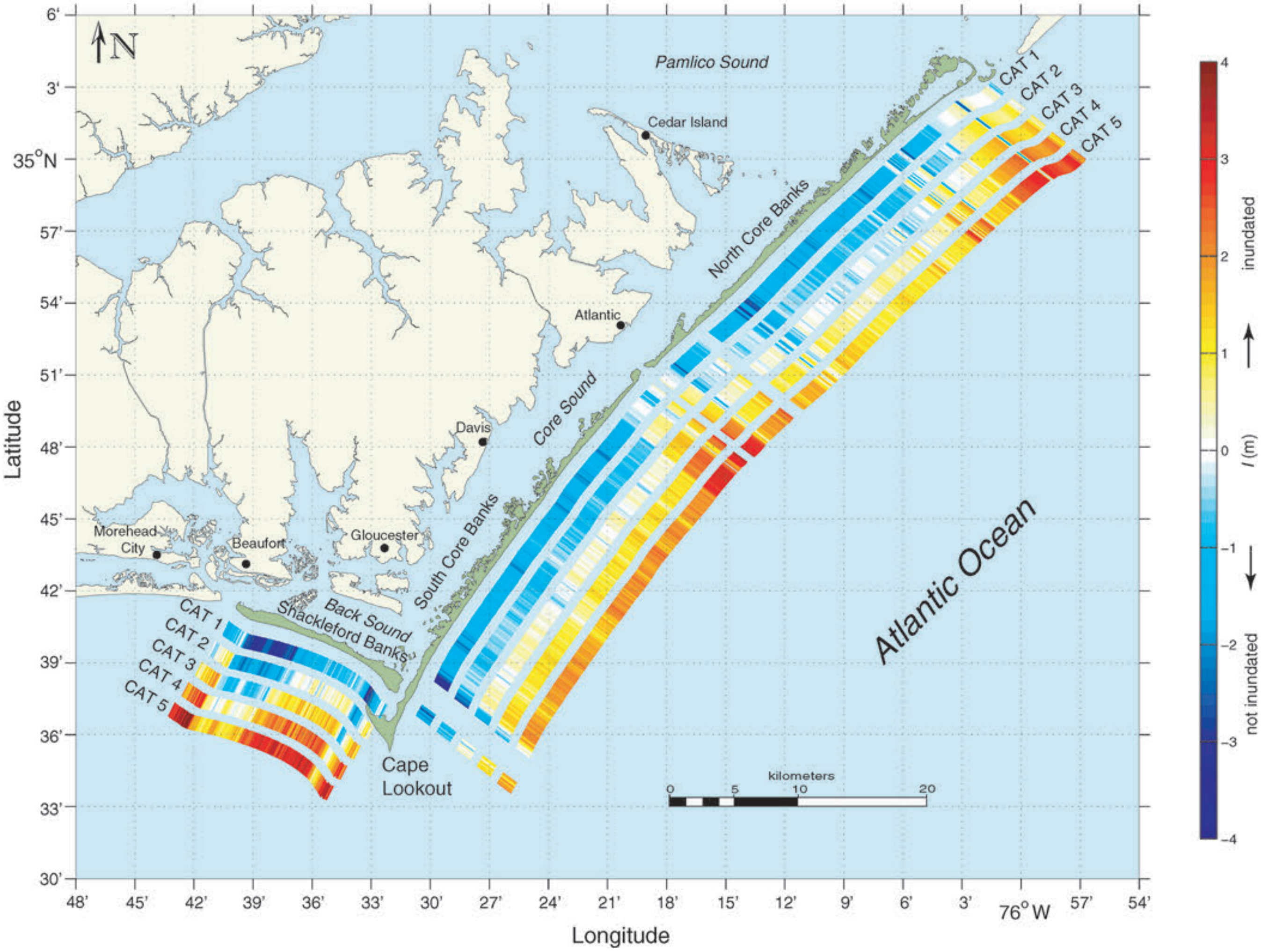


Figure 34. Potential inundation of the beach system at the park for Categories 1-5 hurricanes. Positive values indicate that modeled storm surge exceeds the elevation of the dune crest suggesting that the beach system is more vulnerable to inundation and the associated extreme coastal changes. Based on NOAA SLOSH model and October 1-2 2005 LiDAR elevations of dunes. Figure 5 from Stockdon and Thompson (2007).

quarters and Portsmouth Village (table 10) (Peek et al. 2015).

Ecological Impacts of Hurricanes on Estuaries

Both extratropical (Wright et al.1994; Kim et al. 1997) and tropical (e.g., Wren and Leonard 2005) storms mobilize significant amounts of shelf sediment (Thieler et al. 2014). Major storms often cause changes that may persist for weeks to decades (Zhang et al. 2002, 2004; List et al. 2006; Riggs and Ames 2007).

Perturbations caused by hurricanes affect Pamlico Sound's phytoplankton communities, which account for at least 80% of primary production sustaining the food webs of the sound and its tributaries, according to a study by Paerl et al. (2006). This study found that hurricanes with high rainfall and high flooding increase nutrient loading as well as size and frequency of phytoplankton blooms and low oxygen conditions. In contrast, hurricanes with low rainfall result in lower nutrient inputs and low to moderate stimulation of primary production and phytoplankton biomass. Hurricane-related flooding adds nutrients, organic material, sediments, and toxic chemicals to the estuary, and can enhance vertical stratification of the water column, which allows low oxygen conditions in the bottom water. The authors found that salinity levels in the sound can take months to return to normal pre-hurricane levels (Paerl et al. 2006). An exception may occur when a storm causes an island breach, allowing flushing between the sound and ocean and improving water quality. This occurred during the 2012 Hurricane

Sandy breach through Fire Island National Seashore, New York (Methratta et al. 2017).

The opening of new inlets will also affect estuarine physical and chemical dynamics, including increases in astronomical tidal range, salinity content, and water column mixing. These changes, and the associated changes in nutrient dynamics and turbidity, will impact fisheries, benthic ecosystems, and intertidal wetlands. Estuaries would also be impacted by changes in precipitation patterns that affect river flow, which in turn influence nutrient delivery and cycling, flushing rates, and salinity values in the estuaries. Each of these responses would influence the structure (e.g., plant and animal composition) and function (e.g., plant and animal production, nutrient cycling) of the estuarine system (Culver et al. 2008a).

Impact of Climate Change on Hurricanes

The strength of Atlantic hurricanes is likely to increase in this century, with higher peak winds, rainfall intensity, and storm-surge height and strength, but the number of storms and their paths may not change (Saunders et al. 2012; Caffrey 2013). An increase in storm activity will increase the rate and extent of shoreline retreat, associated land loss, and the openings of new inlets throughout the coastal system of North Carolina (Culver et al. 2008a).

Climate change is also contributing to changes in the coastline. There is an increasing trend in the height of hurricane-generated waves over the last three decades, and associated changes in the directions from which the waves approach the shoreline, which tends to tend to reshape sandy coasts (Slott et al. 2006, as cited in Moore et al. 2013). The effects of a changing Atlantic Ocean wave climate are already detectable on the cuspate Carolina coastline including along and around Cape Lookout (Moore et al. 2013).

Storm Recovery

Cape Lookout National Seashore is the first park to have developed a formal Storm Recovery Plan for actions following storm impacts. The plan is designed to ensure wise fiscal decisions and to manage public expectations for what facilities and services can be restored following these major events (Kenney 2015). This differs from a Storm Response Plan, in which many parks have detailed how to prepare for a coming storm and to implement the Incident Management System (IMS) locally. The park has both a Hurricane Plan to guide hurricane preparations, and a park Storm Recovery Plan (CALO 2011) that is intended to be implemented following landfall of the storm.

The Storm Recovery Plan incorporates sensitivity to park natural and cultural resources in storm response and recovery, and uses a survey approach to measure the priority resources at the park. It details recovery tasks that need to occur over different time periods. Short-term tasks include resource-specific assessments and stabilization measures. Medium-term activities address storm impacts on resources, and long-term activities include reviewing the annual plan. The plan also includes information on expected storm-related changes to the islands, such as clarifying that overwash is not necessarily negative unless it threatens certain types of assets. A natural resource specialist is listed as being a necessary member of the IMS resource assessment team assisting the park. Finally, the plan incorporates consideration of sea level rise in revising the plan and for long-range planning efforts, as related to maintenance, relocation, and replacement of historic structures and camps.

After a storm, the park works to maintain two key public access points on Core Banks: one at Long Point and one at Great Island, both of which have channels and basins to allow ferry access. For the most part, the park leaves sand in place following storms, but may need to move it to provide public access (e.g., grading the back road, reopening off road vehicle ramps and access to buildings, and dredging access for ferries). If shipwrecks are exposed or washed ashore, they are documented and tagged by the North Carolina Office of State Archeology and left in place; individual artifacts of value would be recovered and archived (Pat Kenney, Cape Lookout National Seashore, superintendent, conference call, 16 June 2015).

Inlet Modifications

Inlet dynamics are a critical component of natural barrier island processes at Cape Lookout National Seashore (see the "Geologic and Environmental Features and Processes" chapter for additional information). Inlet size and location adjust in response to each storm (Riggs et al. 2009). Anthropogenic attempts to stabilize an inlet's width and depth, such as dredging and jetty stabilization, disrupt the inlet's ability to respond to storms and to function as a key component of sediment transport processes in the barrier island system (Riggs et al. 2009). Inlet stabilization is one of many examples of human efforts to protect coastal development from natural processes; often, these efforts have altered the behavior of coasts considerably (Williams 2013).

Several inlets through the Outer Banks are actively maintained through dredging. Newly opened inlets are often closed artificially to maintain the highway infrastructure. Due to conflicting Congressional mandates— one for the USACE to maintain navigational inlets, and one for NPS to protect park resources—the Corps will need NPS authorization (e.g. a Special Use Permit, or NPS participation in the planning process) before dredging within the park boundary (NPS 2011a).

Beaufort Inlet

The Morehead City Harbor Federal Navigation Project, for which dredging began in 1911, includes construction and maintenance of a channel for navigation through Beaufort Inlet. The inlet forms the western boundary of the park, and is at the downdrift end of the park. The maintenance of Beaufort Inlet has impacted sediment transport to and from Cape Lookout National Seashore.

The channel location was maintained in a fixed position beginning in 1936, and design depth gradually increased to 14 m (47 ft) deep and 137 m (450 ft) wide by 1994. Maintenance dredging volumes have increased with these increased depths; as of 2006, recent annual dredging averaged 894,500 m^3/yr (1,170,000 yd^3/yr) (Olsen Associates, Inc. 2006). Between 1911 and 2007, 55.1 million m^3 (72.1 million yd^3) of sediment were dredged from the inner and outer channels during 96 episodes (Olsen Associates, Inc. 2006 as cited in Coburn et al. 2010). Until 1997, material dredged from the outer channel was disposed of offshore. Now, the USACE requires that sediment be placed in a nearshore disposal area, which can include Bogue Banks (Olsen Associates, Inc. 2006).

Net sand transport across Beaufort Inlet has decreased over time. Between 1900 and 1933, the average annual net sand transport across Beaufort Inlet was 71,900 m^3/yr (94,000 yd^3/yr) from east to west. During this period, the ebb tidal delta was growing by about 159,000 m^3/yr (208,000 yd^3/yr), and Bogue Banks grew eastward into the inlet (Olsen Associates, Inc. 2006 as cited in Coburn et al. 2010).

Dredging has caused a reversal of shoreline processes, in which Bogue Banks retreated and Shackleford Banks advanced westward (Olsen Associates, Inc. 2006 as cited in Coburn et al. 2010). Since 1936, the ebb tidal delta has lost volume, becoming flatter and wider as a result of the channel deepening and maintenance dredging. From 1933 through 2004, the inlet complex eroded by about 231,600 m^3/yr (303,000 yd^3/yr) (Olsen Associates, Inc. 2006 as cited in Coburn et al. 2010). Dredging has also affected waves and sediment transport patterns within 6.5 km (4 mi) west of the inlet and along the western 5 km (3 mi) of Shackleford Banks (Olsen Associates, Inc. 2006 as cited in Coburn et al. 2010).

The elevation of the western end of Shackleford Banks has been decreasing, and nearshore profiles have become steeper, according to surveys from 2000 to 2010 in depths of less than 9 m (30 ft) (Linda York, NPS Southeast Region, coastal geologist, telephone, 10 June 2015). The shoreline along the western tip of the island is dynamic and sometimes extends into the authorized shipping channel. It has proved difficult for USACE to maintain the 13.7 m (45 ft) target depth; shoaling has reduced the available draft to 10 m (30 ft) at mean low water (Hibbs 2015). Senate Bill 160, which passed in 2015, authorized the state to begin negotiations for a land-swap to acquire federal land (presumably Shackleford Banks, although this is not specified) in order to manage the navigation channel to the Port of Morehead City (General Assembly of North Carolina 2015).

Moving the dredged navigation channel away from the edge of Shackleford Banks may also reduce the erosion along the island's western tip. As of June 2016, USACE was modeling the Beaufort Inlet complex to analyze and recommend changes to the orientation of the Morehead City Harbor navigation channel. Realignment would require a plan separate from the recent DMMP and EIS (USACE 2016b). The proposed project would allow dredging to the authorized depth of 13.7 m (45 ft) within the least-shoaled areas at the time, which could include both the current location and a proposed realignment area 91 m (300 ft) westward of the existing channel (Harvey 2016; USACE 2016). The dredged beach-quality sand would be placed in nearshore areas or on County beaches (USACE 2016).

One of the proposed disposal areas is a 1,094 ac nearshore area off Shackleford Banks, about 1.6 km (1 mi) from the Inlet and about 460 m (1,500 ft) offshore, in water depths from -4.9 m (-16 ft) to -11 m (-36 ft). Sand could be placed in this area between January and March of any year (USACE 2016b). Sediment placement on Shackleford Banks was also considered as part of the Morehead City Harbor Dredged Material Management Plan but the park ultimately requested that this alternative be dismissed (USACE 2016b) for several reasons. The local community argued that the sand should be reserved for the adjacent developed Bogue Banks instead. The park recognized the need for additional information about sediment loss rate and the proportion of erosion that could be attributed to channel maintenance rather than natural processes, and consideration of whether to intervene in proposed wilderness areas to mitigate the impacts of human actions (Kinzer and Kenney 2015).

Barden Inlet

Barden Inlet separates Cape Lookout from Shackleford Banks. This inlet was originally open from about 1770 to about 1860; its closure joined South Core Banks to Shackleford Banks (Payne 1985 as cited in Riggs and Ames 2007). Barden Inlet opened again in the hurricane of 1933. In 1937, it was dredged to a depth of 2.1 m (7 ft); it is maintained but the channel is not fixed in place (Stick 1958 as cited in Coburn et al. 2010). The inlet is now 1 km (0.6 mi) wide and up to 9 m (29 ft) deep. Tidal currents in Barden Inlet are typically 0.25 m/s (0.8 ft/s) but sometimes exceed 1.5 m/s (4.9 ft/s) (Wells 1988). The inlet served as a source of sediment for the 2006 beach nourishment project on Cape Lookout. Between 1937 and 2007, 69 dredging episodes removed 10,000 m^3 (13,080 yd^3).

Drum Inlet

Drum Inlet separates North Core Banks from South Core Banks. When the natural inlet began infilling, a3.7 m (12-ft) deep channel was dredged in 1938 (Stick 1958 as cited in Coburn et al. 2010) and then at least four more times through 1952, removing a total of 381,621 m3 (Coburn et al. 2010). The dredge spoils were placed directly behind the throat of the inlet (Riggs and Ames 2007). After the inlet migrated and closed naturally, USACE created New Drum Inlet in 1971 about 4 km (2.5 mi) southwest of the natural inlet site. USACE dredged the new inlet at least 10 times through 1998, removing a total of 1,468,066 m3 (1,920,157.8 yd3) (Coburn et al. 2010). Neither of these two inlets is believed to have any discernable impact on sediment transport along the park (Coburn et al. 2010).

Ocracoke Inlet

Ocracoke Inlet was first dredged in 1826 but rapidly shoaled (Stick 1958 as cited in Coburn et al. 2010). The channel was reopened in 1895 but not maintained. Dredging began again in 1954 and recurs periodically, impacting the park to varying degrees depending on the frequency and scope of dredging, and the distance between the dredged channel and northern Portsmouth Island (Coburn et al. 2010). Between 1828 and 1995, 516,082 m^3 were removed during 5 dredging episodes.

The inlet has undergone maintenance dredging at various times over the past two centuries (Riggs and Ames 2007). It is the largest and most stable of the inlets north of Cape Lookout. Based on a USACE (1964) study, the width of Ocracoke Inlet varied from a maximum of 3,170 m (10,400 ft) in 1856 to a minimum of 1,250 m (4,100 ft) in 1943 and 1946. It has a depth of 9 to 19 m (30 to 62 ft) below MLW and is dredged irregularly for maintenance (Riggs and Ames 2007).

Ferry Infrastructure and Use

Several channels provide access for ferries and other boats to facilitate visitation and park management. The channel into Great Island is outside of the park boundary and has never been dredged (NPS 2016). The channel into Long Point at North Core Banks is outside of the park boundary and has been dredged twice since 1992. Dredging efforts were state-funded and the dredged material was pumped onto the beach. The park performed maintenance dredging (less than 765 m3 [1000 yd3]) of the boat/ferry basins inside of the park boundary at both Long Point (twice in 20 years) and Great Island (three times in 20 years), and both basins were dredged again in calendar year 2010 in response to hurricane impacts. If additional dredging occurs, it could impact the park’s marine and estuarine resources, particularly submerged aquatic vegetation beds, due to disturbance and relocation of marine sediments (NPS 2016). The park wants to perform maintenance dredging in the area around the dock at Les and Sally's, south of the lighthouse, in order for the park to use the location for operations (Jeri DeYoung, Resources Management Chief, Cape Lookout National Seashore, email, 9 June 2016). The park is interested in developing dredging management plans for the Great Island, Long Point, and Les and Sally’s docks.

Coastal Engineering and Shoreline Armoring

NPS management policies (NPS 2006) require that natural coastal processes be allowed to continue without interference and that anthropogenic impacts be mitigated. Exceptions require special evaluation and are granted for the protection of cultural or natural resources, safety during emergencies, and congressional directives.

Many forms of estuarine shoreline armoring are permitted by the state of North Carolina (NCDCM 2009). The state's Coastal Area Management Act requires local land-use plans to contain policies that minimize threats to natural resources resulting from development in areas subject to erosion, storm surge, and sea level rise, among other forces (Feldman et al. 2009).

Since 1985, state regulations have disallowed the installation of hardened structures such as seawalls and groins to prevent ocean shoreline retreat, and require that new construction be located a certain distance from the shoreline. However, Senate Bill 151, the Coastal Policy Reform Act of 2013, permits the construction of up to four new terminal groins at North Carolina inlets if structures or infrastructure are threatened by erosion. This act represents a significant change to the state's coastal policy laws, which previously required an imminent erosion threat and determination that nonstructural methods (e.g., relocation) were impractical.

Seawalls and other structures that attempt to inhibit wave action are expensive and do not prevent sediment loss in front of the structures. Instead, they commonly accelerate erosion locally (Dolan and Godfrey 1972; Dolan and Lins 1986) and are aesthetically displeasing. Jetties and other structures designed to inhibit currents that transport sand cause localized erosion in the direction of longshore transport and adjacent to the structures (Dolan and Godfrey 1972).

Alternative erosion control structures, such as sandbags and beach nourishment, are permitted. The state allows the use of sandbags as a temporary measure to provide time to arrange for beach nourishment or to move a structure threatened by erosion. Bulkheads composed of sandbags act similarly to those composed of rock or steel. The beach in front of the sandbags is lost to wave energy and erosion on adjacent beaches increases (Riggs et al. 2008b).

Beach nourishment, another temporary solution, requires the availability of compatible sediment within a reasonable transport distance. The idea of artificial beach nourishment seems attractive because (1) placement of sand on a beach does not alter the suitability of the area for recreation, (2) addition of sediment does not always affect areas beyond the problem area, and (3) no structural debris must be removed if the effort fails (Dolan and Godfrey 1972; Dolan and Lins 1986).

However, the sourcing of sufficiently large quantities of sand compatible with the eroding beach in terms of size and mineralogy can be difficult. Finer sands tend to wash away too quickly; coarser sands create artificial beach berms and impact nearshore habitats. Sources of large quantities of sand may be limited to offshore areas, such as Diamond Shoals and coastal inlets (Dolan and Lins 1986). The means of obtaining suitable sand, such as dredging, can have substantial impacts on other areas (Dolan and Godfrey 1972). In North Carolina, the most commonly used nourishment sand is sourced from inlet deltas and channels; this sand is compatible, but its removal destabilizes the inlets and impacts longshore sediment transport and long-term sediment budgets for the barrier islands and inlets (Riggs et al. 2008b).

Alternatives to protecting infrastructure in place include adapting the design or function of a structure (e.g., elevating the structure); relocating the structure to a less vulnerable location; or letting the structure deteriorate and abandoning it in place (with documentation in the case of cultural resources) (Beavers et al. 2016).

The Coastal Engineering Inventory (Coburn et al. 2010) identified 15 projects in and adjacent to the park as of 2009 (fig. 35; table 12). Five are navigation dredging projects and two are beach nourishment projects. Eight are erosion control structures, five of which are currently impacting sediment transport: the jetty at Cape Lookout Bight, two groins on Shackleford Banks, the jetty at Fort Macon State Park, and the bulkhead at the park headquarters on Harkers Island. These projects are described below.

Beginning in 1912, there was an effort to turn the protected embayment known as Cape Lookout Bight into a harbor of refuge for ocean-going ships, and to connect Cape Lookout with the railroad at Beaufort (Stick 1958, as cited in Coburn et al. 2010). To this end, sand fencing was constructed in 1913, and in 1914,

Figure 35. Location of coastal engineering structures impacting the park. Figure 13 from Coburn et al. (2010). Table 12 lists the erosion control structures and dredging locations (numbers indicate location in figure).

construction of a 2,150 m (7,050 ft) breakwater to protect the harbor began. Only 1,460 m (4,800 ft) of this breakwater was constructed before the project was discontinued in 1917 due to the start of World War I. Accretion resulting from the jetty elongated the spit towards Shackleford Banks and increased the area of Cape Lookout Bight (Coburn et al. 2010).

Three erosion control structures were identified on Shackleford Banks: a now-landlocked jetty built at Shackleford Point in 1882 and two groins built prior to 1882 on the sound side of the island. USACE built the breakwater and the eastern groin to stabilize Shackleford Point and improve navigation through Beaufort Inlet. The two groins interrupt the westward sediment transport, resulting in a small fillet of sand trapped on the eastern, or updrift, side of each groin, and a sediment deficit of unknown quantity on the western, or downdrift, side. When originally constructed in 1882, the jetty extended several hundred feet into Beaufort Inlet; it is now landlocked due to accretion on the western end of Shackleford Banks, and is not impacting sediment transport (Coburn et al. 2010). Two erosion control structures are located on the eastern end of Bogue Banks at Fort Macon State Park. The jetty constructed in 1962 impounds some of the sediment being transported eastward, but is permeable (Coburn et al. 2010).

The southeastern shoreline of the park headquarters on Harkers Island, including the boat basin, is protected with timber bulkheads to minimize erosion impacts caused primarily by wave action, occasional inundation at high tide, and to a lesser extent, wake from boat traffic. Portions are being repaired and replaced, and a new stone breakwater extension is being constructed at the basin entrance in order to widen the entrance channel and to remove the peninsula adjacent to the channel (Coburn et al. 2010).

As of 2015, two beach nourishment projects comprising a total of eleven beach nourishment episodes were identified in, or within 3.2 km (2 mi) of, Cape Lookout National Seashore. A single nourishment episode occurred on Core Banks in 2006, when 58,000 m^3 (75,700 yd^3) were placed along 792 m (2,600 ft) of the sound shoreline to protect the lighthouse (fig. 36). Additionally, a 381 m (1,250 ft) long berm was built to 2.3 m (7.5 ft) elevation (Coburn et al. 2010).

The other ten episodes occurred between 1961 and 2014 at Fort Macon State Park on Bogue Banks (outside the park boundary), totaling approximately 4,378,000 m^3 (5,727,000 yd^3) (Coburn et al. 2010, Carteret County 2015, PSDS 2016). Until 1997, sediment dredged from the Morehead Inlet area by USACE was dumped

Table 12. Erosion control structures and dredging locations. Refer to figure 35 for locations.

Location Number (fig. 35)	Type	Location	Material Used or Number of Nourishment/ Dredging Episodes
1	Bulkhead	Harkers Island	Wood
2	Groin	Shackleford Banks	Rock
3	Groin	Shackleford Banks	Rock
4	Jetty	Fort Macon State Park	Rock
5	Jetty	Cape Lookout Bight	Rock
6	Breakwater	Shackleford Banks	Rock
7	Groin	Fort Macon State Park	Rock
8	Groin	Fort Macon State Park	Concrete/rock
9	Nourishment - complete	Cape Lookout	1
10	Nourishment - ongoing	Fort Macon	9
11	Dredging - ongoing	Beaufort Inlet	96
12	Dredging - ongoing	Barden Inlet	69
13	Dredging - ongoing	Ocracoke Inlet	5
14	Dredging- complete	New Drum Inlet	10
17	Dredging - complete	Drum Inlet	4

Source: Tables 3 and 5 from Coburn et al. (2010).

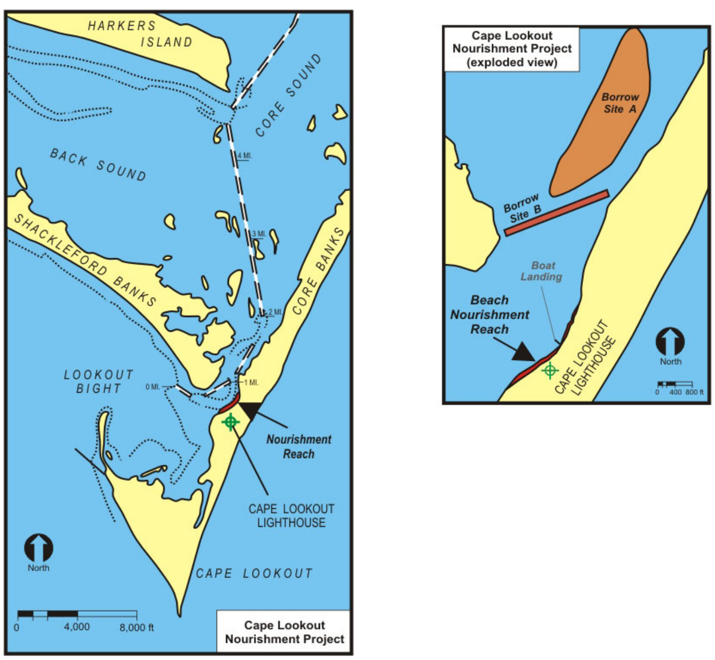


Figure 36. Sediment dredge and placement locations for Cape Lookout beach nourishment in 2006. Figure from Carteret County Shore Protection Office, http://www.carteretcountync.gov/DocumentCenter/View/1657 (accessed 3 June 2016).

offshore, but USACE now disposes of some dredged sediment onto Bogue Banks.

Five dredging projects, with at least 184 episodes, have been identified within 3.2 km (2 mi) of the park. These projects, occurring at four different inlets, are described in the "Inlet Modifications" section of this chapter (Coburn et al. 2010). Relict ditches, dug in the 1970s to drain wetlands for mosquito control, continue to hold water on Core Banks although they are no longer maintained or functional (Rasmussen et al. 2009).

A few short-lived dune-building projects also occurred on Core Banks, but are not documented in the Coastal Engineering Inventory. From 1961 through at least 1964, by the State of North Carolina and the USACE conducted experimental dune-building studies along 6 km (4 mi) of shoreline northeast of Old Drum Inlet to reduce coastal erosion. Subsequently, during the 1970s, NC State University carried out extensive sand fencing and grass-planting studies (Riggs and Ames 2007).

Grazing Horses on Shackleford Banks

Europeans introduced horses (*Equus caballus*) and other grazing livestock (cattle, goats, sheep, and pigs) to Shackleford Banks around 1790 (Levin et al. 2002). By 1810, there were about a thousand grazing animals on Portsmouth Island, and heavy grazing continued until the 1950s (Burk et al. 1981). NPS removed the goats and cows in 1987-1988, leaving horses as the only feral ungulates on the island. The horse population was at its highest, 225 horses, in 1994, and dropped to 108 in 1997 due to a cull (Levin et al. 2002).

The Shackleford Banks Wild Horse Protection Act (P.L. 105-229) legislates the management of the horses, assigns co-management of the herd to both NPS and a private foundation. A later amendment (P.L. 109-117) established a minimum of 110 horses and a target population of 120-130 horses, which was not derived from scientific studies based on carrying capacity or genetic diversity. The legislation specifies that the natural resources on the island must not be adversely impacted by the horses. These two goals may conflict when considering protection of a functioning marsh.

The horses continue to degrade estuarine biodiversity on Shackleford Banks, and may reduce the value of marshes as nursery grounds for fishes and crabs (Levin et al. 2002). Horse-grazed marshes on Shackleford Banks were found to have a lower total number of birds (such as Laughing Gulls and Forster's Terns, which nest in Spartina and aggressively exclude other nesting birds), but higher diversity of foraging birds that forage for benthic invertebrates (Levin et al. 2002). Horse-grazed marshes also had higher densities of crabs, and a lower density and species richness of fishes than in ungrazed marshes. In subtidal habitats adjacent to grazed marshes, fish density was reduced and the potential for crab predation on fishes was higher (Levin et al. 2002).

Horse-grazed marshes on Shackleford Banks were found to have less vegetation than ungrazed marsh areas (Levin et al. 2002). Horses grazed primarily on *Spartina* sp. (50%), *Uniola paniculata* and other upland grasses (37%), with some grazing on sedges, forbs, and woody leaves (Wood et al. 1987); horses were often observed grazing in the salt marsh and not often observed in the maritime forest (Wood et al. 1987).

Figure 37. Horse exclosures (part of the Fenced Areas unit on the ECU map) were built to study grazing impacts on vegetation growth and composition. Figure A36 from Riggs et al. (2015).

Stuska et al. (2009) found that in spring and summer, sea oats, smooth cordgrass, and pennywort comprise up to 65% of the horses' diet, and that in fall and winter, sea oats, centipede grass, and smooth cordgrass are 80% of the diet. Studies at both Shackleford Banks and at another barrier island park, Assateague Island National Seashore in Maryland (see GRI report by Schupp 2013), show that feral horse grazing causes large decreases in standing biomass, percent cover, blade height, culm density, seed production, and belowground biomass of *Spartina* (fig. 37) (Turner 1987; Wood et al. 1987; Furbish and Albano 1994). Grazing also significantly changes the marsh plant assemblage due to the decreased abundance of *Spartina*, which in ungrazed marshes forms a near monoculture (Zervanos and Keiper 1979; Wood et al. 1987; Hay and Wells 1991; Furbish and Albano 1994). Trampling by horses may also limit the ability of marshes to accumulate sediment to balance marsh erosion (fig. 38) (Furbish and Albano 1994) and defecation can also damage wetland ecosystems and surface waters (Noon and Martin 2004 as cited in Burkholder et al. 2017).

Other island ecosystems are likely degraded also. An exclosure study on Shackleford Banks from 1978-1981, when up to 491 feral ungulates on the island included horses, cattle, sheep, and goats, found that ungulates influenced vegetation community dynamics by reducing aboveground productivity in salt marsh and grass-shrub areas, slowed the rate of succession in grass-shrub areas, and interfered with expansion of the maritime forest (Wood et al. 1987). Studies at Assateague Island found that horse grazing influences plant community structure in forest and shrub habitats (Sturm 2007)

Figure 38. Horse hoof prints are visible on this Inlet Tidal Mud Flat (inlet_tidal_mud_flat) on Shackleford Banks. Figure A30 from Riggs et al. (2015).

and accelerates dune erosion due to heavy grazing on American beachgrass (*Ammophila brevigulata*) (Seliskar 2003), which has roots and rhizomes that stabilize dunes. At Cumberland Island National Seashore in Georgia, selective grazing by horses on oak seeds and seedlings may have resulted in changes to the maritime forest community structure (Turner and Bratton 1987).

Recreational and Watershed Land Use

Water Quality

The park's surface aquatic habitat is healthy and stable overall (NPS 2012), and surface water quality rated in "good" condition in the recent Natural Resource Condition Assessment (Burkholder et al. 2017). The wetlands, tidal marshes, seagrass beds, and freshwater ponds support nursery habitat and form the aquatic base of the barrier island ecosystem. This resource also contributes to unique, resource-compatible recreational opportunities at the park. Due to its isolation from the mainland and limited development, water quality is better inside the park than surrounding areas. There have been no recent reports of fish kills, algal blooms, beach closures, or shellfish closures related to water quality. Monitoring data from the NPS Southeast Coast Inventory and Monitoring Network indicate that overall sediment conditions were good at all sites sampled, showing only trace amounts of metals and little or no organic contamination (NPS 2010). Core Sound is classified as federal Outstanding Resource Waters; no new or expanded wastewater discharges are allowed, and there are stricter requirements for managing stormwater within the watershed.

The state of North Carolina is not able to convey submerged lands to NPS ownership, but it has conveyed easements to the NPS so that the NPS now has the authority to regulate activities at the park down to the MLW line on the Atlantic side of the island and to 46 m (150 ft) beyond the MLW line on the sound side (NPS 2011a).

Only sparse information on groundwater quality, at few locations, is available. This resource is threatened by point source pollution (visitor trash, shipping debris and petrochemicals) and nonpoint source pollution (septic tank runoff from adjacent communities) (NPS 2012). Some wells in the park contain elevated nitrate levels, most likely due to septic leachate (Parman et al. 2012). Mallin et al. (2004) reported high levels of metals and petrochemical-related contaminants in the water on Core Banks, possibly from an above-ground storage tank, incinerator, and refueling pad on the island. Other potential threats to water quality in and around the park include urban runoff from impervious surfaces in Beaufort, Morehead City, a large military base, and a complex of smaller bases within 40 km (25 mi). Additionally, dredging activities in Beaufort Inlet have the potential to re-suspend toxins or contaminates that have been deposited and "locked up" in the sediment, back into the water column (Rinehart 2014). Core Sound is on North Carolina's 303(d) list of impaired waters due to fecal coliform bacteria, with possible sources including septic systems, marinas, urban runoff, and agriculture (NCDENR 2007).

The recent Natural Resource Condition Assessment (Burkholder et al. 2017) assessed groundwater as being in "fair" condition and recommended that groundwater recharge/discharge areas in and around the park be re-mapped and quantified in order to evaluate the resource trends accurately.

Off-Road Vehicles

Off-road vehicles (ORVs) have been used at the park since the 1930s, when they were transported to the islands by shallow draft ferries and used to access commercial and recreational fishing spots, and for other recreational pursuits such as sightseeing and camping. The park's 1966 enabling legislation does not address ORV use but does specifically authorize fishing. Other national seashores also allow ORV use on beaches, including nearby Cape Hatteras National Seashore (Schupp 2015).

Currently, ORVs provide vehicular access to the beaches for a variety of recreational purposes, and are allowed on North and South Core Banks from March 16 through December 31. Annual vehicle use is approximately 2,400 ORVs/yr on North Core Banks (up to 124 vehicles at one time) and approximately 3,100 ORVs/yr on South Core Banks (up to 218 vehicles at one time) (NPS 2016).

Under the park's Off-Road Vehicle Management Plan (NPS 2016), driving will be permitted on up to 81% of the park's entire ocean shoreline length: on the beach in front of the primary dune line and on proposed routes including limited access to the sound side, ferry landings, and cabins. On North Core Banks, a designated and maintained ORV route that is locally referred to as the backroad runs behind the primary dune line from just south of mile marker 4 to just north of mile marker 18, excluding the area between mile markers 6 and 7 (plate 1, in pocket). Due to the reopening of Old Drum Inlet in 1999, the backroad from mile marker 19 to Ophelia Inlet at mile marker 22 is currently closed. On South Core Banks, the backroad extends from just south of mile marker 24 to the point of Cape Lookout at mile marker 45 (NPS 2016).

The backroad, which runs through the shrub zone, is critical for management of protected species and for allowing a safe route for ORV travel, allowing access around full beach closures or areas where the high tide line limits driving on the ocean beach (NPS 2016). In areas where the backroad is available, ramps to the beach exist at approximately 1.6 km (1 mi) intervals (NPS 2016). The ramps are placed in areas with few dunes, and ORV use prevents growth of new dunes (Pat Kenney, conference call, 16 June 2015). Vehicles must use those ramps when crossing between the beach and the backroad (NPS 2016). Up to 9 additional ramps may be built.

Some areas are off-limits to ORVs. Shackleford Banks is a proposed wilderness area and is closed to vehicle use. On South Core Banks, no vehicles are allowed in the vicinity of the lighthouse or at the end of Power Squadron Spit. Some portions along the ocean beach are periodically closed to ORV use to protect wildlife during the summer nesting season (NPS 2016).

Studies conducted along beaches similar to those at Cape Lookout National Seashore have shown that ORV use can have a variety of ecologic and geomorphic impacts. Driving on the unvegetated beach displaces sediment and may interfere with beach-dune morphology and evolution, but the sediment is not necessarily lost to the beach-dune system. A study conducted at Fire Island National Seashore, New York, estimated that 119,300 m^3 (156,040 yd^3) of sediment was displaced (but not necessarily lost to the beach-dune system) by 45,000 vehicles annually (Anders and Leatherman 1987a, 1987b), and a study performed on North Stradbroke Island, Australia, estimated 38,018 m^3 (49,725 yd^3)/year sediment displacement for every 500 cars (Schlacher and Thompson 2008).

A recent study of the ORV zone at Assateague Island National Seashore, Maryland (Houser 2012) suggested that ORV use causes no net seaward loss of sediment from the beachface. Rather, ORV use disrupts the landward exchange of sediment between the beach and dune, preventing dune recovery after storms. In comparison with those in adjacent no-vehicle zones, dunes in the ORV zone were found to be smaller, shorter, farther landward, and more susceptible to scarping. This study also determined that sediment volume was greater on the leeward sides of dunes in the ORV zone, which reduces their resilience to storms, preventing the recovery of pre-disturbance height and elevation. This effect can accelerate shoreline retreat and island transgression in response to relative sea level rise.

Off-road driving can also damage vegetation, which destabilizes backshore and embryo dunes, the precursors to larger stable dunes (Liddle and Greig-Smith 1975; Steiner and Leatherman 1981; Anders and Leatherman 1987a). Loss of vegetation seaward of a dune can promote erosion of the dune toe and steepening of the seaward beach, which can lead to further erosion and scarping by tides (Anders and Leatherman 1987a). In contrast, dunes in vegetated control sections extend seaward and provide greater protection during storms. Even a low frequency of ORVs can cause extensive degradation of vegetation and habitat, limiting seaward dune growth (Anders and Leatherman 1987a). Godfrey and Godfrey (1980) found that 50 vehicle passes on Cape Cod were sufficient to inhibit seaward dune development, resulting in a scarped rather than sloped dune profile. The number of vehicles using a path makes little difference once vegetation has been damaged.

Recreational Infrastructure and Use

The park's Foundation Statement (NPS 2012) describes several concerns with the impact of recreational uses on the natural resources. The constructed boardwalks, which are used to reduce pedestrian damage to dunes and vegetation, may not be properly designed to protect the primary ocean and sound-side dunes. This may cause breaches in the dune system and increase gaps between the dunes (NPS 2012). Pedestrians and certain recreational activities also threaten the park bird populations. Visitor litter and marine debris, including petrochemical spills, threaten sea turtles and their habitat at the park (NPS 2012). Ocean currents deposit a problematic volume of marine debris on Shackleford Banks (Jeri DeYoung, Resources Management Chief, Cape Lookout National Seashore, email, 9 June 2016).

The number of motorized vehicles (including boats) at the park is increasing, and motorized vehicle types are getting larger (NPS 2012). Visitor boat propellers have scarred seagrass beds, and boat wake contributes to sound side erosion. Personal water craft were banned from the park beginning in 2002, with the exception of 10 access points.

Paleontological Resource Inventory and Protection

All paleontological resources are non-renewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix B). As of March 2017, Department of the Interior regulations associated with the Act were being finalized.

A field-based paleontological resource survey can provide detailed, site-specific descriptions and resource management recommendations that are beyond the scope of this report. Although a park-specific NPS field survey has not yet been completed for the park, Tweet et al. (2009) has summarized multiple documents detailing ages and variety of fossils found at the park. Additionally, a variety of publications and resources provide park-specific or servicewide information and paleontological resource management guidance (e.g. Brunner et al. 2009). One useful resource is Santucci et al. (2009), which details five methods and vital signs for monitoring in situ paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use.

If a paleontological survey yields significant findings, the park may want to consider the following actions (Brunner et al. 2009):

- Develop resource management plans including inventory and monitoring to identify human and natural threats to these resources;
- Incorporate findings or suggestions into park general management plans (GMP);
- Train park staff (including interpreters and law enforcement) in resource protection, as the fossil trade "black market" has become quite lucrative for sellers and often results in illegal collecting from federal lands;
- Track down collections taken from the area residing in outside repositories for inventory purposes;
- Use fossils in interpretive programs.
- Continue and increase visitor education efforts to highlight that the NPS resource conservation and stewardship includes fossils; that newly exposed fossils is a natural process; and that leaving the fossils in place allow the next visitor to personally experience that process also.
- Provide education, outreach, and warnings in encounters with casual collectors; and citations and confiscation for directed and commercial collecting.
- Work with the NPS social science program to develop signs, brochures, and media that effectively reduce theft of NPS resources and increase the willingness of the public to bring new discoveries to the park's attention.
- Encourage and support more fossil monitoring and data collection by scientists, students, and local fossil clubs. These volunteers might help the park to monitor coasts for newly exposed fossils, alert park staff about unauthorized collectors, and help park staff collect exposed fossils and related data for scientific study and park museum collections.

Additional Information Needs

An understanding of geomorphic processes and landform evolution along the park is critical to park managers' ability to prepare for the island's response to coastal processes and its evolution throughout the coming decades. SECN now measures 16 vital signs at the park, including 6 that are particularly relevant to coastal geology: coastal shoreline change, salt marsh elevation, water quality, weather and climate, groundwater dynamics, and land management and disturbance. This report and accompanying geomorphic maps address the need for geomorphic mapping at the park that was identified at the GRI scoping meeting (NPS 2000).

Monitoring of topographic change along all islands could be accomplished by collecting LiDAR elevation data or ground-based topographic profiles. Additionally, the park can submit a technical assistance request to GRD or SECN to develop a monitoring plan that focuses on volumetric (both topographic and bathymetric) changes related to sediment dynamics in and around Beaufort Inlet. Ongoing USACE monitoring in the area of Bogue Banks and Morehead City Harbor may be able to complement or support this effort. The resulting information will be important as Shackleford Banks continues to migrate westward into the authorized shipping channel for the Morehead City Port, and in the event that the state proposes a related swap or changes to the park boundary, as is being considered in the North Carolina state legislature as of the 2015-2016 legislative session (see the "Inlet Modifications" section of this chapter for additional information).

Park resource management would benefit from additional geologic products identified in the Foundation Document (NPS 2012) and at the 2000 GRI scoping meeting (NPS 2000):

- Maps of habitats and habitat changes
- Sea-floor mapping for the inner shelf component out to approximately five nautical miles offshore, to include bathymetry, sediment texture, and subsurface
- Analysis of overwash processes relative to developed areas (ramps, roads)
- Shoreline and island movement over time
- LIDAR elevation changes of beaches and dunes
- Map of geologic hazards (i.e. to show potential inlets, historical inlets, overwash, erosional hot spots);
- Post-storm beach recovery patterns
- Aerial photographs taken once per decade and following major storm events
- Distribution of paleontological features/fossils

The recent Natural Resource Condition Assessment (Burkholder et al. 2017) recommended monthly sampling of groundwater at least every other year in order to characterize pH, salinity, conductivity, chloride, and concentrations of potential pollutants known to contaminate groundwater from septic effluent leachate, especially nitrate, nitrite, total phosphorus, soluble reactive phosphate, and fecal bacteria. It also recommended that contamination of groundwater and soil from known sources be characterized to determine the nature, extent, and persistence of hazardous substances.

Examination of the effects of overwash in increasing the salinity of the surface lens would be possible by analyzing the pore water salinity data collected by the NPS SECN at a sentinel site on North Core Banks.

Resource managers may find *Geological Monitoring* (Young and Norby 2009; http://go.nps.gov/geomonitoring) useful for addressing these geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies. Chapters describe the methods and vital signs for monitoring aeolian features and processes including dune morphology (Lancaster 2009), coastal features and processes (Bush and Young 2009), and marine features and processes (Bush 2009). Two NPS Geologic Resources Division websites provide additional information: the Aeolian Resource Monitoring website, http://go.nps.gov/monitor_aeolian, and the Coastal Geology website, http://go.nps.gov/grd_coastal.

Additional Planning Needs

The park's Foundation Document (NPS 2012) identified the following planning needs to protect Fundamental Resources and Values including the intact barrier island system driven by coastal geologic processes, its undeveloped character, and aquatic and terrestrial habitats and species (NPS 2012):

- Continue to serve as a cooperating agency in the development of the Dredged Material Management Plan for Beaufort Inlet
- Continue to develop off-road vehicle management plan (completed 2016)

- Evaluate the impact of individual park facilities on the barrier island system
- Develop the resource stewardship strategy
- Develop a transportation plan (including strategies for documenting and managing ramps and roads network)
- Initiate climate change scenario planning.

Geologic History

This chapter describes the chronology of geologic events that formed the present landscape.

The North Carolina barrier islands are very young in terms of geologic time. The oldest known parts of the modern Outer Banks formed less than 3,000 years ago (Culver et al. 2008b). The construction of the geologic framework occurred within the Cenozoic Era (the past 66 million years) and primarily since the Miocene, which began 23 million years ago. This framework controls the sediments available to the barrier islands, and the ways in which the islands respond to natural and anthropogenic processes. The geologic story at Cape Lookout National Seashore is one of rising and falling relative sea levels.

Coastal processes continue to shape the modern landforms and rework the Quaternary sediments (see the "Geologic and Environmental Features and Processes" chapter for additional information on the influence of the geologic framework on modern coastal geomorphology). This chapter focuses on the Late Tertiary and Quaternary periods because older units occur in the subsurface and do not play an active role in modern coastal processes and issues along the park coastline. See table 2 for a stratigraphic column.

Miocene (23 million to 5.3 million years ago)

During the Middle and Late Miocene, shelf sands were deposited under relatively low-energy conditions in the Albemarle Embayment, which was protected from shelf currents by the Cape Lookout High to the south (Popenoe 1985). Upper units of early Miocene age are sandy to silty clay beds that were deposited in depths of approximately 50 m (164 ft) (Zarra 1989) with a sea level similar to today's sea level (Greenlee and Moore 1988).

Pliocene (5.3 million to 2.6 million years ago)

In the Early Pliocene, the Atlantic Ocean covered the eastern portion of the coastal plain of present-day North Carolina (Richards 1968). This transgression deposited marine sediments along the east coast that document the last major marine advances over the coastal plain. The Yorktown Formation, a Late Miocene/Pliocene sequence of marine sediments, forms part of the upper 5 to 50 m (16 to 164 ft) of the material below Pamlico Sound (Wells and Kim 1989). Beneath Core Banks, the unconsolidated sediments of this formation are typically green-gray, well sorted, very fine to fine-grained clayey sand (Moslow and Heron 1979). The Yorktown Formation is sometimes referred to as the Duplin Formation in areas extending from the Neuse River southward to South Carolina; the two units are approximately equivalent (Carter et al. 1988).

Before the Middle Pliocene, subaerial exposure in the Core Banks area resulted in erosion and alteration of the upper 2.4 to 3.1 m (7.9 to 10.2 ft) of the Yorktown sediments. The unconformity between the Yorktown Formation and the overlying beds represents a break of over 6 million years, from the early Pliocene to the late Pleistocene, although early and mid-Pleistocene transgressions are recorded elsewhere on the North Carolina Coastal Plain (Moslow and Heron 1979).

The Pliocene-Pleistocene submarine unconformity dips southward. It is only 20 m (66 ft) deep at Cape Lookout, but slopes to 70 m (230 ft) below the surface at Cape Hatteras (fig. 39, 40) (Thieler et al. 2014).

Quaternary (2.6 million years ago to present)

The Quaternary Period, which includes the Holocene and Pleistocene epochs, represents a time of dramatic climate and sea level fluctuations associated with the advance and retreat of continental ice sheets.

The Albemarle Embayment is a structural basin bounded by the Norfolk Arch to the north and Cape Lookout High (fig. 2) to the south (Brown et al. 1972). It contains well-preserved Quaternary stratigraphy that is approximately 90 m (295 ft) thick (Mallinson et.al. 2005; Culver et al. 2008b; Mallinson et al. 2010a), thinning to 20 m (66 ft) at the southern end of Pamlico Sound (Mallinson et al. 2010a). Sediments were deposited during many sea level fluctuations that occurred during the glaciations ("ice ages") and interglacial periods of the Quaternary (Riggs et al. 1995; Riggs and Ames 2006). The sediments thicken northward and consist of slightly indurated to unconsolidated mud, muddy sand, sand, and peat (Popenoe 1985; Mallinson et al. 2005; Riggs and Ames 2006; Culver et al. 2008b). Holocene deposits are thinner and Pleistocene sediments occur within a few meters of the surface, except in ancient river valleys such as the paleo–Roanoke River drainage system (Culver et al. 2008b).

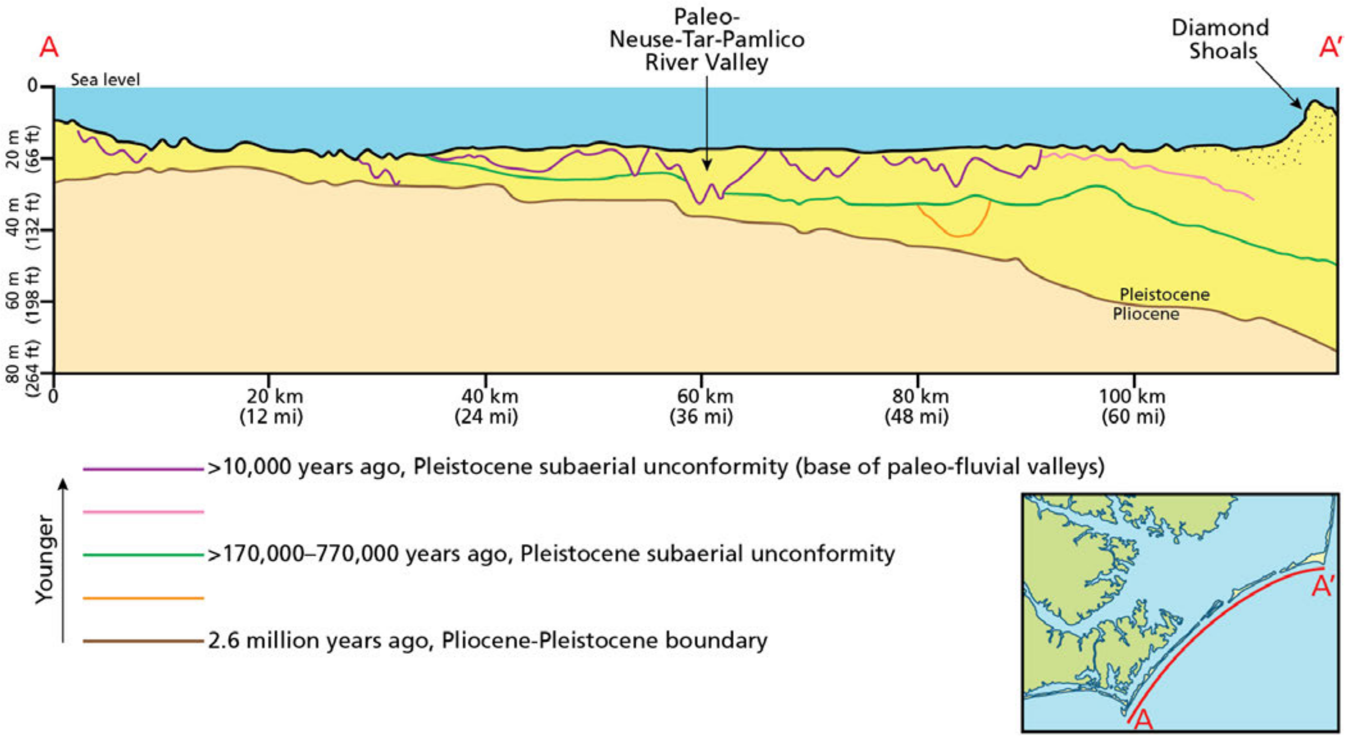


Figure 39. Interpreted seismic section (A-A') for the inner shelf study area, showing major seismic reflections from Cape Lookout (left) to Cape Hatteras (right). The Pliocene-Pleistocene boundary, a submarine unconformity, dips northward from Cape Lookout (A) to Cape Hatteras (A’) and the overlying unit thickens northward. The Pleistocene subaerial unconformity is older than 170,000-770,000 years. The reflection delineated in purple is a subaerial unconformity (the low stand erosional surface) that defines the base of the major paleo-fluvial valleys. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 4 from Thieler et al. (2014) and Mallinson et al. (2010a).

Pliocene and Quaternary sequences dip and thicken toward the center of the Albemarle basin beneath northern Pamlico Sound. At the southern end of Pamlico Sound, the sequences thin onto an older high (Thieler et al. 2014).

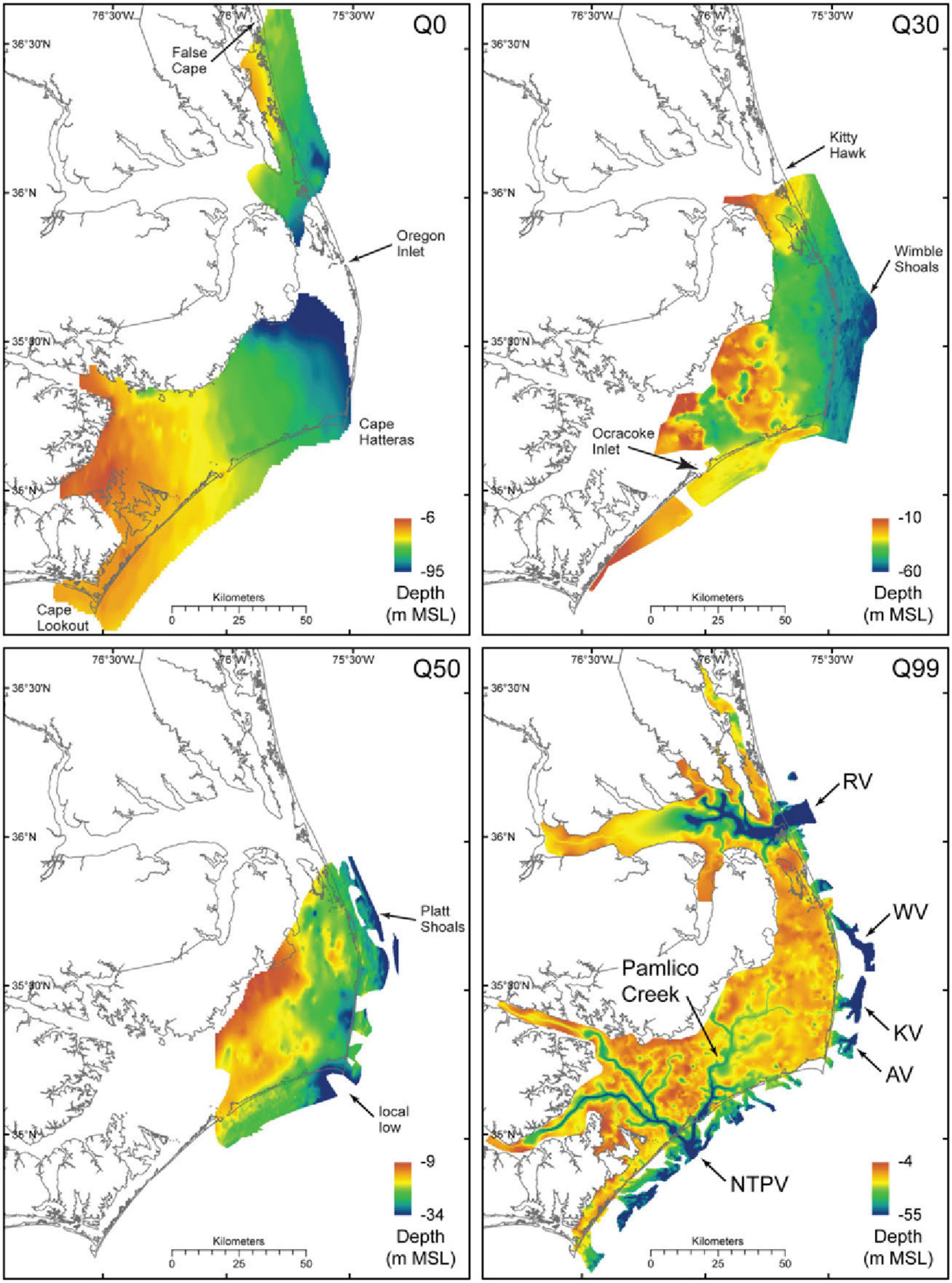
Pleistocene (2.6 million years ago to 10,000 years ago)

Early through Late Pleistocene sediments, which lie unconformably upon Late Pliocene deposits (Culver et al. 2008b), suggest an open inner- to mid-shelf marine environment (Mallinson et al. 2010a) under cooler climate conditions (Culver et al. 2008b).

During multiple ice ages in the Pleistocene, when sea level was lower, stream channels cut irregular depressions in the upper surface of the Yorktown Formation. The topography that it formed may be responsible for many of the modern sea floor features in the lagoon. (Mallinson et al. 2010a):

- Swash Inlet, a recurring inlet through North Core Banks that coincides with the Neuse/Tar fluvial paleo-valley;
- the trunk estuaries that occur within the flooded paleo-valleys of the Roanoke, Pamlico/Tar, and Neuse Rivers; and
- Bluff Shoal and the widest portion of Portsmouth Island that occur on the Neuse River and Pamlico/Tar River interstream divide.

Figure 40 (facing page). Maps showing the depths of regional seismic reflections. A cross-sectional view of these reflections is shown in Figure 39. Q0) This submarine unconformity represents the Pliocene-Pleistocene boundary; map indicates thickness of Quaternary sediments. Q30) The Pleistocene subaerial unconformity is older than 170-770 thousand years. Q50) Another Pleistocene surface. Q99) This subaerial unconformity (the low stand erosional surface) defines the base of the major paleo-fluvial valleys. Major paleofluvial valleys are identified: RV = Roanoke Valley, WV=Wimble Valley, KV= Kinnakeet Valley, AV= Avon Valley, NTPV= Neuse-Tar-Pamlico Valley. Figure 3 from Thieler et al. (2014) and Mallinson et al. (2010a).


Q0
False Cape
Oregon Inlet
Cape Hatteras
Cape Lookout
-6
-95
Depth (m MSL)
Kilometers
0 25 50
Q30
Kitty Hawk
Wimble Shoals
Ocracoke Inlet
-10
-60
Depth (m MSL)
Q50
Platt Shoals
local low
-9
-34
Depth (m MSL)
Q99
RV
WV
KV
AV
Pamlico Creek
NTPV
-4
-55
Depth (m MSL)
76°30'W
76°W
75°30'W
36°30'N
36°N
35°30'N
35°N

Early to Middle Pleistocene (2.6 million to 126,000 years ago)

The Early Pleistocene Epoch was characterized by ice ages and corresponding changes in sea level with a periodicity of approximately 41,000 years, transitioning to a periodicity of 100,000 years between approximately 1 million and 800,000 years ago (Mallinson et al. 2010a). During glacial periods, when large volumes of Earth's water were incorporated into glacial ice, sea level was lower and rivers cut deep channels into coastal systems along the continental margin. During interglacial periods, the flooding of meltwater flow back into the oceans backfilled the incised valleys with fluvial and estuarine sediments. The advancing shoreface produced an erosional surface that migrated landward with rising sea level (Riggs et al. 1995) and truncated large portions of previously deposited coastal sediments (Mallinson et al. 2010a). Beneath the western part of Pamlico Sound, the Early Pleistocene inner shelf occurs at a depth of 20 to 40 m (66 to 131 ft); the mid- to outer-shelf, beneath the modern barrier islands and northern Pamlico Sound, occurs at a deeper level, about 45 to 70 m (148 to 230 ft) (Mallinson et al. 2010a).

Seismic surveys along the Raleigh Bay inner shelf between Cape Hatteras and Cape Lookout identified several Pleistocene sequences. One Pleistocene subaerial unconformity is older than 170,000-770,000 years and dips eastward, from a depth of 14 m (46 ft) near Cape Lookout to 60 m (197 ft) off of Wimble Shoals (see fig. 44, 45). Incised valleys, filled with reworked sequences formed by inlet formation and migration, penetrate this Pleistocene surface just south of Ocracoke Inlet (Thieler et al. 2014). The inlet fill deposits are preserved because there are few processes that can rework them (Moslow and Heron 1978).

Atop the Pleistocene open shelf deposits, there are units of fine sand that record well-oxygenated, inner shelf environments from the mid-Pleistocene (600,000 to 250,000 years ago). These units are, in turn, overlain by muddy deposits of another cool climate and associated sea level low stand and brackish to freshwater conditions, also deposited in the mid-Pleistocene (Culver et al. 2008b).

Late Pleistocene (126,000 to 10,000 years ago)

The magnitude of sea level fluctuation increased during the Middle to Late Pleistocene (Mallinson et al. 2010a). During the last interglacial warm period (approximately 125,000 years before present), when most of the world's glaciers and many ice sheets on Greenland had melted, sea level was approximately 6 to 8 m (20 to 26 ft) higher than present (Williams 2013).

The Core Creek sand that was deposited beneath modern-day Core Banks is a nearshore marine and tidal delta facies, containing silty and clayey, highly fossiliferous, fine- to coarse-grained quartz sand (Moslow and Heron 1979). It was deposited as a terrace formation when the ocean advanced 32 km (20 mi) inland from its present position in the late Pleistocene (during the late Sangamon interglacial period), 80,000 to 120,000 years before present.

The Wisconsin Glaciation was the most recent major advance of the North American ice sheet. The glacial period lasted from about 85,000 to 11,000 years ago. During early Wisconsin seaward regression, the upper beds of the Core Creek unit were eroded from the area beneath Core Banks (Moslow and Heron 1979). During the latter part of the mid-Wisconsin transgression before 35,000 years ago, the Atlantic Sand was deposited as a barrier complex (back barrier and barrier shoreface environments) (Mixon and Pilkey 1976). This unit is found -14.6 m to -19.8 m (-48 to -65 ft) MSL below the modern Core Banks. It consists of very fine- to coarse-grained, well sorted, clean quartz sands (Moslow and Heron 1979).

During the late Wisconsin regression, about 29,000 to 24,000 years ago, the Diamond City Clay was deposited as a regressive lagoonal sequence. It is found at -9 m to -10 m (-30 to -33 ft) MSL. It represents a lagoon environment that was wider and deeper than present-day Core Sound. During the Last Glacial Maximum (approximately 21,000 years before present), sea level was 120 to 130 m (394 to 425 ft) lower than present and the coastal system extended all the way to the present-day continental shelf (Williams 2013).

Thick Late Pleistocene units contain numerous filled fluvial valleys that were incised into older Pleistocene deposits (Culver et al. 2008b; Mallinson et al. 2010a), suggesting that large rivers entered the area from the west along with their south- and north-flowing tributaries. The late Pleistocene stratigraphic units compose the underlying geologic framework that controls many modern coastal features including inner shelf shoals, shore-oblique bars, and barrier islands (Riggs et al. 1995; McNinch 2004; Mallinson

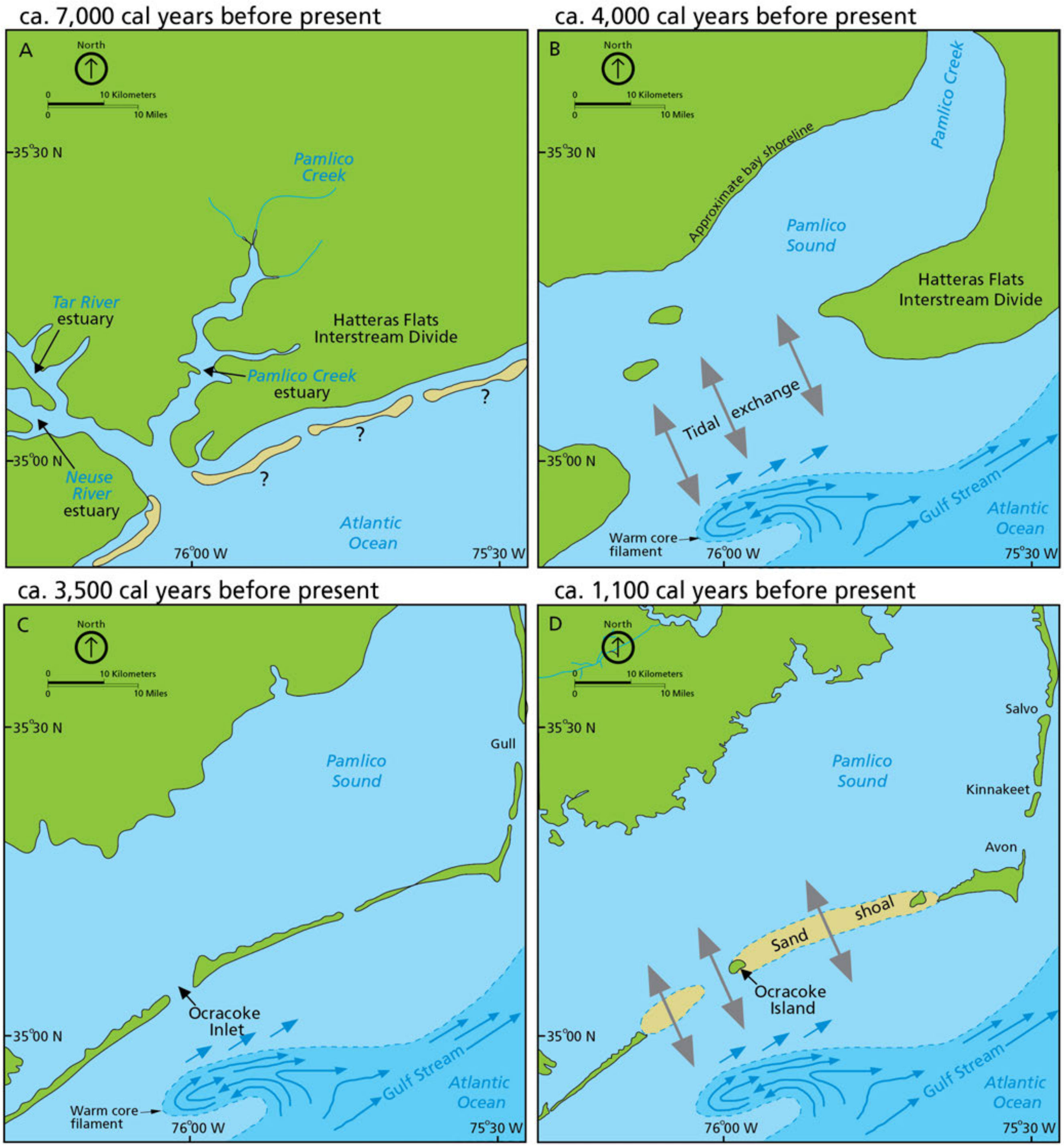


Figure 41. Paleogeographic reconstructions for the southern Pamlico Basin during the Holocene. Graphic redrafted by Trista Thornberry-Ehrlich (Colorado State University) after Figure 3 in Culver et al. (2007) and Figure 7 in Mallinson et al. (2009).

et al. 2010a; Thieler et al. 2014). The base of the major ancient river valleys is defined by an unconformity that extends across the region from the upper reaches of the Albemarle-Pamlico estuarine system to the seaward limit of recent inner shelf surveys (fig. 39, 40) (Thieler et al. 2014). The same surveys also mapped three paleo-valleys offshore of Core Banks. Two of them originate just landward of the barrier island, widening to 2.5–3.5 km (1.5 to 2.2 mi) and going as deep as 32 m (105 ft) below sea level. The southernmost mapped valley is just

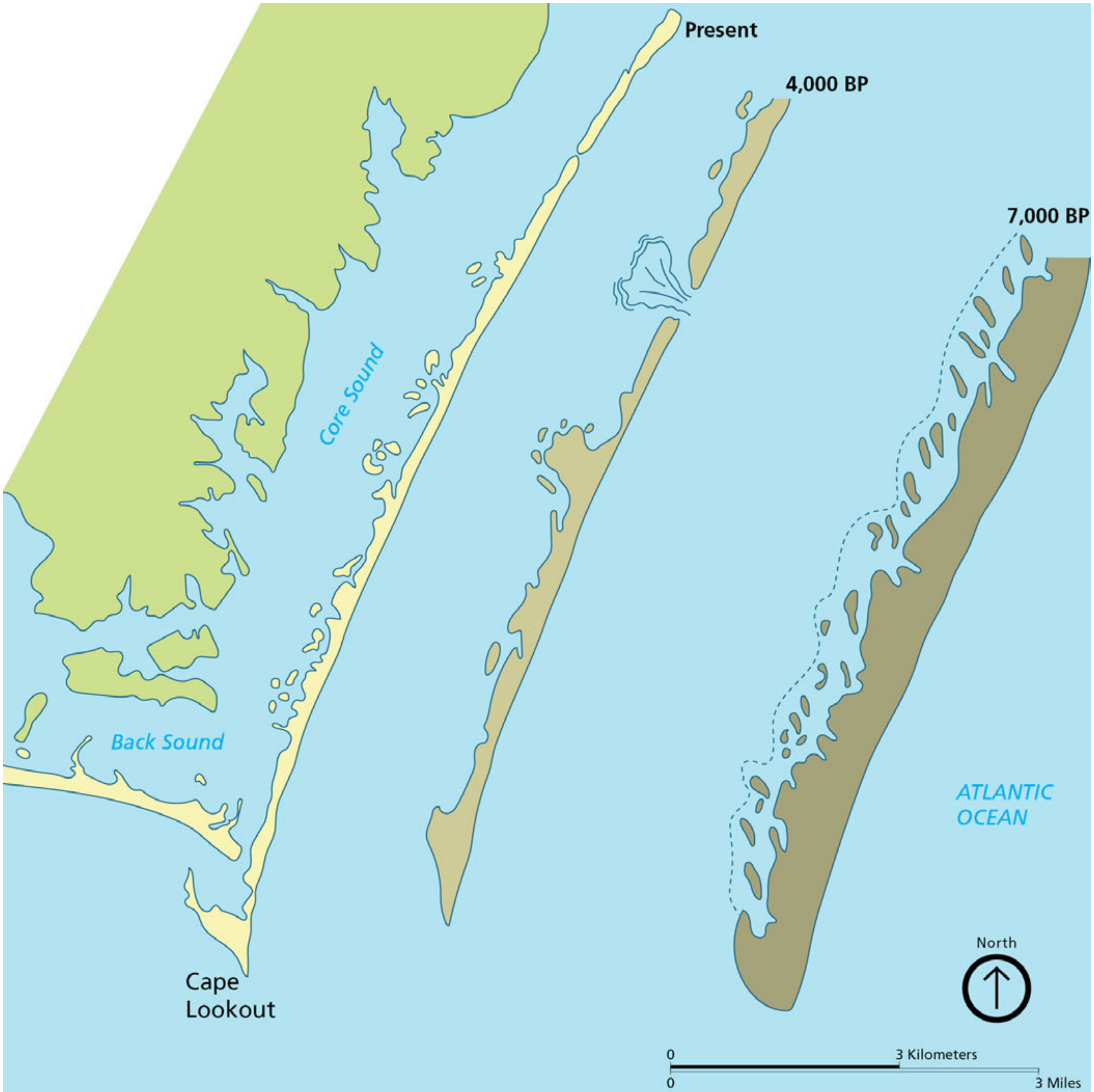


Figure 42. Late Holocene evolution of Core Banks (7,000 BP to present). Graphic redrafted by Trista Thornberry-Ehrlich (Colorado State University) after figure 2.26 from Moslow and Heron (1994).

north of Cape Lookout, originating in Back Sound to the west of Core Banks. The valley traces a 5–6 km (3-4 mi) wide path to the southeast and deepens to 26 m (85 ft) below sea level (Thieler et al. 2014).

Between 21,000 and 6,000 years ago, global sea level rose at an average rate of 10 mm (0.4 in)/year. During two brief warmer episodes, this rate may have reached 40 to 50 mm (1.6 to 2 in)/year (Williams 2013). By about 18,000 to 14,000 years ago, sea level was about 91 m (300 ft) lower than at present, and North Carolina's Atlantic coastline was 80 to 120 km (50 to 75 miles) farther east (Dolan and Lins 1986). By 11,000 years ago, the shoreline was about 30.5 m (100 ft) below present sea level (Riggs et al. 2011).

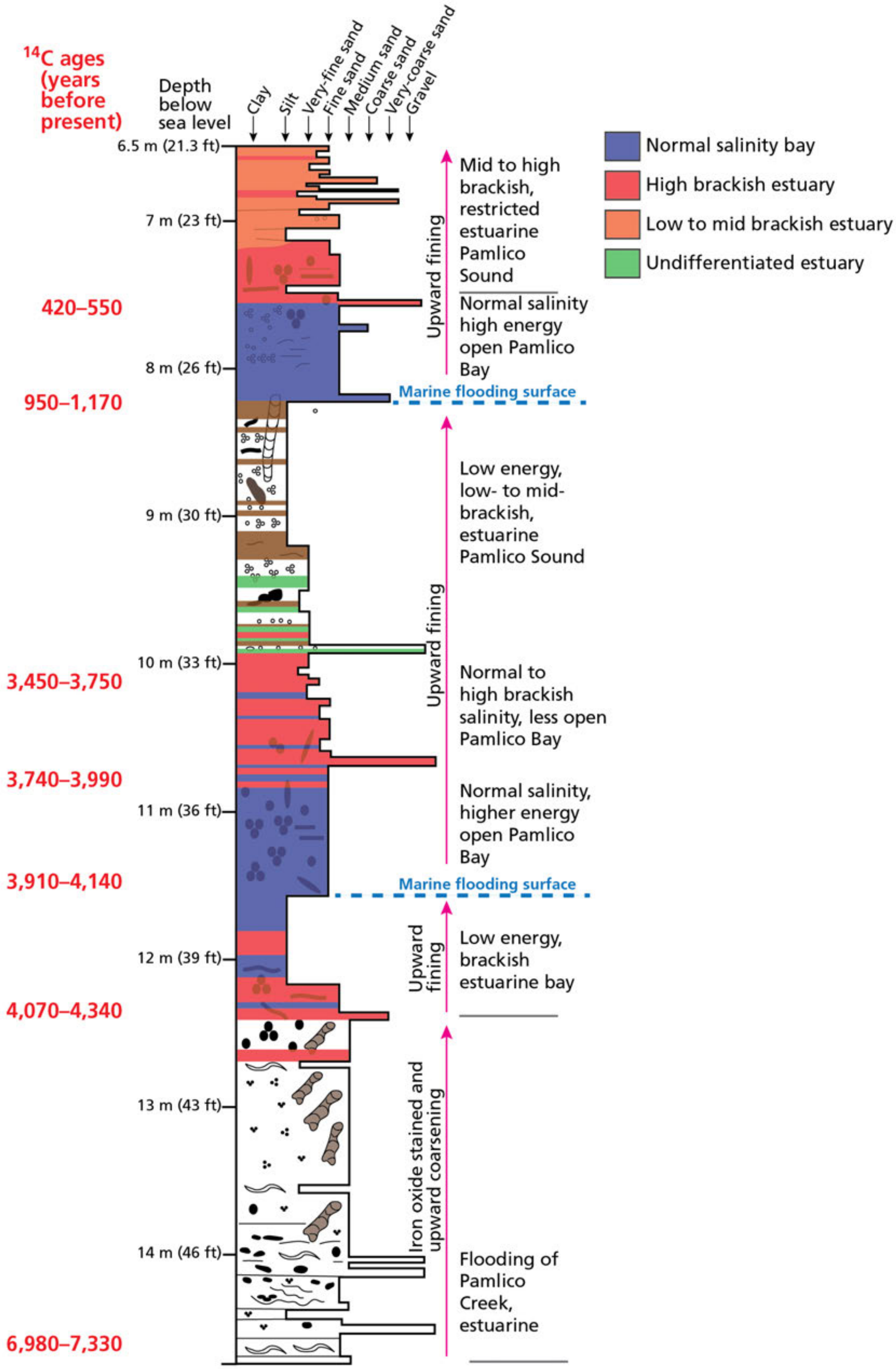


Figure 43. A vibracore (8.21 m [26.9 ft] long) collected from the estuarine south central Pamlico Sound, north of Core Banks and Ocracoke Inlet, is representative of more than 100 vibracores collected in the area including Core Banks. Foraminiferal assemblages were analyzed to determine depositional environments. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) based on Figure from Culver et al. (2007).

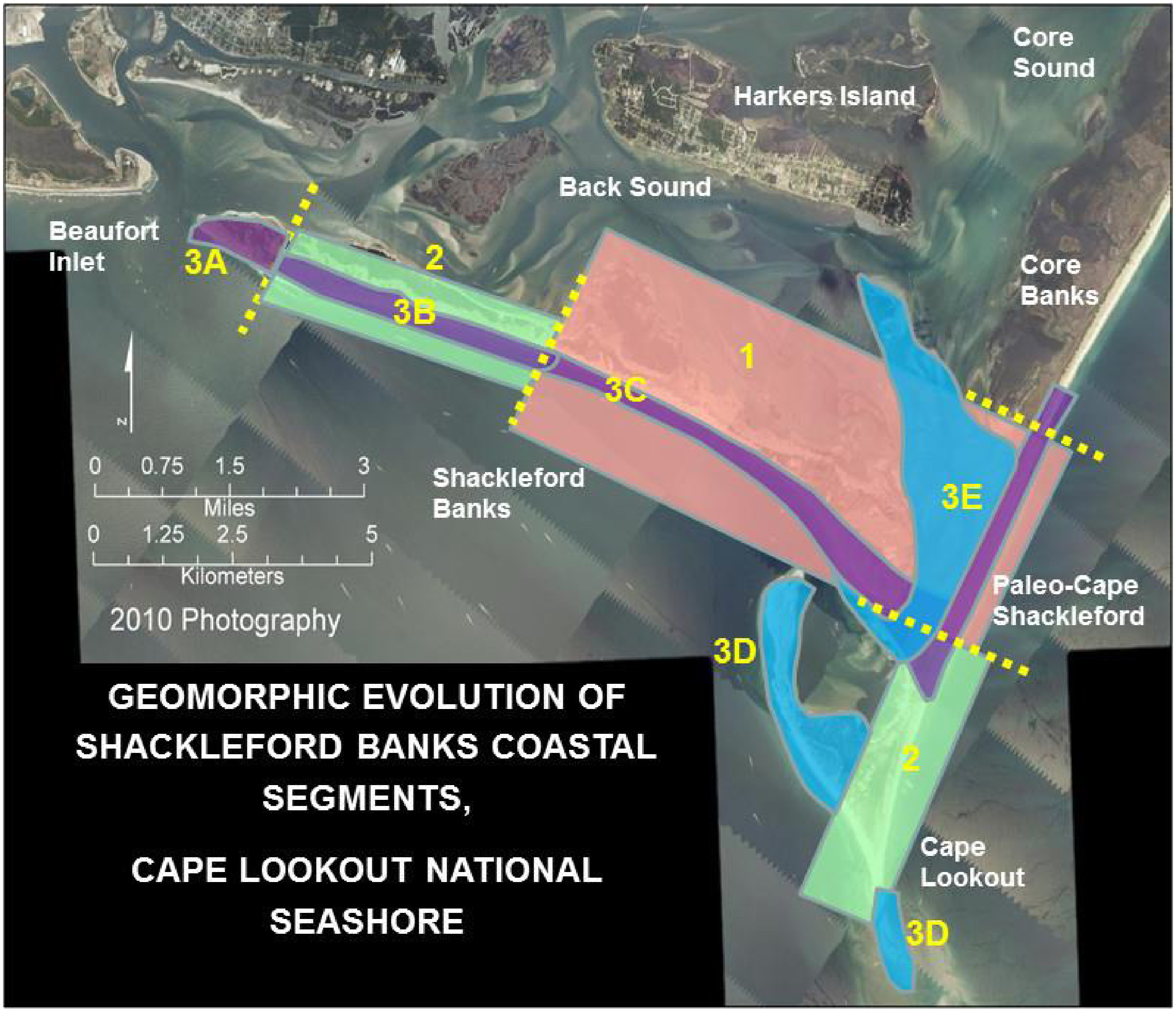


Figure 44. Shackleford Banks is composed of distinct geomorphic components. Island segments are described in table 13. Figure 25 from Riggs et al. (2016).

Early to Middle Holocene (approximately 10,000 to 3,000 years ago)

The modern barrier islands and estuarine sediments consisting of compact peat and mud and unconsolidated sands, gravels, and shell beds (Moslow and Heron 1979; Mallinson et al. 2010a) are perched upon the Hatteras Flats Interstream Divide. The Divide is a late Pleistocene feature that separated the southwest-flowing Pamlico Creek from another creek to the east (Riggs and Ames 2006; Culver et al. 2007). Beneath Core Banks, the Holocene/Pleistocene contact is about -9 m (-30 ft) MSL, and the sequence of Holocene sediments is 10-12 m (33-39 ft) thick (Moslow and Heron 1979).

Between 11,000 and 8,000 years ago, sea level rose at a rate of 5.3 mm/yr (0.21 in/yr) (Riggs et al. 2011). Marine water flooded the Pamlico Creek drainage, and the Tar and Neuse river valleys approximately 9,000 to 7,000 years before present (Mallinson et al. 2005; Culver et al. 2007, 2008b). Around 7,000 years ago, as sea level rise continued, flooding of the drowned-river valleys formed Pamlico Sound (fig. 41a) (Culver et al. 2007; Mallinson et al. 2010a). Barrier islands may have existed in a similar pattern as today, but farther offshore (fig. 42).

The shoals extending from Cape Lookout may have formed as early as 7050 BCE (Thieler and Ashton 2011).

Table 13. Descriptions of coastal segments of Shackleford Banks.

Island Segment	Age	Description
1	550 BCE – 1450 CE	Contains the paleo-topographic land in Back Sound with large ridge and swale deposits to form the older eastern portion of Shackleford Banks. Sea level was 2.7 m (8.9 ft) below MSL.
2	1450 CE – 1700 CE	A second set of recurved ridges and swales were deposited, constraining Shackleford Bay. Cape Lookout spit began to form. Sea level was 0.8 m (2.6 ft) below MSL. As it rose, swales along Back Sound were submerged and truncated.
3A	1700 CE – 2015 CE	Deposition and erosion of the westernmost spit (Island Segment 2) of Shackleford Banks that defines modern Beaufort Inlet. Sea level was 0.55 to 0 m (1.8 to 0 ft) below mean sea level.
3B	1700 CE – 2015 CE	Extensive maritime forest forms on older ridge structures. Deposition of high interior dune field that migrated over southern portion of the maritime forest in Segment 2.
3C	1700 CE – 2015 CE	Ocean shoreline recession of Segment 1 supplied sand for overwash fans on the older interior flats and deposition of major dune fields in Segments 1 and 2.
3D	1700 CE – 2015 CE	Southward pro-gradation of Cape Lookout Point onto the inner continental shelf and deposition of the hook to form Cape Lookout Bight.
3E	1700 CE – 2015 CE	Opening and dredging of Barden Inlet, formation of flood- and ebb-tide delta sand shoal deposits around Barden Inlet, and formation of ocean beach ridge features on the eastern portion of Segment 1.

CE: Common Era; BCE: Before Common Era. Colors correspond to segments on fig. 44.

Source: Figure 25 from Riggs et al. (2016).

Geologic and morphologic data indicate that a cuspate foreland also existed in Raleigh Bay between Cape Hatteras and Cape Lookout from 7050 to 2050 BCE (Thieler and Ashton 2011), at which time there was a period of barrier island collapse (Culver et al. 2007). Five to eight remnant ridges and swales are present on the middle and outer shelf, approximately 20 km (12 mi) offshore of Ocracoke Inlet at depths of 25 m to 33 m (82 ft to 108 ft) . The ridges are up to 5 m (16 ft) high and spaced several hundred meters apart, with crests extending out to 20 km (12 mi). Their morphology is much larger than modern ebb-tidal deltas along this coast (Thieler and Ashton 2011).

From 6,000 to 3,000 years ago, the rate of global sea level rise slowed to about 0.5 mm (0.02 in)/year (Williams 2013). By 5,000 years ago, river valleys along the coast were flooded, and barrier systems, including shoals and shore-parallel spits, cut off open marine access to form sounds (fig. 41b) (Culver et al. 2007, 2008b). Upward-fining, muddy units in Pamlico Sound, deposited approximately 4,070 to 4,340 calibrated years before present (cal yr BP, equal to years before 1950 CE), indicate that conditions were highly brackish at that time as rising seas overtopped the Hatteras Flats Interstream Divide (fig. 43) (Culver et al. 2007).

By approximately 4,000 cal yr BP, flooding began to occur in the region that is now Ocracoke Island (Culver et al. 2007), and Core Banks was present 3-5 km (2-3 mi) seaward of its modern position (Moslow and Heron 1981). When portions of the Neuse and Tar rivers and Pamlico Creek flooded, tidal exchange occurred and normal salinity oceanic waters extended into the southern part of the Pamlico basin (fig. 41b), as confirmed by microfossil data (fig. 43) (Culver et al. 2007). Models indicate that at this time (4,240–3,592 cal yr BP), mean sea level (MSL) in the southern Pamlico and Core Sounds had risen rapidly to -4.2 m ± 0.4 m from its elevation of -35.7 ± 1.1 m MSL at 11,062–10,576 cal yr BP (Horton et al. 2009). Around 3,600 years ago, the shoreline was about 4.2 m (13.8 ft) below present sea level (fig. 24) (Horton et al. 2009).

Late Holocene (approximately 3,000 years ago to present)

As sea level rose in the late Holocene, barrier islands began to form. The rate of sea level rise slowed episodically, eventually reaching a near still-stand (0 to 0.2 mm [0.008 in]/year) about 3,000 years ago (Williams 2013), when sea level was about 2.6 m (8.5 ft) below present MSL (Horton et al. 2009). By 3,500 cal yr BP, the initial configuration of barrier islands had formed slightly seaward of their modern location (Culver et al. 2007). Their formation effectively blocked the drowned river drainages to form semi-enclosed estuaries, including Pamlico Bay (Riggs et al. 2011), (fig. 41c, 42). The decreased rate of sea level rise over the past 4000 years and the increase in sedimentation from washover and tidal exchange has resulted in a shallowing of Core Sound, which has in turn decreased the number of inlets along present-day Core Banks (Moslow and Heron 1979).

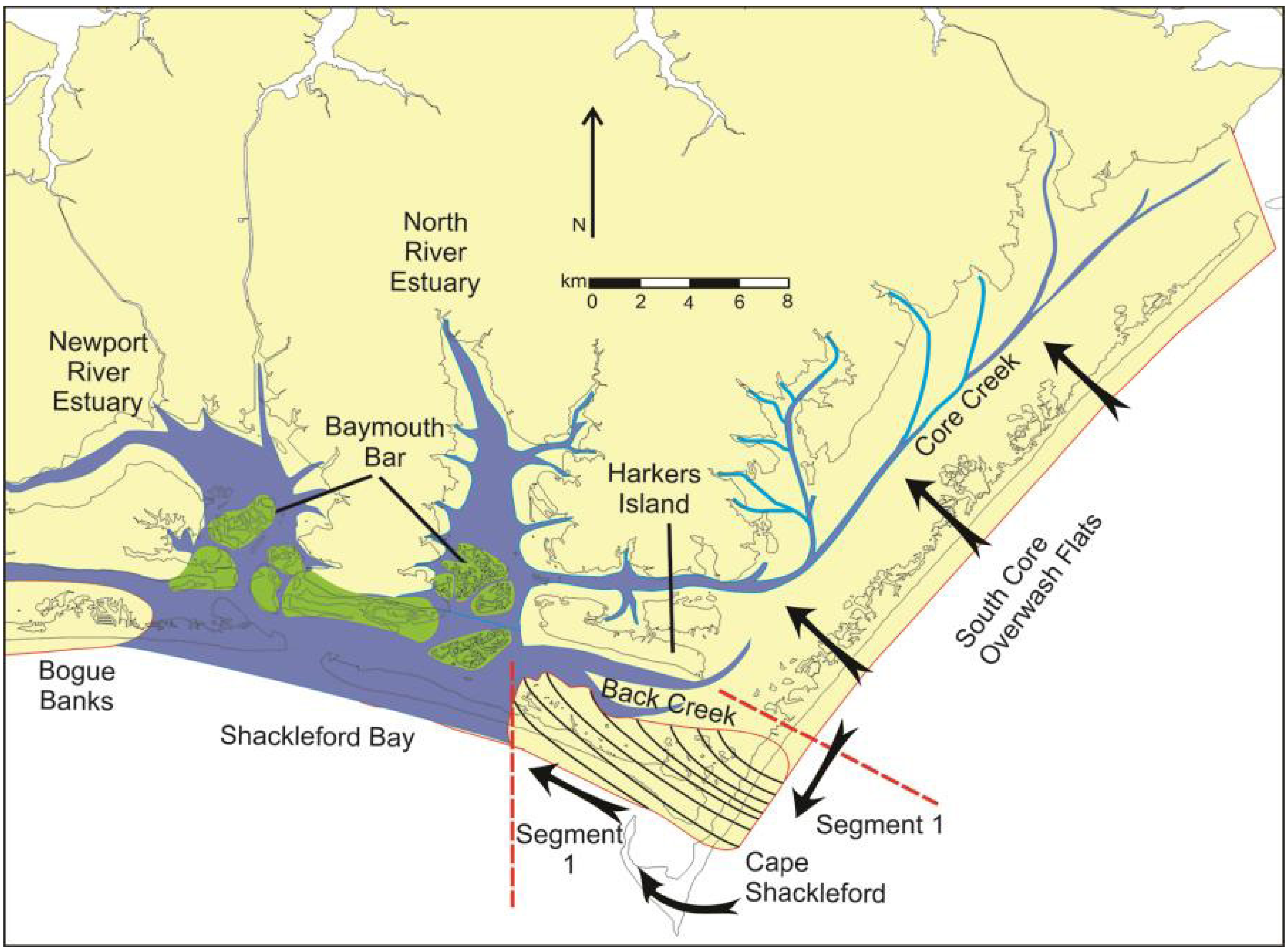


Figure 45. Reconstruction of the Shackleford Banks region about 2500 cal yr BP (550 BCE) when sea level was about -2.7 m (-8.9 ft) below mean sea level. Notice the development of beach ridges forming Segment 1 of Shackleford Banks as it pro-graded westward into Shackleford Bay from Cape Shackleford at the southern terminus of South Core Banks. Shackleford Bay was an open marine environment with development of extensive salt marshes within the Bay (green). Core Creek had not yet been flooded by rising sea level. Consequently, the Core Banks strand-plain beaches were pro-grading onto the Carteret Headland and filling the Core Creek drainage with overwash sediments. The modern shoreline is denoted by a gray outline. Figure 26 from Riggs et al. (2016).

850 BCE to 1450 CE

Approximately 550 BCE to 1450 CE, sea level was 2.7 to 0.8 m (10 to 2.7 ft) below mean sea level (MSL). According to Kemp et al. (2011), sea level in the region of present-day North Carolina was stable from 100 BCE to 950 CE. Sea level then rose over the subsequent 450 years (950 CE to 1400 CE) at a rate of 0.6 mm (0.02 in)/year due to warming conditions, and then remained stable from 1400 CE until the end of the 19th century (fig. 24). As sea level rose, the ocean shorelines of simple barrier islands receded westward.

New archeological data including dated materials from middens allowed reinterpretation of the evolutionary history of Shackleford Banks and Back Sound (fig. 44; table 13) (Riggs et al. 2016), and illustrate that the eastern and western portions of the island were formed during different time periods and through different processes (Riggs et al. 2016). The oldest portion of Shackleford Banks is composed of a set of ridge and swale features.

On top of the higher elevation land, recurved ridge and swale deposits extend westward from Cape Shackleford on South Core Banks to mile marker 51.6 on Shackleford Banks. Core Creek and North Creek were channels flowing seaward through Shackleford Bay immediately east of where mile marker 52 is today. These ridges and associated shallow flats now constitute the shallow submarine ridges and flats of southeastern Back Sound on which modern marshes developed, including Middle Marsh, Carrot Island, and Radio Island (Riggs et al. 2016). The western portion of Shackleford Banks did not yet exist. Instead, Shackleford Bay was a broad and shallow, open marine embayment to the west of mile marker 52 (fig. 45) (Riggs et al. 2016).

About 1,100 cal yr BP (850 BCE), a large segment of the barrier collapsed due to storm activity, causing a rapid change (Culver et al. 2007). Sand was eroded from the islands and deposited as a shoal (fig. 41d), and the southern Pamlico basin salinity was the same as the ocean, as confirmed by microfossil data (Riggs et al. 2007).

1450 CE to 1700 CE

From approximately 1450 CE to 1700 CE, sea level was 0.8 to 0.5 m (2.6 to 1.7 ft) below MSL (Riggs et al. 2016). The southern Pamlico basin was an open bay rather than a restricted estuary until just prior to 1584 CE (Culver et al. 2007). Barrier islands were re-established in this area after 600 years, according to radiocarbon age estimates and early maps (1590 CE) (Riggs et al. 2016).

On Shackleford Banks, a second set of recurved ridge and swale deposits prograded westward from mile marker 51.6, filling the North Creek, Harker’s Creek, and Core Creek paleo-channels and forcing the channel migration to the west as the island spit grew. This growth created an extensive sequence of north-south ridge and swale features that filled the paleo-drainage channels, diverting estuarine discharge to the northwest and maintaining a deep estuary.

Rising sea level began flooding the older ridge and swale features that were deposited before 1450 CE. The swales became shallow estuarine environments, with submerged aquatic vegetation trapping fine sand and mud. The truncated ridges became inter-tidal, supporting oyster reefs and clam beds on the crests (Riggs et al. 2016). Harker's Creek and Core Creek were flooded, becoming drowned river estuaries now known as Back Sound and Core Sound. Core Creek is shallow because overwash built extensive shoals west of South Core Banks. Cape Lookout began to prograde southward from Cape Shackleford (fig. 46) (Riggs et al. 2016).

By the 17th and 18th centuries, most of the inlets had closed, re-establishing Pamlico Sound as an estuary (Riggs et al. 2008). Many of these dates were established by York and Wehmiller (1992), who sampled *Mercenaria* (quahog clam) shells along much of the Outer Banks including the northern Core Banks area and *Mulinia lateralis* (dwarf surf clam) in Cape Lookout.

These processes have left inlet fills and a transgressive barrier island sequence described in the "Geologic Framework and Barrier Evolution" section of the previous chapter.

1700 CE to Present

By 1700 CE, sea level was 0.55 to 0 m (-1.8 to 0 ft) below MSL, and the shallow flats and associated ridge features in Shackleford Bay had been permanently flooded by rising sea level (Riggs et al. 2016). This period was documented with maps, technical surveys, aerial photographs, and written records that capture

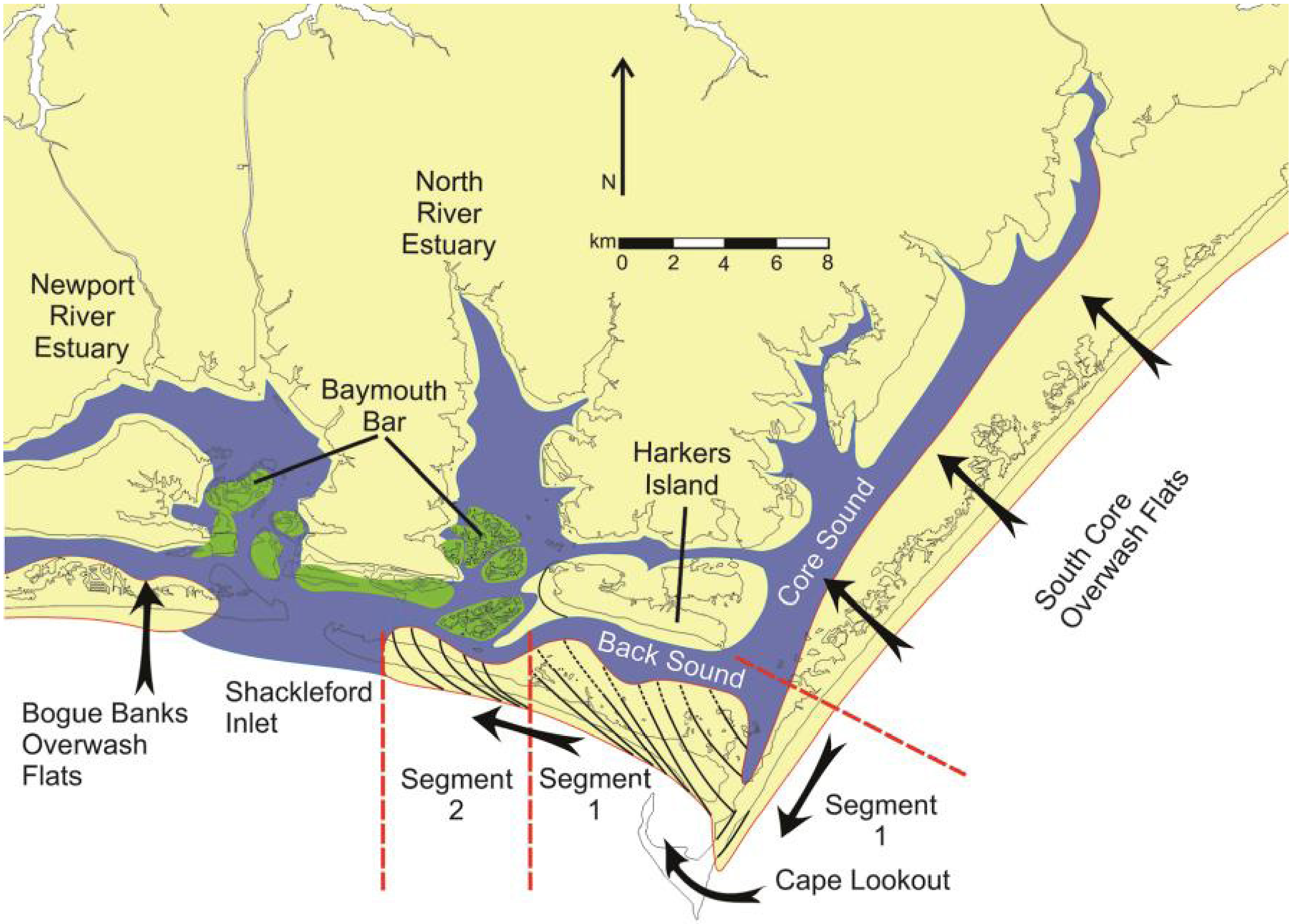


Figure 46. Reconstruction of the Shackleford Banks region about 1450 CE when sea level was about 0.8 m (2.6 ft) below mean sea level. Beach ridges developed, forming Segment 2. The island has grown westward into Shackleford Bay, creating Shackleford Inlet. Cape Lookout has begun to develop, and Core Creek has flooded, forming the shallow estuarine waters of Back and Core Sounds. BP indicates years before present. Figure 28 from Riggs et al. (2016).

the complex barrier island processes that modified the older geomorphic features.

The segment of Shackleford Banks that has developed since 1700 CE primarily resulted from five processes (fig. 47) (Riggs et al. 2016):

- Growth of the western-most island spit that oscillates within Beaufort Inlet.
- Formation of extensive maritime forest and a high interior dune field that then migrated, burying the southern portion of the maritime forest.
- Ocean shoreline recession of the oldest portion of Shackleford Banks supplied sand for overwash fans on older interior flats and deposition of major dune fields.
- Southward growth of Cape Lookout Point and deposition of the hook that forms Cape Lookout Bight.
- Opening of Barden Inlet and associated tidal deltas and ocean beach ridges.

By 1853, the western end of Shackleford Banks had prograded from mile marker 54.8 to form the modern Beaufort Inlet, and then subsequently eroded back to its former position by 1883, when rock jetties and a bulkhead were constructed to stabilize the end of the island. The spit continued its cycles of growth and erosion at least until aerial photographs documented the 1946 shoreline (Riggs et al. 2016).

The oldest island segment, which extends from mile marker 48.5 to mile marker 51.6, is dominated by ocean

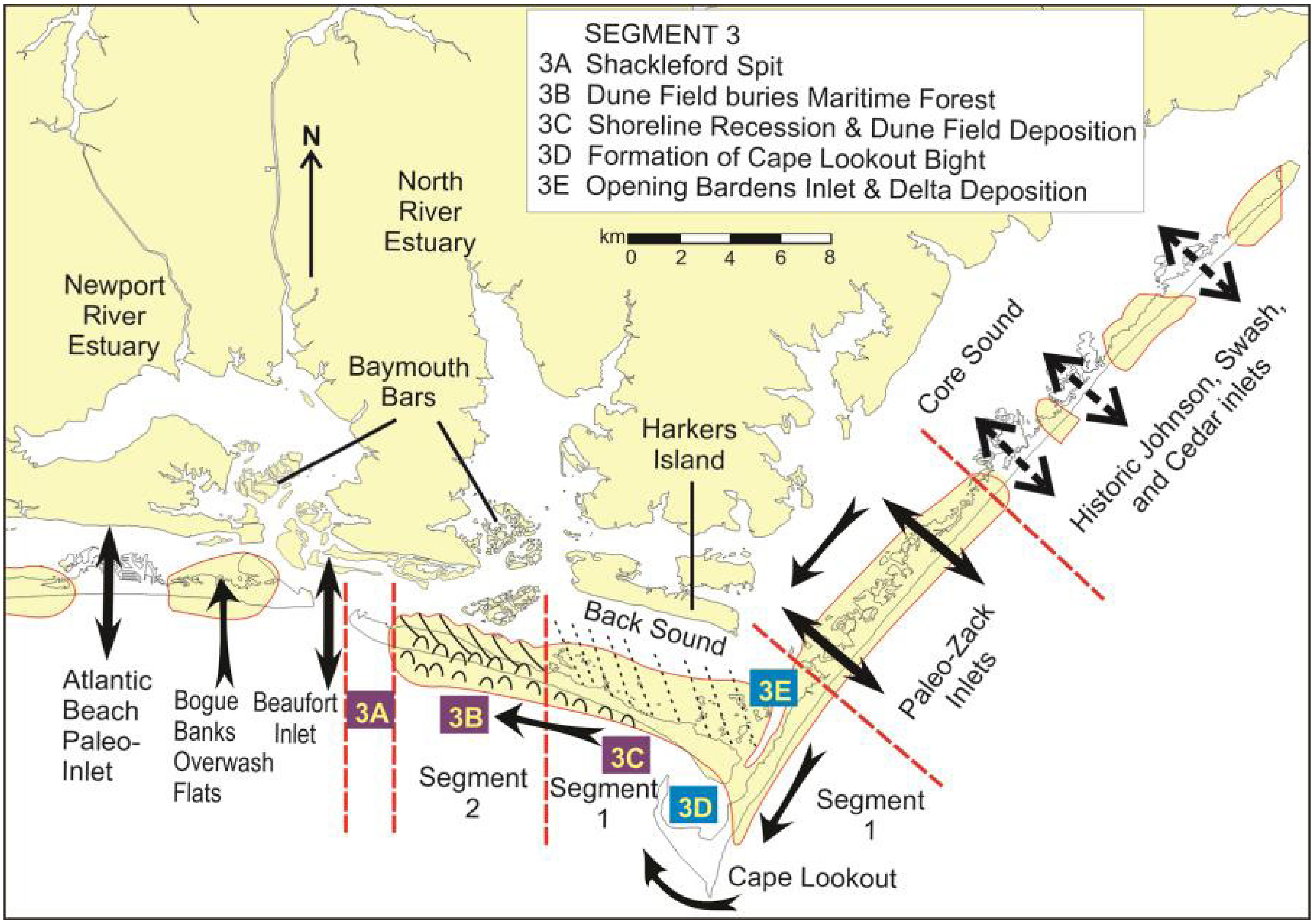


Figure 47. Reconstruction of the Shackleford Banks region from 250 cal yr BP (calibrated years before 1950) (1700 CE) when sea level was about 0.55 m (1.8 ft) below mean sea level to present. Segments 3A through 3E occurred within the post-European period. Back and Core sounds have been flooded and connect with Pamlico Sound to the north and the Atlantic Ocean through both Beaufort and Barden inlets. Core Banks has become a simple barrier island dominated by its own inlets. Figure 30-I from Riggs et al. (2016).

shoreline recession (300 m [984 ft] since 1853) as a result of wave refraction around Cape Lookout and the hook. This area also has slightly increased water levels during storms. The beach face is low and scarped, with an intermittent foredune and small overwash fans that have produced a narrow ramp sloping gently into the estuary and Back Sound. An 1883 navigation chart shows extensive maritime forest covering much of the island, but only small sand dunes adjacent to the ocean beach; the high interior dune field is absent from the map.

The 5 km (3 mi) portion of Shackleford Banks that extends from mile marker 51.6 to mile marker 54.8 has moderate ocean shoreline recession, steep beaches, and a high scarped foredune ridge. The area between mile marker 53 and mile marker 54.8 is dominated by ridge and swale features covered with maritime forest. This forest used to extend across the area between mile marker 51.6 to mile marker 53 also, according to an 1883 navigation map, but the forest in this area has since been buried by overwash. Now, the area features high interior dunes with interspersed interior flats that are sometimes sparsely vegetated and sometimes heavily vegetated with scrub-shrub and very wet (Riggs et al. 2015). The influx of sand may have occurred during three major hurricanes in 1954 (Riggs et al. 2015). A sharp depositional boundary occurs between the high interior dune field and the older truncated ridge and swale dominated maritime forest (Riggs et al. 2016).

Cape Lookout and Shackleford Banks were once connected by a narrow overwash zone sometimes referred to as the “haul over” or the “drain” (Riggs

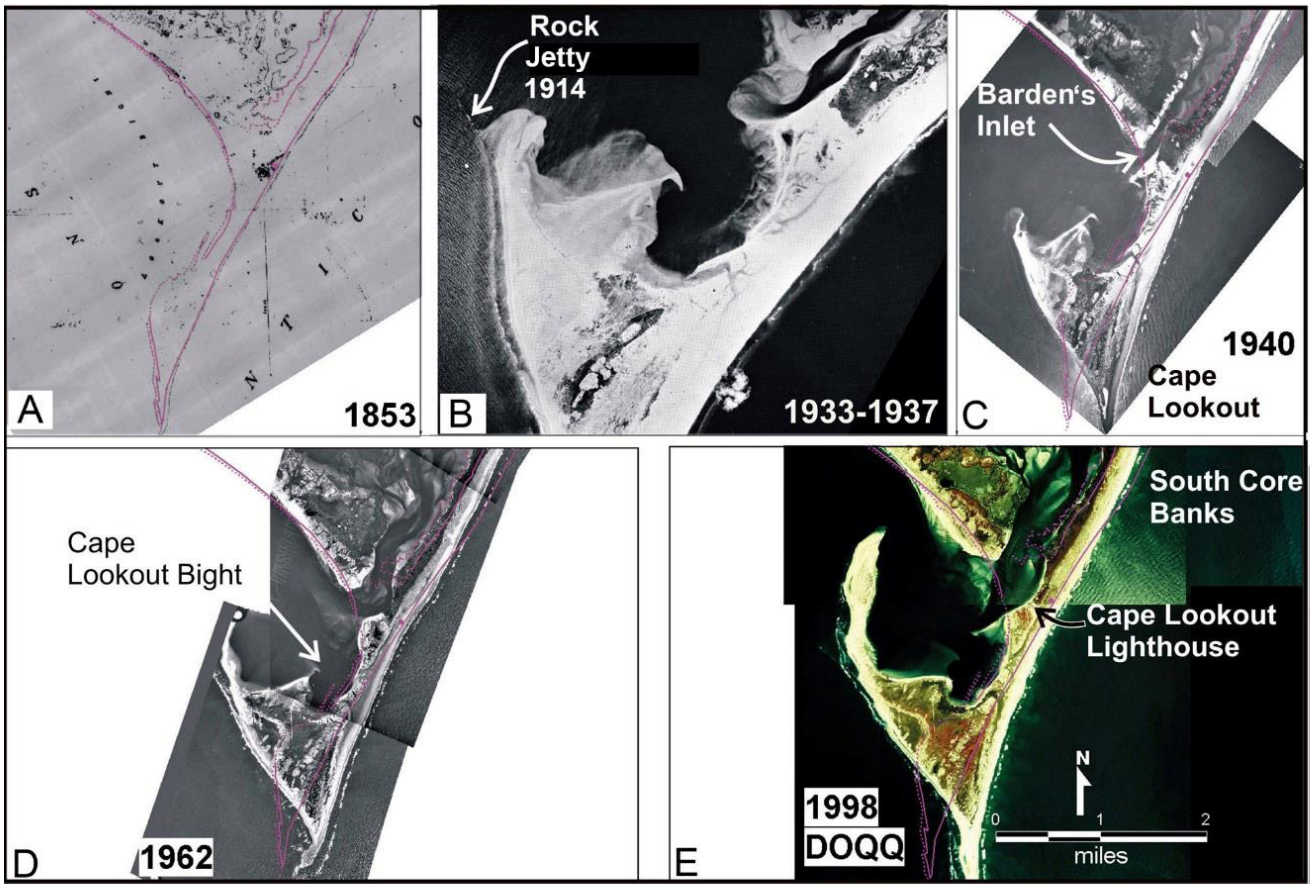


Figure 48. Time series showing the evolution of Cape Lookout, Cape Lookout Bight, and Barden Inlet from 1853 to 1998. Panel A is an 1853 topographic survey that shows Shackleford Banks connected to Cape Lookout with no inlet, hook, or bight. Panel B is an aerial photograph taken sometime after 1933 when Barden Inlet opened in response to a hurricane as a small ephemeral inlet that was locally called the "haul-over" and the "drain" and before 1937 when the inlet was dredged for the first time. Panel C is a 1940 aerial that shows Barden Inlet after it was dredged in 1937. Panels D and E from 1962 and 1998 show the northward progradation of the hook on Cape Lookout to semi-enclose the bight, formation of a substantial flood-tide delta inside the inlet, and the southward accretion of Shackleford Banks ocean beach within the protection of the hook. Figure 37 from Riggs et al. (2015).

et al. 2016). Between 1912 and 1914, coastal engineering efforts including sand fencing and rock jetty construction were implemented in an effort to protect Cape Lookout Bight as a harbor for ocean-going ships. The 1,463 m (4,800 ft) jetty caused sand accretion and spit elongation northwards towards Shackleford Banks, enlarging the bight (fig. 48). The hook prograded northward, semi-enclosing the bight and forming a substantial flood-tidal delta inside the inlet. The protection of the hook allowed Shackleford Banks to accrete southward. Barden Inlet opened during a 1933 hurricane, and was ephemeral until being dredged in 1937. It is maintained as a permanent inlet, separating Shackleford Banks from South Core Banks and Cape Lookout. Its ebb-tidal delta provides sand to the shore-parallel beach ridges on the southern end of Shackleford Banks (Riggs et al. 2015).

Future Geomorphology

Culver et al. (2007, 2008b) predicted that open shelf conditions will likely return to the Outer Banks region in the near future if the current trend of relative sea level rise continues. The resulting barrier island collapse would substantially change the way in which the coastal population and its economy proceed. If, on the other hand, sea level lowers, the swales will first contain fresh water lakes and marshes. With rising sea level the low swales will evolve into low to high brackish salt marshes depending upon whether they are open to tidal flooding or sealed off by a strandplain beach and prograding spit across the marsh swales by sand derived from the eroding sand ridges (Riggs et al. 2015).

Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI program. GRI GIS data produced for the park follows the source maps listed here and includes components described in this chapter. Posters (in pocket) display the map data draped over imagery of the park and vicinity. Complete GIS data are available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, these maps portray the spatial distribution and temporal relationships of rocks and unconsolidated deposits. Surficial geologic maps typically encompass deposits that are unconsolidated and formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Surficial geologic maps often depict geomorphic features and anthropogenic features such as inlet jetties. The American Geosciences Institute website, http://www.americangeosciences.org/environment/publications/mapping, provides more information about geologic maps and their uses.

Source Maps

The GRI team digitizes paper maps and converts digital data to conform to the GRI GIS data model. The GRI digital geologic map product includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references.

The maps for Cape Lookout National Seashore were developed by two different groups using distinct methodologies and resulting in unique sets of geomorphic units. None of the maps describe the geomorphology of Harkers Island. The maps developed by the North Carolina Geological Survey are by Coffey and Nickerson (2008a, 2008b, 2008c, 2008d). The maps developed by East Carolina University are by Ames and Riggs (2007a, 2007b, 2007c) using the methods and unit descriptions described in Ames and Riggs (2008) and Riggs et al. (2015). The map for the Portsmouth to Cricket Island area (Ames and Riggs 2007c) was not included in the GRI dataset due to inconsistent spatial offset issues in the source orthophotographs (1998 Color Infrared DOQQs geo-referenced by USGS).

The GRI team used the following sources to produce the digital geologic data sets and this report.

East Carolina University Maps

Ames, D.V., and Riggs, S. R. 2008. Geomorphic framework of the North Carolina Outer Banks, East Carolina University, Greenville, North Carolina, 112p.

Ames, D.V., and Riggs, S. R. 2007a. Geomorphic framework of the North Carolina Outer Banks (Drum Inlets Site digital data), East Carolina University, Greenville, North Carolina, scale 1:10,000.

Ames, D.V., and Riggs, S. R. 2007b. Geomorphic framework of the North Carolina Outer Banks (Hogpen Bay to Cape Lookout Site digital data), East Carolina University, Greenville, North Carolina, scale 1:10,000.

Ames, D.V., and Riggs, S. R. 2007c. Geomorphic framework of the North Carolina Outer Banks (Portsmouth to Cricket Island Site digital data), East Carolina University, Greenville, North Carolina, scale 1:10,000.

Riggs, S. R., and D. V. Ames. 2006. Barrier island evolution: a model for development of the geomorphic framework, North Carolina Outer Banks. East Carolina University, Greenville, North Carolina.

Riggs, S. R., D. V. Ames, and D. J. Mallinson. 2015. Environmental and geological evolution of Shackleford Banks, Cape Lookout National Seashore North Carolina. A report to NPS. Department of Geological Sciences, East Carolina University, Greenville, North Carolina.

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North Carolina Geological Survey Maps

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Coffey, B. P. and J. G. Nickerson. 2008b. Geomorphology of Portsmouth Island, Cape Lookout National Seashore, NCGS digital publication, plates 1, 2 and 3, scale 1:24,000.

Coffey, B. P. and J. G. Nickerson. 2008c. Geomorphology of the Shackleford Banks Area, Cape Lookout National Seashore, NCGS digital publication, plate 6, scale 1:24,000.

Coffey, B. P. and J. G. Nickerson. 2008d. Geomorphology of the South Core Banks Area, Cape Lookout National Seashore, NCGS digital publication, plates 4, 5 and 6, scale 1:24,000.

Units for each of the data sets are described in the "Barrier Island System Unit Mapping" and "Barrier Island System Units" sections at the end of this chapter. See also tables 15 and 16.

GRI GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is available at http://go.nps.gov/gridatamodel. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Cape Lookout National Seashore using data model version 2.0 (North Carolina Geological Survey ["CALO" data] and East Carolina University ["CALG" data] maps) and 2.2 (ECU Shackleford Banks ["SHKB" data] map). The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about GRI map products.

GRI GIS data are available on the GRI publications website http://go.nps.gov/gripubs and through the NPS Integrated Resource Management Applications (IRMA) portal https://irma.nps.gov/App/Portal/Home. Enter "GRI" as the search text and select a park from the unit list. The following components are part of the data set:

- A GIS readme file (calo_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information;
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology (table 14);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information documents (calo_geology.hlp and shkb_geology.pdf) that contain information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross sections, and figures;
- ESRI map documents that displays the digital geologic data (calo_geology.mxd [NCGS data], calg_geology.mxd [ECU data], and shkb_geology.mxd [ECU Shackleford Banks map]); and
- Google Earth compatible files for the Shackleford Banks ECU map (shkb_geology.kmz).

Table 14. Geology data layers in the Cape Lookout National Seashore GIS data.

Data Layer	On Poster?	Google Earth Layer?
Geologic Attitude and Observation Points	No	None
Geomorphic Ridge Lines	Yes, calo	None
Ridge Axes	Yes, shkb	Yes, shkb only
Geomorphic Contacts (Detailed)	Yes, calo	None
Geomorphic Units (Detailed)	Yes, calo	None
Geomorphic Contacts	Yes, calo, calg, shkb	Yes, shkb only
Geomorphic Units	Yes, calo, calg, shkb	Yes, shkb only

"calo" = NCGS map, "calg" = ECU map, "shkb" = Shackleford Banks ECU map.

GRI Map Posters

Posters of the GRI digital geologic data draped over imagery of the park and surrounding area are included with this report. Not all GIS feature classes may be included on the posters (table 14). Geographic information and selected park features have been added to the posters. Digital elevation data and added geographic information are not included in the GRI GIS data set, but are available online from a variety of sources. Contact GRI for assistance locating these data.

Use Constraints

Graphic and written information provided in this report is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Please contact the GRI team with any questions.

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the poster. Based on the source map scale (1:10,000 and 1:24,000) and US National Map Accuracy Standards, geologic features represented in the geologic map data are expected to be horizontally within 5.0 m (16 ft) or 12 m (40 ft) (for 1:10,000 and 1:24,000 scale data, respectively) of their true locations.

Barrier Island System Unit Mapping

This report is supported by three digital maps of Cape Lookout National Seashore surficial geology. The maps were developed by two different groups using distinct methodologies and resulting in unique sets of geomorphic units. None of the maps describe the geomorphology of Harkers Island, on which the park manages a small portion of land for the headquarters building.

- The North Carolina Geological Survey (Coffey and Nickerson 2008a, 2008b, 2008c, 2008d) used lidar data, orthophotographs, color infrared photographs, wetland delineation maps, and historical shoreline data to map the surficial geology of the park.
- East Carolina University (Ames and Riggs 2008) performed field surveys of representative sites, analyzed a time series of historical aerial photographs and topographic surveys and 2001 lidar, and developed and ground-truthed a geomorphic map based on 1988 digital orthophoto quarter quads (DOQQs).
- East Carolina University (Riggs et al. 2015, 2016) used new archeological data to reinterpret the geomorphological history of Shackleford Banks, and created new surficial geology maps.

Barrier Island System Units (North Carolina Geological Survey Remote Sensing Map)

The North Carolina Geological Survey mapped surficial geologic environments for the subaerial portion of the park and created geomorphic maps, GIS data, and unit descriptions (Coffey and Nickerson 2008a, 2008b, 2008c, 2008d).

Landforms were identified using remote sensing products. LiDAR elevation data from 2001 (available from the state at http://www.ncfloodmaps.com/default_swf.asp) in combination with 1-m resolution color infrared othophotographs were analyzed, and landforms were then digitized in ArcGIS 9.1 and 9.2. Use of color infrared (CIR) images enables better analysis of vegetation patterns that locally follow geomorphic trends.

The map incorporates an ocean shoreline that is the interpreted wet/dry ocean shoreline based on 1998 orthophotographs (NCDCM 2003). Most of the back barrier shoreline was digitized by NCGS using 1998 color infrared orthophotographs and 2006 National Agricultural Image Program aerial photography; both sets of photograph have a spatial resolution of 1 m (3 ft) and the back barrier shorelines between the two sets appeared to be in very close agreement (Coffey and Nickerson 2008a).

Preliminary mapping was completed prior to the 2011 landfall of Hurricane Isabel, which altered the beach considerably in some areas; those changes are not reflected in the map because post-Isabel LiDAR data were not available to NCGS prior to map publication. LiDAR data used for this map had a 20-foot grid cell size and a vertical accuracy of 0.2 m.

Further descriptions of source data, mapping methodology, and unit delineation are available in Coffey and Nickerson (2008a).

Landforms (table 15) were grouped into four categories—intertidal, supratidal, relict, and anthropogenic—based upon their location and elevation on the barrier island landscape. Interpretations and classifications of features were refined through collaborations with Dr. Stan Riggs

Table 15. Summary of barrier island system units at Cape Lookout National Seashore, as mapped by North Carolina Geological Survey ("CALO" map data).

Group	***Subgroup*** **or Map Unit (symbol)**
Intertidal	Beach (beach)
Intertidal	***Spit Complex***: Sand Flat (sand_flat)
Intertidal	***Spit Complex***: Ridge and Swale (ridge_swale)
Intertidal	Marsh Platform (pf_marsh)
Intertidal	Fringing Berm (pf_mrsh_fbrm)
Intertidal	***Tidal Complex***: Tidal Flat (tidal_tflat)
Intertidal	***Tidal Complex***: Sand Flat (tidal_sflat)
Inlet	Inlet (inlet)
Supratidal	***Fore-Island Dune Complex***: Dune Ridges (dunerdge)
Supratidal	***Fore-Island Dune Complex***: Intradune Swales (intswale)
Supratidal	***Fore-Island Dune Complex***: Dune Saddle (dnesadl)
Supratidal	***Overwash Complex***: Overwash Flat (owflat)
Supratidal	***Overwash Complex***: Overwash Channel (owchannel)
Supratidal	***Overwash Complex***: Overwash Fan (owfan)
Supratidal	***Overwash Complex***: Isolated Dune (isodune)
Supratidal	Interior Dune (intdune)
Supratidal	Interior Marsh (intmarsh)
Supratidal	Back-Barrier Berm (bk_br_brm)
Relict	Relict Beach Ridge Complex (rel_bch_rdge)
Relict	Relict Spit Complex (rel_splt)
Relict	Water Body (water)
Anthropogenic	Airport/Landing Strip (airport_land)

of East Carolina University, who was conducting companion field-based mapping studies.

Intertidal Map Units

Beach (beach)

The mapped beach extends between the wet/dry ocean shoreline, as defined by NCDCM (2003), and the toe of the fore-island dune complex, which was delineated by lidar-derived slope and aerial imagery. Sub-environments within the beach zone were not delineated. The beach sometimes merges laterally with sand flats of the Spit Complex unit when the beach experiences periodic flooding.

Spit Complex

This unit occurs adjacent to the three active inlets in the map area and comprises two subunits: the sand flat component and ridge and swale component.

Sand Flat (sand_flat): This unvegetated, low elevation (less than 4 feet), low relief feature is subject to regular tidal flooding and overwash. Sand flats may contain areas of episodically ponded water, small isolated dunes, and seasonally may become encrusted with cyanobacterial algae. Sand flats merge with the beach unit along the shoreline away from the inlet, where the fore-island dune complex begins to form.

Ridge and Swale (ridge_swale): When present, it runs along the sand flat and merges inland with the fore-island dune and overwash complexes. Ridges and swales typically trend subparallel to the axis of the barrier and then curve toward the back of the island (convex) as they approach the inlet. Ridges can be incipient features, well-formed continuous structures, or heavily dissected remnants. Ridge axes are delineated with lines in the project GIS database, but these display only at scales of 1:12,000 and larger. Ridge and swale areas are interpreted to represent older, more stabilized portions of spit complexes.

Marsh Platform (pf_marsh)

These areas are extensive on the backside of the island and along tidal creeks. These areas are low-lying (typically less than 2 feet) and may be subject to regular tidal flooding. Marsh platforms are relatively stable features and are quite extensive in parts of the barrier system. Juncus roemerianus (black needlerush) and Spartina patens are the dominant grass species that inhabit the platform. As the marsh elevation has increased in response to rising sea level, a peat layer up to several feet thick has developed. Where sediment supply is insufficient for marsh aggradation into the sound, wave energy is prone to undercut the peat and cause local shoreline recession. Overwash from the oceanside of the island supplies sand to the marsh platform interior margin, raises the elevation above tidal influence, and builds onto the marsh platform area.

Fringing Berm (pf_marsh_fbrm)

This unit is shore-parallel and occurs on the extreme back-barrier side of the marsh platform. It is usually about 0.3 to 0.6 m (1 to 2 ft) higher than surrounding marsh and likely results from storm deposition of sediment and vegetation wrack. It is clearly visible in the lidar data for Portsmouth Island.

Tidal Complex

The Tidal Complex comprises two subunits that are dominated by local tidal influence: Tidal Flat and Sand Flat.

Tidal Flat (tidal_tflat): These low elevation (less than 0.3 m [1 ft]) areas are drained by water bodies and or tidal creeks, and are subject to regular tidal flooding. They are generally adjacent to the Marsh Platform.

Sand Flat (tidal_sflat): These are emergent bodies of extensive sound-side shoals. They are adjacent to the Marsh Platform. They are not directly attached to inlet spit complexes, which distinguishes them from Spit Complex Sand Flats.

Inlet (inlet)

This unit only occurs on Portsmouth Island, in the vicinity of Old Drum Inlet. The area delineated represents a new inlet opened by Hurricane Dennis in 1999 at the site of Old Drum Inlet. This inlet is sometimes called New-Old Drum Inlet.

Supratidal Map Units

Fore-Island Dune Complex

These shore-parallel units occur between, and are higher elevation than, the beach and island interior units. The complex comprises three subunits: Dune Ridge, Intradune Swale, and Dune Saddle.

Dune Ridge (dunerdge): These linear, shore-parallel ridges are the most prominent and areally extensive portions of the Fore-Island Dune Complex. In some areas there are two distinct ridges separated by intradune swales. Dune heights vary, but generally are less than 6 m (20 ft). Dune toe elevations on each side of the dune are typically 1 to 2.5 m (4 to 8 ft) above MSL.

Intradune Swales (intswale): These closed areas tend to occur between dune ridges as linear troughs less than 3 m (10 ft) in elevation.

Dune Saddle (dnesadl): These gaps along dune ridge lines have elevations of less than 3 m (10 ft).

Overwash Complex

The overwash complex occurs behind the fore-island dune complex and in front of the marsh platform. This area is elevated relative to the marsh platform, tends to have low to moderate relief, typically ranges from 0.6 to 2.5 m (2 to 8 ft) in elevation, and extends to the sound as a downward slope. This depositional feature receives sand that is blown or washed over and through the fore-island dune complex, usually during storm events. Subunits mapped within the overwash complex are Overwash Flat, Overwash Fan, Overwash Channel, and Isolated Dunes.

Overwash Flat (owflat): This is the dominant subunit. It represents the long-term accumulation of sand overwash behind the fore-island dune complex. Discrete events deposit sand lobes that are then reworked by wind, water, and people into a single geomorphic unit.

Overwash Fan (owfan): These are located just inland of the dune. Each fan is created when water carries sand through an overwash channel and deposits it in a fan shape.

Overwash Channel (owchannel): Overwash channels cut through the fore-island dune and lead to an overwash fan.

Isolated Dunes (isodune): These occur within or soundward of the overwash flat area. Some may be remnants of former fore-island dune ridges or large overwash fans, or may form when sand is trapped by vegetation or anthropogenic features such as sand fencing

Interior Dune (intdune)

Interior Dunes occur in several areas soundward of the fore-island dune complex and are larger features than the Isolated Dunes of the Overwash Complex. Interior dunes are significant geomorphic features of sizable areal extent and sometimes represent the highest elevation points (3 to 9 m [10 to 30 ft]) on the island. They may be isolated single ridges or more laterally extensive elevated features as seen on Shackleford Banks. Most are vegetated and thus appear to be relatively stable features. Their origins appear to be separate from fore-island dune building processes. The sand sources for these features are not readily apparent from the data layers used in this mapping.

Interior Marsh (intmarsh)
Interior marshes lack a connection to the waters of the ocean or sound, but often are located adjacent to water bodies. They most commonly develop in the swales of extensive relict beach ridge complexes, such as those in the Buxton area, or in interior lows behind the Fore-Island Dune Complex.

Back Barrier Berm (bk_br_brm)
These landforms occur in the back portions of the barrier island system through much of the mapped area. They vary from very subtle linear features with only slightly higher elevation than the surrounding marsh platform to significant features (over 3 m [10 ft] in elevation) with complex internal geometry. Many berms form a broad arc in areas of apparent relict flood tidal deltas. This suggests that wave reworking of delta sand bodies may have facilitated berm development in some cases.

Relict Map Units

Relict Beach Ridge Complex (rel_bch_rdge)
Relict beach ridge complexes occur as sets of parallel ridges and swales within the island interior. Later dune sets truncate parallel dune sets and are oriented at a slightly different angle, allowing delineation of individual sets of relict beach ridges, and also providing relative age relationships. Elevations are commonly less than 3 m (10 ft).

Relict Spit Complex (rel_spit)
These subtle arcuate-shaped ridge and swale features are located in mid- to back-island areas. They exhibit topography and geomorphic attributes that are similar to modern spit complexes, but they often lack a connection to an active inlet. These areas are interpreted as older, inactive spit complexes that developed adjacent to former inlets. Relict spit complexes are evident in the vicinity of the now-closed Whalebone Inlet on Portsmouth Island.

Water Body (water)
Water bodies that appeared to be ephemeral features, such as on sand flats or in intradune swales, were not included in this map unit.

Anthropogenic Map Units

Airport/Landing Strip (airport_land)
Only two anthropogenic features, both Airport Landing Strips, were mapped in the park: one on northern South Core Banks, and the other the Portsmouth Village area. Although the fore-island dune complex has been significantly modified since the 1930s, it was not classified as anthropogenic because it has become part of the naturalized landscape. The Morris Fish Camp buildings in the Long Point Cabins area on Portsmouth Island were not mapped.

Barrier Island System Units (East Carolina University Field Survey Map)

The map developed for this Geologic Resources Inventory by Ames and Riggs (2008) classifies geomorphic units based on a model of barrier island evolution developed from process-response studies and modern field surveys of the North Carolina Outer Banks (Riggs and Ames 2006). Additional analyses of historical aerial photography dating back to 1932 and topographic surveys dating back to the 1850s assisted the identification of geomorphic features that evolved over the last century (Ames and Riggs 2008).

The ECU geospatial maps and files do not include the area between Portsmouth Island and Cricket Island due to inconsistent offset errors of up to 220 m in the USGS source imagery in the six 1998 CIR DOQQs for that area (Stephanie O'Meara, Colorado State University, GIS Specialist, email, 6 May 2015). That map area can only be used in hardcopy format. The aerial photographs may be useful for understanding which units and features are in what general area, but the spatial errors minimize their utility for measuring distances or area (Jason Kenworthy, NPS, geologist, written communication, 22 December 2015).

The map identifies subgroups and units of the following regional geomorphic features (table 16): beach, overwash-plain, polydemic, and anthropogenic features. The unit descriptions are taken primarily from Ames and Riggs (2008), and supplemented by information from publications where cited. The dominant vegetation is included with the detailed geomorphic units because vegetation is a critical component of barrier island dynamics, but the level of detail is insufficient to utilize these maps as detailed vegetation maps. If the geomorphic unit is polydemic (i.e., occurs in many different parts of the barrier island) or if the vegetation has been severely modified, the vegetation type of the geomorphic unit is undifferentiated (Ames and Riggs 2008).

Table 16. Summary of barrier island system units on Core Banks, as mapped by East Carolina University (Ames and Riggs 2008; "CALG" map data)

Features Group	*Subgroup* or Map Unit (symbol)
Beach	Ocean Beach (BF_ocbeach)
Beach	Inlet Flat (BF_inlet_flt)
Beach	Inlet Spit (BF_inlet_spt)
Overwash-Plain	***Upper Overwash Ramp***: Sparse to unvegetated (UO_unveg)
Overwash-Plain	***Upper Overwash Ramp***: Grass (UO_grass)
Overwash-Plain	***Upper Overwash Ramp***: Scrub Shrub (UO_scrb_shrb)
Overwash-Plain	***Upper Overwash Ramp***: Foredune (UO_fdune)
Overwash-Plain	***Middle Overwash Ramp***: Sparse to Unvegetated (MO_unveg)
Overwash-Plain	***Middle Overwash Ramp***: Grass (MO_grass)
Overwash-Plain	***Middle Overwash Ramp***: Scrub Shrub (MO_scrb_shrb)
Overwash-Plain	***Middle Overwash Ramp***: Forest (MO_forest)
Overwash-Plain	***Middle Overwash Ramp***: Interior Marsh (MO_intmarsh)
Overwash-Plain	***Middle Overwash Ramp***: Isolated Dunes (MO_isodune)
Overwash-Plain	***Middle Overwash Ramp***: Dune/Beach Ridge (MO_dunerdge)
Overwash-Plain	***Lower Overwash Ramp***: Platform Marsh (LO_pf_marsh)
Overwash-Plain	***Lower Overwash Ramp***: Fringing Berm (LO_fring_brm)
Overwash-Plain	***Lower Overwash Ramp***: Strandplain Beach (LO_spln_bch)
Overwash-Plain	***Lower Overwash Ramp***: Back-Barrier Berm (LO_bk_br_bm)
Polydemic	Tidal Channels (PF_tidal_chn)
Polydemic	Pond (PF_pond)
Polydemic	Transverse Ridges (PF_trnv_rdge)
Polydemic	Dune Flat (PF_dune_flat)
Polydemic	Dune Field (PF_dunef)
Polydemic	Algal Flat (PF_algal_flt)
Polydemic	Ridge and Swale (PF_rdg_swl)
Polydemic	Overwash Channel (PF_owchannel)
Polydemic	Paleo-Inlet Spit (PF_p_inl_spt)
Anthropic	Rock Jetty (AF_jetty)
Anthropic	Airport/Landing Strip (airport_land)
Anthropic	Dredged Channels/Spoils (AF_drdge)
Sound	Upper Shoals (SF_up_shoal)
Sound	Lower Shoals (SF_low_shoal)
Sound	Flood-Tide Delta Shoals (SF_fld_tide)
Sound	Tidal Delta (SF_tidal_del)

The mapped Anthropic Features unit includes rock jetty, airport landing strip, and dredged channels/spoils, but does not include dirt roads, power-lines or buildings (Ames and Riggs 2008).

Beach Features

Ocean Beach Unit (BF_ocbeach)

The ocean beach (fig. 49) extends from the wet-dry ocean shoreline to the bases of natural dune fields or scarped dunes or dune fields. Where no dune is present, the beach extends to the island berm crest, which is the crest of an overwash island, represents the highest point on the overwash plain, and separates surface water flow between the ocean and back-barrier estuary.

Macroscopic vegetation is sparse in this unit. However, wrack commonly occurs along the upper swash lines associated with the storm beaches. The wrack may consist of offshore algae (*Sargassum* spp.), dune grasses, estuarine submerged aquatic vegetation, or estuarine marsh grasses.

Beaches and adjacent marine waters are used for mating and nesting by sea turtles, mainly *Caretta caretta* (loggerhead sea turtle) and *Chelonia mydas* (green sea turtle), but also by *Lepidochelys kempii* (Kemp's Ridley sea turtle) and *Dermochelys coriacea* (leatherback sea turtle) (Mallin et al. 2006).

Inlet Flat Unit (BF_inlet_flt)

Inlet flats (fig. 49) occur adjacent to modern inlets or paleo-inlets. An inlet flat is a gently ramped surface that slopes gradually from the ocean-beach berm toward the inlet and estuary and forms during regular

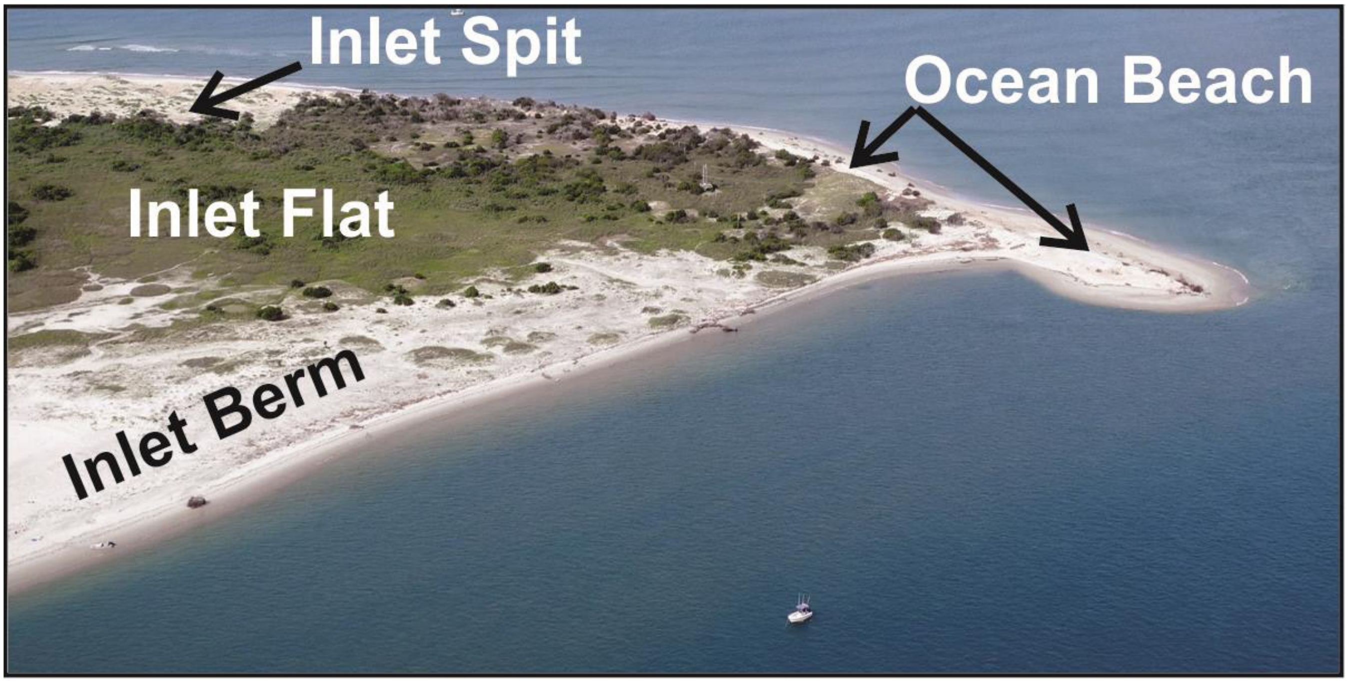

Figure 49. The west end of Shackleford Banks includes the Inlet Spit, Inlet Flat, Inlet Berm, and Ocean Beach units. Photograph is looking southeast with Back Sound at the bottom, Beaufort Inlet to the right, and the Atlantic Ocean at the top of the oblique aerial photograph. Figure A5 from Riggs et al. (2015).

overwash events. Waves and tidal currents interact during high-water overflow conditions associated with spring tides and small storm tides. Active inlet flats are unvegetated. The vegetation on older inlet flats often consists of mixed grasses that include *Spartina patens*. Fine-grained areas in the lower portions of inlet flats are frequently dominated by microbial mats.

Inlet Spit Unit (BF_inlet_spt)

An inlet spit (fig. 49) consists of one or more subparallel and curved ridges that occur adjacent to a modern inlet or a paleo-inlet. The ridges form on a gentle ramped flat that results from regular overwash events and forms by the combined interaction of waves and tidal currents during high-water overflow conditions associated with high tides, spring tides, or small storm tides. Higher ridges that formed in response to previous storm events can be subsequently truncated, breached, or even enlarged by the accretion of secondary ridges. An older inlet spit often contains small active dune fields that form subsequent to spit formation. Paleo-inlet spits can occur anywhere from the eroding beach to the middle- or lower-overwash ramp, and are classified as polydemic features.

New and active inlet spits are unvegetated or grassed with *Spartina patens*. The vegetation on older inlet spits is a function of its location on the barrier island, as well as elevation relative to mean sea level, and often consists of mixed grasses that also include *Spartina patens* along with a small growth of scrub shrub.

Overwash-Plain Features

Upper Overwash Ramp Unit

The upper overwash ramp begins at the island's berm crest, which is the highest point on an overwash-dominated barrier island. The upper overwash ramp extends gently downslope to the middle overwash ramp, more steeply to the lower overwash ramp, or, occasionally, directly into the adjacent estuary with an eroding sediment-bank shoreline. The upper overwash ramp is a slightly undulating, high and dry surface that frequently contains small isolated dunes, and is often characterized by a shell gravel pavement resulting from overwash events. A natural dune field or anthropic constructed dune ridge generally occurs on the upper overwash ramp along the island berm crest. In the latter situation, the ocean side of the upper overwash ramp begins at the depositional or scarped boundary at the top of the ocean beach. As the major source of dune sands is directly off the beach, most natural dune fields

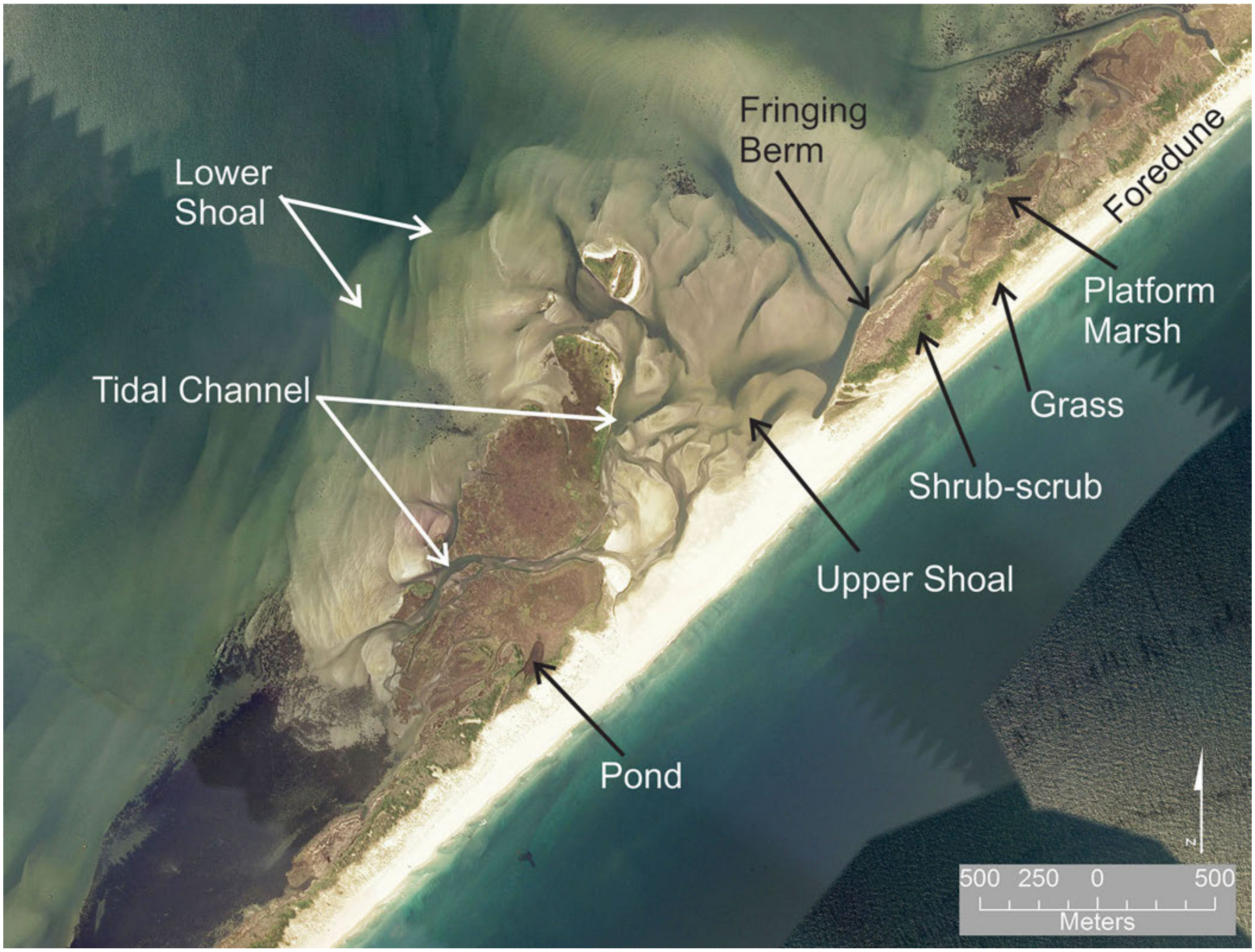

Figure 50. The 2010 aerial photograph shows the former Old Drum Inlet flood-tide delta in the central portion of Core Banks. Core Sound is in the upper left and the Atlantic Ocean is in the lower right. The units are defined by Ames and Riggs (2008). Graphic by Dorothea Ames (ECU) using NAIP 2010 GE imagery available at NAIP 2010 GE on ge-nt.ncmhtd.com.

are superimposed on the uppermost portion of the upper overwash ramp.

Upper Overwash Ramp: Sparse to Unvegetated (UO_unveg)

The upper overwash ramp is predominantly subaerial and may be overwashed during storms by ocean waves that transport sand across the beach and berm onto it, occasionally reaching the sound. This process builds island elevation and erodes the beach and foredunes. Recent overwash deposits have no macrovegetation.

Upper Overwash Ramp: Grass (UO_grass)

This unit (fig. 50) is part of the overwash-plain features group and the upper overwash ramp subgroup. As the upper overwash ramp decreases in elevation away from the ocean beach, fresh groundwater dominates and rises, allowing an increased vegetative cover that grades successively from the xeric community to the grass flat and scrub shrub communities on the upper overwash ramp.

The grass community is dominated by the following species: *Uniola paniculata* (sea oat), *Spartina patens* (salt meadow hay), *Andropogon scoparius* (broomstraw rush), *Hydrocotyle bonariensis* (pennywort), and *Cakile edentula* (sea rocket). Where the uppermost portion of the upper overwash ramp is dominated by salty groundwater or a relatively deep freshwater table, the surface is characterized by a xeric vegetation community. These communities have low species diversity and are dominated by sparse growth of the following species: *Gaillardia pulchella* (firewheel), *Opuntia spp*. (prickly pear cactus), scattered *Juniper virginiana* (eastern red cedar), and irregular and splotchy growth of lichens and moss on the sand surface.

Upper Overwash Ramp: Scrub Shrub (UO_scrb_shrb)
As the upper overwash ramp decreases in elevation away from the ocean beach, fresh groundwater dominates and rises relative to the land surface, resulting in an increased vegetative cover that grades successively from the xeric community to the grass flat and scrub shrub communities on the upper overwash ramp. Where the upper overwash ramp is very wide with a significant natural dune field or constructed dune ridge, an extensive scrub shrub community (fig. 50) expands in the oceanward direction.

This community is dominated by the following species, along with abundant grasses and vines: *Baccharis halimifolia* (salt myrtle), *Myrica cerifera* (wax myrtle), *Ilex vomitoria* (yaupon holly), *Iva frutescens* (marsh elder), *Myrica pensylvanica* (bayberry), *Juniper virginiana* (eastern red cedar), *Spartina patens* (salt meadow hay), *Smilax* spp. (cat brier), *Toxicodendron radicans* (poison ivy), and *Parthenocissus quinquefolia* (Virginia creeper).

Upper Overwash Ramp: Foredune (UO_fdune)
Natural foredunes (fig. 50) often form along the uppermost portion of the overwash plain. Foredune size depends largely on sand availability. The dunes have an irregular geometry and are variable in size and number. As the wind blows in many different directions throughout the seasons, any single dune is built and modified continuously through time with abundant blowouts, cut and fill structures, and scarping along the ocean side or along overwash channels through the dune field. Foredunes occasionally develop concentric rings of alternating vegetated and unvegetated areas.

Foredunes are mostly vegetated with *Uniola paniculata* (sea oats). However, on the back side of a large dune field or as the distance from the ocean increases, salt spray is diminished, with a corresponding increase in vegetation diversity. Plants that commonly occur on the lee side of the dune field include the following: *Spartina patens* (salt meadow hay), *Cakile edentula* (sea rocket), *Solidago sempervirens* (goldenrod), and *Myrica cerifera* (wax myrtle). Occasionally *Juniper virginiana* (eastern red cedar) and groundcover plants such as *Hydrocotyle bonariensis* (pennywort)

Overwash channels may occur between foredunes on the upper overwash plain. These shore-perpendicular features are formed by oceanside overwash events that scour interdunal channels and may become isolated, ephemeral ponds due to overwash deposition during the waning stages of a storm event.

Middle Overwash Ramp Unit
The middle overwash ramp is a relatively flat and dry to slightly wet surface that slopes gently away from the upper overwash ramp. The boundary between the upper and middle overwash ramps is characterized by a dramatic step down when the island segment is heavily vegetated. The dense scrub shrub or forest vegetation disrupts the storm-surge flow, causing rapid deposition of sediments during overwash events. The step down is generally composed of sand with interbeds of beach shell gravel.

The middle overwash ramp may be very extensive on a wide island, particularly in the presence of a well-developed molar-tooth structure with major tidal channels on the lower overwash ramp. In contrast, the middle overwash ramp may be absent on a narrow island. In this situation, the upper overwash ramp is steep and drops directly onto the lower overwash ramp or even into the back-barrier estuary, with an eroding sediment-bank shoreline supplying sand for development of an estuarine strandplain beach.

Vegetation on the middle overwash ramp displays downslope zonation as a direct function of water table depth, frequency and magnitude of overwash events, and time since the last overwash event. Storm events that deposit new overwash sediment may also rip up and/or bury existing vegetation. The resulting increase in middle overwash ramp elevation resets the clock with respect to the location and succession of dominant vegetation that emerges in the years following the overwash event.

Middle Overwash Ramp: Sparse to Unvegetated (MO_unveg)
Immediately after a major storm event that delivers a new overwash fan across the middle overwash ramp, the sediment surface is essentially an unvegetated flat. In subsequent years, grasses begin to develop and the

new overwash plain slowly evolves into one of the following dominant vegetation groups, depending upon subsequent storm and flooding patterns; elevation, width, and dissection of the middle overwash ramp with tidal channels; and composition and location of the groundwater table.

Middle Overwash Ramp: Grass (MO_grass)

When the upper portion of the middle overwash ramp frequently receives minor amounts of salt spray, aeolian sand, and overwash sediment, the flats will be dominated by *Spartina patens* (salt meadow hay) and *Andropogon scoparius* (broom straw).

Middle Overwash Ramp: Scrub Shrub (MO_grass)

When the upper portion of the middle overwash ramp has not been impacted recently by major storm events and overwash sediment fans, the flats are dominated by scrub shrub. Established scrub shrub disrupts flow during small overwash events, resulting in deposition of the overwash sediment as a series of “stair” steps within the scrub shrub flat. Large overwash events can kill or partially or entirely uproot the scrub shrub, resetting the process of vegetation succession.

The scrub shrub flat is dominated by the following species: *Baccharis halimifolia* (salt myrtle), *Myrica cerifera* (wax myrtle), *Ilex vomitoria* (yaupon holly), *Iva frutescens* (marsh elder), *Myrica pensylvanica* (bayberry), *Juniper virginiana* (eastern red cedar), *Spartina patens* (salt meadow hay), *Smilax* spp. (cat brier), *Toxicodendron radicans* (poison ivy), and *Parthenocissus quinquefolia* (Virginia creeper).

Middle Overwash Ramp: Forest (MO_forest)

In the absence of major storm events and overwash sediment fans, the scrub shrub flats can locally evolve into a forest-dominated middle overwash ramp characterized by larger growth with a well-developed overstory. Establishment of a forest within the middle overwash ramp indicates that overwash events are rare, due to a low frequency of major storm activity, low rates of ocean shoreline recession, and/or the presence of a large natural dune field or large constructed dune ridges. However, a large overwash event can kill trees and erode out large portions or all of the forest. Such an event resets the process of vegetation succession.

The forested flat is dominated by *Pinus* sp. (pine), *Quercus virginiana* (live oak), and *Juniper virginiana* (eastern red cedar). Almost all forested flats contain a major understory of shrubs, including *Myrica cerifera* (wax myrtle), *Ilex vomitoria* (yaupon holly), *Smilax* sp. (cat brier), *Toxicodendron radicans* (poison ivy), and *Vitis rotundifolia* (muscadine grape). The shrubs and vines occur throughout the forest, but their densest growth is generally near the periphery.

Middle Overwash Ramp: Interior Marsh (MO_intmarsh)

The lower portion of the middle overwash ramp is in the supratidal zone, which has a high water table that is frequently flooded by irregular wind and storm tides with estuarine waters flowing through associated tidal channels. This process can result in the formation of vast algal mats and interior marsh. With time and subsequent overwash events, the elevation of the middle overwash ramp increases and the irregularly flooded algal flats and interior marsh may evolve into dry grass flats.

The interior marsh is characterized by organic-rich sandy soil with a water table that fluctuates from a few inches below ground level to above ground level, depending on rainfall and irregular wind tides. The interior marsh of this irregularly flooded wind-tidal system is similar to the high marsh of the regularly flooded astronomically tidal system.

The interior marsh grades into the platform marsh of the lower overwash ramp with a gentle decline in elevation that ranges from a few feet to a few inches above MSL. The interior marsh has a sand substrate, whereas the substrate in the platform marsh is generally sandy peat, with less sand content and more organic matter. Submerged aquatic vegetation and marsh-grass wrack are blown into the interior marsh through tidal channels during storm flooding.

The dominant vegetation of the interior marsh is extremely variable, depending on the frequency of flooding and the water chemistry. Higher-salinity marsh plants include *Spartina alterniflora* (smooth cordgrass), *Spartina patens* (salt meadow hay), *Juncus roemerianus* (black needlerush), *Distichlis spicata* (saltgrass), and *Borrichia frutescens* (sea oxeye). Dominant plants in areas characterized by lower-salinity to freshwater conditions include *Scirpus robustus* (soft-stemmed bulrush), *Cladium jamaicense* (sawgrass), *Phragmites australis* (common reed), *Spartina cynosuroides* (giant cordgrass), and *Typha angustifolia* (cattail).

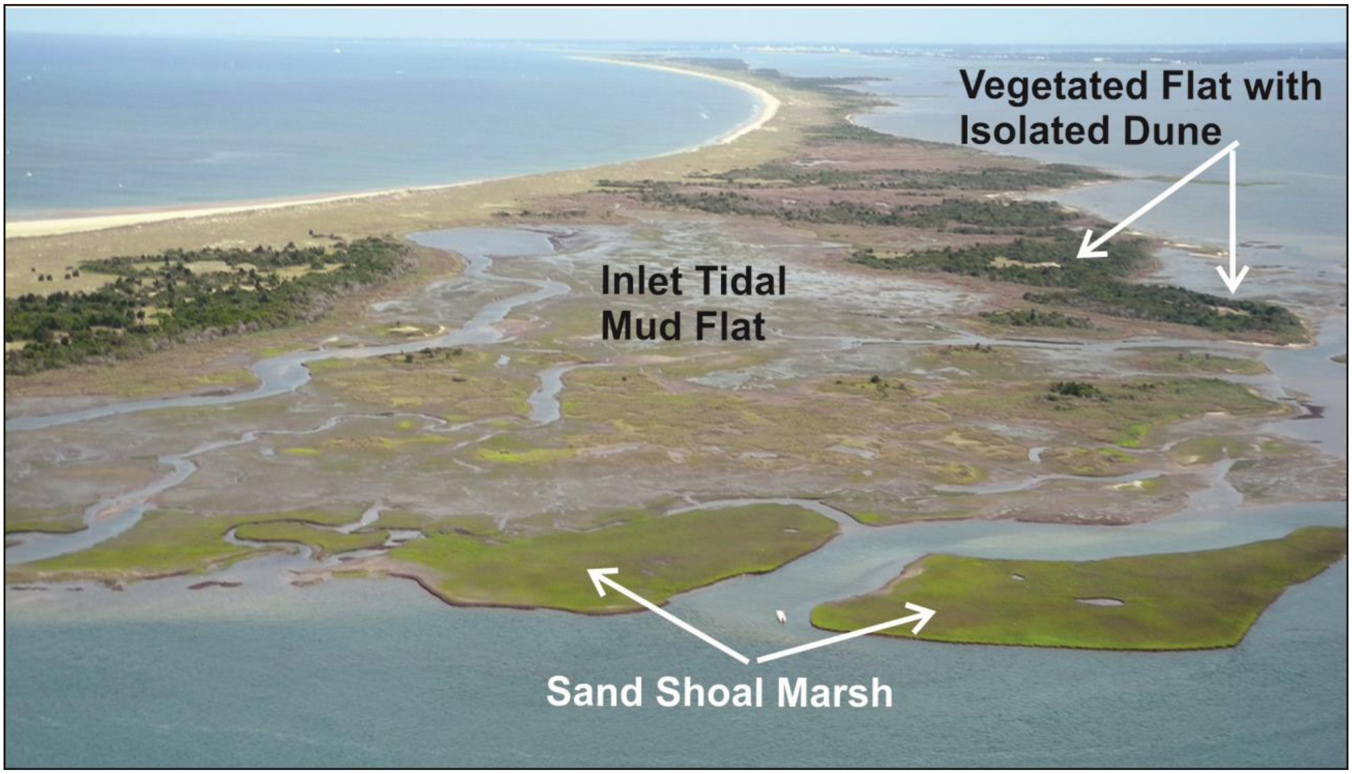

Figure 51. The 2007 oblique aerial photograph looks west across the east end of Shackleford Banks. Barden Inlet is at the bottom with Back Sound on the right and the Atlantic Ocean is on the left side of the photograph. Figure A29 from Riggs et al. (2015).

Middle Overwash Ramp: Isolated Dunes (MO_isodune)

Small-scale isolated dunes (fig. 51) are common on the sparse to unvegetated portions of active middle overwash ramps and within the algal flats that frequently occur on the ramps' lower portions. Isolated dunes in these habitats are particularly active and move across the flats during the dry season. These dunes may have almost any geometry due to the multiplicity of wind and water dynamics affecting the middle overwash ramp.

The density and diversity of vegetation on a stable dune generally increase over time, with *Spartina patens* (salt meadow hay) or scrub shrub predominating. Vegetation spreads inward toward the dune nucleus until a major flood event occurs, destroying the dune or reworking it into a regular ringed beach ridge, as described below.

Middle Overwash Ramp: Dune/Beach Ridge Unit (MO_dunerdge)

If the Middle Overwash Ramp encroaches upon an older component of the barrier island, such as Portsmouth Village, a dune/beach ridge system can form oceanward of the older barrier component. The grasses along the older stabilized component will trap wind-blown sand during the dry periods. The Middle Overwash Ramp flats then become flooded during subsequent stormy periods and the trapped sand is reworked into dune/beach ridges by high water and wave action. The resulting dune/beach ridges are sub-parallel to the portion of land mass that has trapped the sands.

Dune/beach ridges on the middle overwash ramp may initially be stabilized by *Spartina patens* (salt meadow hay) and *Borrichia frutescens* (sea oxeye). The density and diversity of vegetation on a large stabilized dune may increase over time to include scrub shrub.

Lower Overwash Ramp Unit

The lower overwash ramp is a flat, wet, intertidal surface that extends into the back-barrier estuary. It is usually made up of an extensive platform marsh with a thin (<1 m [3.3 ft]) sandy peat substrate on a fine sand base. The lower overwash ramp may be very extensive on a wide island, particularly true in the presence of a well-developed molar-tooth structure with tidal channels cutting through the lower overwash ramp into the lowermost portion of the middle overwash ramp. In contrast, the middle overwash ramp and even the lower overwash ramp may be absent on a narrow island. In this case, the upper overwash ramp is steep and drops directly onto the lower overwash ramp or into the back-barrier estuary with a strandplain beach.

The lower overwash ramp is also characterized across the flat by strong vegetation zonation, which is controlled by salinity gradients and water-level fluctuations caused by the regular astronomical tides (in the vicinity of inlets) and by irregular wind tides that occur within the adjacent estuarine water body. The outer edge of the platform marsh is generally an erosional scarp along the higher-energy, open shorelines and associated tidal channels. However, marsh shorelines in more protected embayments occur as ramps sloping gradually onto shallow back-barrier shoals.

Lower Overwash Ramp: Platform Marsh (LO_pf_marsh)

The platform marsh (fig. 50) is the major component of the lower overwash ramp. It is irregularly flooded by wind tides, except near inlets, where it is also flooded by small, regular astronomical tides. The platform marsh is characterized by a thin (<1 m [3.3 ft]) peat or sandy peat substrate that is permanently saturated with standing water and grades downward into a fine sand base. Tidal creeks form extensive drainage networks in many platform marsh environments, with occasional small ponds scattered within the marsh. The marshes have a low diversity of vegetation that is strongly zoned subparallel to the outer marsh perimeter and the back-barrier berms occurring within the platform marsh.

Platform marshes slope slightly toward the sound and end abruptly at the estuarine shoreline with an erosional, undercut scarp that ranges from a few centimeters to <1 m (3.3 ft) above the estuarine floor. In areas with sufficient sand, the soundward edge of a platform marsh may contain a strandplain beach located in front of and burying the scarp. The outer perimeters of most platform marshes contain elevated fringing berms just landward of and parallel to the erosional scarps. This fringing berm (fig. 50) is generally <1 m (3.3 ft) high and is composed of a mixture of fine sand and wrack.

Wrack, which plays a critical role in the platform marsh, occurs as small to large irregular patches or in shore-parallel rows that represent different storm water levels. Wrack deposits are composed of dead submerged aquatic vegetation or marsh vegetation, occur at varying distances within the marsh as a function of water-level elevation, and are products of specific events and therefore in various stages of decay.

Depressions may form in a marsh as a result of the accumulation of multiple wrack deposits in the same area over time, which prevents recolonization and causes some peat compaction. Depressions that are below MSL collect water. Ponds within the platform marsh may vary from hypo- to hypersaline, depending on groundwater flow, weather (wet versus dry season), and location relative to active inlets. Marsh plants that colonize a decomposing wrack pile or shallow pond differ markedly from the predominant marsh grasses in platform marshes.

The dominant platform marsh grasses in the study area include *Spartina patens* (salt meadow hay) or *Spartina alterniflora* (smooth cordgrass) growing in narrow fringes along outer platform marsh perimeters. The outer fringe of a marsh may be severely eroded and even stripped of vegetation. The eroded areas often have *Juncus roemerianus* (black needlerush) at the water's edge, and *Salicornia bigelovii* (annual marsh glasswort) may colonize the stripped zone. The platform marsh grades inward to vast areas of *Juncus roemerianus* (black needlerush). In the proximity of major inlets, the *Spartina alterniflora* fringe becomes more expansive at the expense of *Spartina patens*, and replaces *Juncus roemerianus* (black needlerush) on most of the platform.

Thick wrack deposits kill the underlying dominant platform marsh vegetation. As wrack decomposes, rows or patches of different plants locally recolonize the denuded areas. The type of recolonizing vegetation is a function of elevation and salinity, with dominant plants including *Borrichia frutescens* (sea oxeye), *Salicornia bigelovii* (annual marsh glasswort), *Salicornia virginica* (perennial marsh glasswort), *Distichlis spicata* (saltgrass). There is also small growth of the scrub shrub species *Myrica cerifera* (wax myrtle), *Iva frutescens* (marsh elder), and *Baccharis halimifolia* (salt myrtle).

Lower Overwash Ramp: Fringing Berm (LO_fring_brm)

Most sound-side shorelines within platform marshes are composed of scarped and undercut sandy peat banks that range from a few centimeters to 1 m (3.3 ft) in height. Storms deposit one or more elongate fringing berms (fig. 50) parallel to the shore at regular distances from the sound shoreline. The most prominent fringing berm is generally <10 m (33 ft) inside of the marsh perimeter and is a product of the average storm surge resulting from the most common winter storms. These fringing berms are composed of submerged aquatic vegetation wrack and/or marsh-grass wrack mixed with sand and other debris; they may be up to 1 m (3.3 ft) thick in rows 1 to 3 m (3.3 to 10 ft) wide. As the scarped marsh peat erodes along the shorelines over time, the fringing berm is systematically moved landward in response to the cumulative impact of many annual winter storms. Depending upon the exposure, the marsh grasses in front of the fringing berm may be ripped off by the wave energy, leaving a barren peat surface exposed. This surface is frequently colonized by *Salicornia bigelovii*.

The fringing berms are generally dominated by *Spartina patens* (salt meadow hay) and *Spartina cynosuroides* (giant cordgrass), with some woody shrubs, including *Myrica cerifera* (wax myrtle), *Iva frutescens* (marsh elder), and *Baccharis halimifolia* (salt myrtle). The back side of the fringing berm drops off more abruptly, with vegetation grading into vast areas of *Juncus roemerianus* (black needlerush). The fringing berm plant assemblage also occurs in the transition zone between platform marsh and back-barrier berms.

Lower Overwash Ramp: Strandplain Beach (LO_spln_bch)

Small strandplain beaches (fig. 52) frequently occur in front of the eroded scarps of adjacent platform marshes, particularly where cross-barrier island features (e.g., transverse ridges, ridge and swale complexes) intersect the estuarine shoreline or where back-barrier shoals are well developed within the adjacent estuary. The presence and development of a strandplain beach are often temporary or seasonal; its presence is in part a direct function of storm frequency, abundance, and patterns.

An active strandplain beach generally has no macrovegetation. However, during extended calm periods, such as the warm summer months, various types of algae may temporarily stabilize the sand on these beaches.

Lower Overwash Ramp: Back-Barrier Berm (LO_bk_br_bm)

Back-barrier berms are sand deposits on top of the lower overwash ramp that form in response to the interaction between estuarine and oceanic storm dynamics. They generally occur as major depositional features that are not subparallel to the estuarine shoreline, in contrast to small-scale fringing berms. Rather, these features are farther inland and occur as ridges that are subparallel to the larger-scale overwash plain. Back-barrier berms tend to be <2 m (6.6 ft) high and <25 m (82 ft) wide, and are composed totally of clean sand. Occasionally, the lateral ends adjacent to the

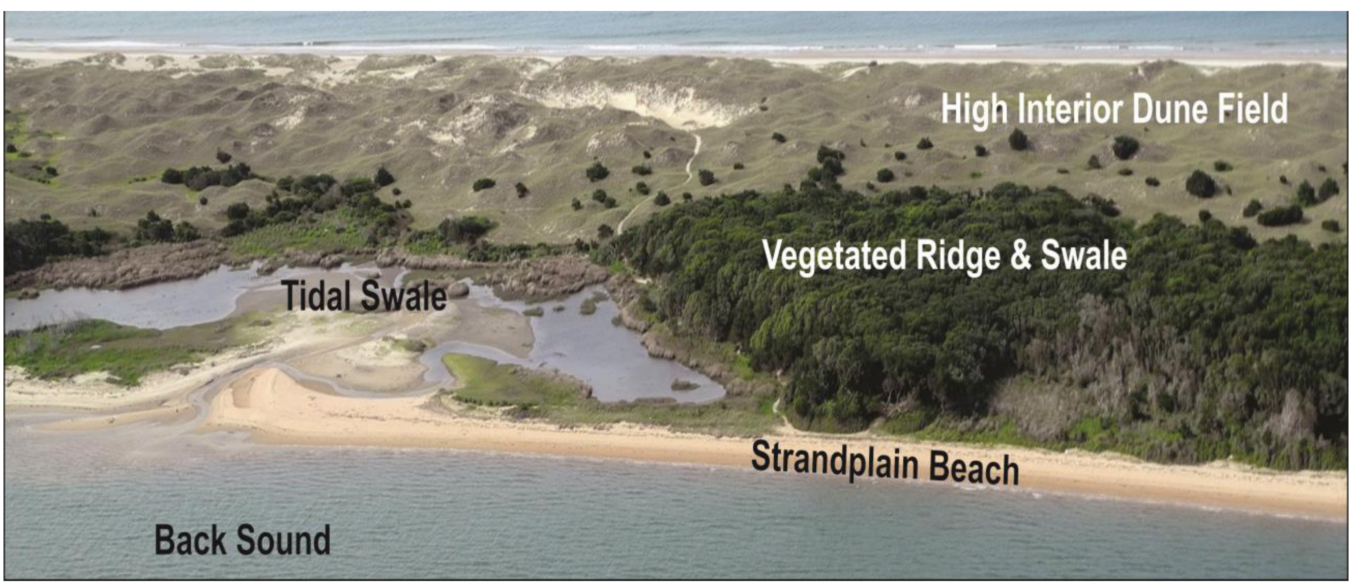

Figure 52. The 2007 oblique aerial photograph looks south across a portion of Shackleford Banks with a High Interior Dune Field unit that buried older vegetated ridge and swale deposits. The Atlantic Ocean is at the top of the figure. Figure A12 from Riggs et al. (2015).

tidal channels have a recurved geometry and turn into the island.

Barrier island segments that have a lower overwash ramp with a well-developed molar-tooth structure also commonly have one or two arcuate back-barrier berms that occur on the platform marsh and extend the entire length of the large-scale lobate overwash plain. Individual back-barrier berms within this system occur along the width of the platform marsh and between adjacent tidal channels.

Vegetation on back-barrier berms is primarily scrub shrub, particularly on smaller and lower features. At the highest elevation, the vegetation becomes sparse and consists mainly of *Juniper virginiana* (eastern red cedar) and *Spartina patens* (salt meadow hay), with large unvegetated areas of exposed sand. In addition, abundant *Baccharis halimifolia* (salt myrtle), *Iva frutescens* (marsh elder), *Myrica cerifera* (wax myrtle), and *Ilex vomitoria* (yaupon holly) may be present.

Some larger and higher back-barrier berms contain maritime forests consisting of various *Pinus* spp. (pine), *Quercus virginiana* (live oak), and *Juniper virginiana* (eastern red cedar) that form an overhead canopy. Shrubs such as *Baccharis halimifolia* (salt myrtle), *Iva frutescens* (marsh elder), *Myrica cerifera* (wax myrtle), and *Ilex vomitoria* (yaupon holly) grow as an understory and mainly near the forest periphery.

Polydemic Features

Polydemic features are those that occur in or inhabit two or more regions on a barrier island. Thus, these features are products of processes that can occur within any portion of the overwash plain or over several different portions of the overwash plain of the simple barrier island model.

Tidal Channel (PF_tidal_chn)

Tidal channels (fig. 50) generally form on flood tidal deltas and persist after the inlet is closed, when the shallow shoals evolve into platform marshes. Tidal channels are common in platform marshes and are often truncated by the overwash ramp as it migrates onto the platform marsh. Tidal channels occasionally extend from the lower overwash ramp well into the middle overwash ramp and even into the upper overwash ramp on some island segments. These segments are generally characterized by rapidly eroding ocean shorelines, where the upper overwash ramp of the migrating barrier has moved landward onto the lower overwash ramp in direct response to major storms and resulting overwash events. The uppermost reaches of these tidal channels tend to be freshwater and fed directly from the groundwater occurring in high portions of the upper overwash ramp.

An active overwash plain will completely bury the headwaters of tidal channels. Water flowing onto and off of the overwash plain carries significant volumes with sufficient energy to erode the tidal channels occurring between segments of the platform marsh. Over time, these portions of the tidal channels are eroded laterally and vertically to produce channels between platform marsh segments. The resulting geomorphology has a classic molar-tooth structure. These shore-perpendicular tidal channels connect the middle overwash ramp directly with the estuary and move overwash water off the island during ocean-overwash events; they also carry estuarine storm-tide water into algal flats and interior marshes on the middle overwash ramp. The tidal channels tend to be deep (up to 3 to 4 m [10 to 13 ft]) and extend completely through the platform marsh, with steeply scarped peat shorelines along the edges. Each end of a tidal channel (inner and outer edges of the lower overwash ramp) shallows, flattens, and broadens out into small-scale deltaic lobes of the submarine structures.

The tidal channel perimeters within the upper overwash ramp and uppermost reaches of the middle overwash ramp are generally dominated by freshwater, with perimeter marshes dominated by *Scirpus robustus* (soft-stemmed bulrush), *Cladium jamaicense* (sawgrass), *Spartina cynosuroides* (giant cordgrass), *Typha angustifolia* (cattail), and *Phragmites australis* (common reed). The vegetation along the fringes of the tidal channels is dominated by *Juncus roemerianus* (black needle rush) marsh grass, which expands laterally into the platform marshes of the lower overwash ramp.

Pond (PF_pond)

Ponds (fig. 50) form in many different places within the general overwash plain in response to very different sets of processes. Consequently, ponds tend to be ephemeral, with variable water composition. The presence of many ponds is a direct function of the patterns, frequencies, and abundance of storms and rainfall. During times of frequent storms and abundant rainfall, most ponds are filled with salt- or freshwater, depending on their locations within the barrier system. Ponds may become wetland marshes during intermediate periods; during periods of low rainfall, they may become algal flats or even dry up completely.

The following list contains general descriptions of important features of ponds occurring on simple barrier islands.

- In regions without constructed dune ridges, storm overwash channels flow through the frontal dune fields on the island berm crest of the upper overwash ramp. These channels frequently leave a series of shore-perpendicular, ephemeral ponds after a storm subsides. They are commonly filled by windblown sand or overwashed sediment. These ponds initially contain saltwater, but those that persist through time may become brackish and ultimately freshwater ponds controlled by rain and groundwater.
- Back-barrier berms that form on the platform marshes of the lower overwash ramp are frequently breached by storm surges, producing a series of smaller, elongate, shore-perpendicular tidal channels. After a storm surge recedes, low depressions in the centers of tidal channels become a series of ponds in the back-barrier berms. These ponds are often permanent and are initially saline, but freshen over time.
- Some active tidal channels are located between platform marshes within the molar-tooth structure on the lower overwash ramp. As fan delta sands build up and become stabilized by marsh grasses, the outside and inside edges of these tidal channels may become blocked, forming ponds. Because these ponds are at MSL, they are flooded by both spring and storm tides and generally remain brackish.
- Small, irregular, and shallow ponds occur frequently within the interior marshes of the middle overwash ramp and the platform marshes of the lower overwash ramp. In some marshes, these ponds are extremely abundant. They can form in several different ways:
    - Many platform marshes contain shallow (<0.5 m [1.6 ft] deep) ponds that appear to form in response to large wrack accumulations that kill the underlying grasses. As unvegetated patches in the marsh dry out, peat compaction, in concert with possible oxidation of some peat, leaves shallow depressions that become filled with water. This water is generally brackish, with variable salinity ranging from hypo- to hypersaline, depending on season and weather conditions.
    - A few platform marshes appear to be in a constructive mode, with marsh growing onto the shallowest portions of the back-barrier sand shoals. Slightly deeper (<0.5 m [1.6 ft]) areas have become ponds with gradual slopes around the edges. These ponds are interconnected to adjacent estuaries and have similar salinities.
    - Some platform marshes appear to be in a destructive mode, with slightly deeper (<1 m [3.3 ft]) ponds. The edges of these ponds are erosional and consist of scarped peat that drops off abruptly into deeper water. This results in a platform marsh with a “Swiss-cheese” fabric of ponds that have variable salinity ranging from hypo- to hypersaline, depending on season and weather conditions.
- After an inlet through a barrier island closes, the flood-tidal delta sand shoals quickly evolve into intertidal marsh islands that separate the many tidal channels radiating out from the main inlet channel. As the ocean shoreline recedes and the barrier migrates on top of the flood tidal delta, overwash begins to fill portions of the channels from the front side while storm surges fill portions from the estuarine side. The remaining long, linear, and relatively deep ponds have various orientations; they occur along the boundary between the middle and lower overwash ramps or within flood-tidal delta marshes.

Transverse Ridge (PF_trnv_rdge)

Transverse ridges are long, low, and fairly straight geomorphic ridges oriented transverse to a barrier island. They can form in several different ways.

In one mechanism, scattered and isolated dune sands are reworked into elongate beach ridges by waves or storm-surge floodwaters that are temporarily ponded on an overwash plain. These ridges are often low (<1 m [3.3 ft] high), narrow (1 to 3 m [3.3 to 10 ft] wide), and up to several hundred meters long.

A second mechanism builds large transverse ridges that incorporate huge volumes of sand as elongate dune structures extending transversely across the upper and middle overwash ramps. These sediment-rich dune features may occur along active inlets on the inlet sides of older inlet spits, or downwind from unvegetated sand flats. In either case, aeolian-driven sands accumulate along the edges of existing features during dry periods. The sand is trapped and stabilized by dune vegetation. During subsequent storms, active overwash across the overwash plain or inlet spit can truncate the dune structure, leading to further elongation and producing a complicated dune structure characterized by erosion and overwash blowouts. Large-volume transverse dune ridges occurring within a barrier island may be important evidence for the existence of former inlets.

Active transverse ridges have large unvegetated areas of exposed sand, with some areas stabilized by *Uniola paniculata* (sea oat) and *Spartina patens* (salt meadow hay). Older and less active portions of transverse dune ridges are vegetated primarily with scrub shrub, including *Baccharis halimifolia* (salt myrtle), *Iva frutescens* (marsh elder), *Myrica cerifera* (wax myrtle), *Ilex vomitoria* (yaupon holly), and *Juniper virginiana* (eastern red cedar). Old transverse ridges are dominated by maritime forests consisting of various pine species (*Pinus* spp.), *Quercus virginiana* (live oak), and *Juniper virginiana* (eastern red cedar). These trees form an overhead canopy along with massive growths of various vines, including *Smilax* sp. (cat brier), *Toxicodendron radicans* (poison ivy), and *Vitis rotundifolia* (muscadine grape). The shrubs and vines occur throughout the forest, but their densest growth is generally near the periphery.

Dune Flat (PF_dune_flat)

When an island segment has ample sediment supply, aeolian processes during non-storm tide conditions can transport large volumes of sand landward of the island berm. This process creates a broad, rolling sand flat with an elevation significantly higher (2 to 3 m [6.6 to 10 ft]) than those of the island berm and upper overwash ramp. The surface of the aeolian dune flat ranges from very flat to slightly undulating, with <2 m (6 ft) of relief related to small-scale deflation and dune features.

Because the aeolian dune flats are composed of clean, well-sorted dune sands with generally higher elevations than overwash plains, a major fresh water aquifer frequently rises to the land surface. This results in broad damp areas and shallow ponds that are dominated by algae and fresh water marsh plants, respectively. The small dunes rose above the water table and were dominated by *Spartina patens* (salt meadow hay) during non-stormy periods. Also, the aeolian dune flats farthest from the ocean front tended to become stabilized by scrub shrub species and ultimately became forested with *Pinus* spp. (pine), *Ilex vomitoria* (yaupon holly), and *Quercus virginiana* (live oak).

Dune Field (PF_dunef)

When island segments have large sediment supplies and are dominated by aeolian processes, natural dune fields form on top of the aeolian dune flats. During non-storm tide conditions, strong winds transport large volumes of sand landward from the barrier beach and berm. This process results in the development of an active dune field, with dune elevations ranging from 3 to 25 m (10 to 82 ft) or more.

Dune fields generally have a complex geomorphic character consisting of depositional dunes produced by different kinds of storm (e.g., fall to spring nor'easters, summer southwesters, and summer to fall tropical storms) with multiple wind directions. The dune fields are further complicated by severe erosional dynamics in concert with the influence of upper water tables that result from the wet temperate climatic conditions, producing abundant over-steepened slopes. These dune fields frequently override forested habitats on the back sides of barrier islands, further complicating their depositional, erosional, and stabilization patterns.

Back-barrier dune fields may contain numerous buried soil profiles. These buried soils reflect various shifts in past climatic conditions, such as storms or dry-season fires that re-activated dune deposition, and periods of wet or fair weather that fostered vegetative stabilization of the dune fields (Havholm et al. 2004).

Natural dune fields are active and essentially barren of vegetation (Frost 2000). Minor vegetation consists of scattered grasses, including *Spartina patens* (salt meadow hay). Swales between dunes contain shallow, freshwater ephemeral ponds dominated by algae and freshwater wetland vegetation.

Algal Flat (PF_algal_flt)

Algal flats usually occur in the lower supratidal portion of a natural, overwash-dominated barrier island segment with a broad middle overwash ramp. They are especially common in the presence of a well-developed molar-tooth structure with tidal channels that dissect the lower overwash ramp. The low elevation and high water table enable irregular wind and storm tides to flood the middle overwash ramp frequently with estuarine waters flowing through the tidal channels. The algal flats form in response to fluctuating habitat conditions, which range from fresh groundwater or rainwater to hypersaline waters due to local ponding and evaporation of ocean or estuarine waters. With time and subsequent overwash events, the elevation of the middle overwash ramp increases and the irregularly flooded algal flats may be taken over by interior marsh or may shift to dry grass flats.

Algal flats also occur in other habitats, including ephemeral ponds or depressions characterized by fresh to hypo- to hypersaline water conditions. As the water table in these ponds drops, the damp floor of the depression frequently develops an algal mat. This mat is periodically ripped up or buried by subsequent storm events. Hypersaline ponds may evaporate, leaving salt flats that become vegetatively zoned with *Salicornia bigelovii* (annual marsh glasswort), and *Salicornia virginica* (perennial marsh glasswort), forming rings around the peripheries of the depressions that, in turn, may be surrounded by an outer zone of *Distichlis spicata* (saltgrass) and *Borrichia frutescens* (sea oxeye).

Ridge and Swale (PF_rdg_swl)

Ridge and swale geomorphic units occur as sets of subparallel couplets consisting of low, regular sand ridges and adjacent shallow low swales. The sand ridges tend to be linear to slightly curved, uniform features that rarely exceed 3 m (10 ft) in elevation. These shoreline features formed during a temporary higher stand of sea level or a series of storm surge deposits (Riggs and Ames 2006).

Lower swales between successive beach ridges represent beach deposition during periods characterized by slightly lowered sea level or non-stormy periods. These swales are generally dominated by wetlands. They are filling with organic peat deposits that are thickest on the estuarine side and thin up onto the subsequent ridge. The centers of many swales, particularly those close to the estuary, contain open water. Over the years, many of the swales have been dredged and opened up as navigation channels, with the dredge spoil disposed of on adjacent marshes or the low flanks of adjacent ridges.

Ridge and swale structures are dominant geomorphic units on complex barrier islands and are not products of overwash-dominated barrier island dynamics. They were produced by processes prevailing in an earlier evolutionary stage of the barrier system. Age-dating of some structures has indicated that they formed during a prior sea level highstand event or as sea level was rising under variable sediment supply and wave energy conditions (Mallinson et al. 2009). Most barrier islands have since collapsed (become unstable, with irreversible changes in form and position), and the modern barrier islands began to reform about 500 years ago (Sager and Riggs 1998; Riggs et al. 2000; Grand Pre 2006; Culver et al. 2007). Thus, the modern inlet and overwash-dominated barrier island components have migrated into and become welded onto the older barrier island, which had ridge and swale structures.

Because most ridge and swale structures are older than surrounding areas of the barrier island and occur on the back sides of barrier island segments, they tend to be dominated by heavy vegetative cover, except where they have been urbanized. The sand ridges have thick forests with mature stands of mixed hardwood and pine. Because the ridges are not very high, the forest grades downslope into an extensive growth of transitional scrub shrub vegetation in the supratidal zone, where adjacent swales are connected to the estuary.

The swales are dominated by wetland vegetation. Land-locked swales and segments far from the estuaries are dominated by swamp forests or linear ponds surrounded by swamp forest. When swales are connected to the estuary, the swamp forest sequentially grades toward the estuary to freshwater and then brackish-water marshes. The brackish marshes generally have freshwater zones immediately adjacent to the ridges due to groundwater discharge from these ridges. This habitat grades outward into a middle zone dominated by *Juncus roemerianus* (black needlerush) and a broad outer zone dominated by *Spartina cynosuroides* (giant cordgrass) in low brackish estuaries, *Spartina patens* (salt meadow hay) in middle brackish estuaries, and *Spartina alterniflora* (smooth cordgrass) in high brackish estuaries.

Paleo-Inlet Spit (PF_p_inl_spt)

Paleo-inlet spits can occur anywhere from the eroding beach to the middle- or lower-overwash ramp, and are classified as polydemic features. See “Inlet Spit Unit” under “Beach Features” for additional description.

Table 17. Summary of barrier island system units at Shackleford Banks, as mapped by East Carolina University (Riggs et al. 2015).

Group	Map Unit (symbol)
W. Shackleford Banks	Inlet Berm (inlet_bm)
W. Shackleford Banks	Inlet Flat (inlet_flat)
W. Shackleford Banks	Inlet Spit (inlet_spit)
W. Shackleford Banks	Inlet tidal sand flat (inlet_tidal_sand_flat)
W. Shackleford Banks	Foredune ridge (fdune_ridge)
W. Shackleford Banks	High interior dune field (high_interior_dune_field)
W. Shackleford Banks	Wet vegetated flat (wet_veg_flat)
W. Shackleford Banks	Interior flat (int_flat)
W. Shackleford Banks	Interior marsh (int_marsh)
W. Shackleford Banks	Vegetated ridge (veg_ridge)
W. Shackleford Banks	Vegetated ridge and swale (veg_ridge_swale)
W. Shackleford Banks	Tidal swale (tidal_swale)
W. Shackleford Banks	Pond (pond)
W. Shackleford Banks	Strandplain beach (strandplain_beach)
W. Shackleford Banks	Ocean beach (oc_beach)
E. Shackleford Banks	Intermittent foredune (intermit_fdune)
E. Shackleford Banks	Low interior dune field (low_int_dune_field)
E. Shackleford Banks	Vegetated flat (veg_flat)
E. Shackleford Banks	Sparsely vegetated flat (sparse_veg_flat)
E. Shackleford Banks	Isolated dune (iso_dune)
E. Shackleford Banks	Tidal marsh (tidal_marsh)
E. Shackleford Banks	Inlet tidal mud flat (inlet_tidal_mud_flat)
Back Sound	Sand flat (sand_flat)
Back Sound	Sand shoal (sand_shoal)
Back Sound	Sand shoal marsh (sand_shoal_marsh)
Back Sound	Subtidal vegetated flats (subtidal_veg_flat)
Back Sound	Organic bank (organic_bank)
Back Sound	Shell bank (shell_bank)
Anthropogenic Features (Polydemic)	Dredge spoil (dredge_spoil)
Anthropogenic Features (Polydemic)	Historic Telephone Line
Anthropogenic Features (Polydemic)	Fenced Area
Anthropogenic Features (Polydemic)	Pen Chute
Anthropogenic Features (Polydemic)	Docks and Buildings
Anthropogenic Features (Polydemic)	Cemetery
Anthropogenic Features (Polydemic)	Remnant Sea Wall and Rock Jetty

W. = West; E. = East

Overwash Channel (PF_owchannel)

Overwash channels are shore-perpendicular features that may occur in between foredunes on the upper overwash plain. They are formed by ocean-side overwash events that scour inter-dunal channels and may become isolated, ephemeral ponds due to overwash deposition during the waning stages of a storm event.

Anthropic Features

Airport/Landing Strip (airport_land)

The Portsmouth Village Airstrip was constructed by private individuals for recreational use shortly after World War II, and was leveled and extended to an approximate length of 500 m (1640 ft) in 1959. The airport was closed in 1996 due to safety concerns and incompatibility with preservation of the historical character (NPS 1996).

Dredged Channel/Spoils (AF_drdge)

A dredged channel or drainage ditch is evidence of sediment removal. Some removed sediment (referred to as spoil) has been pumped or transported off site and deposited as fill material to raise land elevations for urban development. More often, the sediment removed from a dredged channel is deposited immediately adjacent to the structure being dredged, creating linear ridges or a series of circular piles along one or both sides of the channel. These dredge spoil piles generally raise the elevation of adjacent land from a few centimeters to 1 m (3.3 ft); they are generally mapped as a single geomorphic unit with a dredged channel.

Spoil that is utilized to raise land elevations for urban development can support any kind of vegetation. Where spoil is placed within the marsh supratidal zone as linear ridges or concentric piles, the dominant vegetation is composed of transitional-zone species, including *Baccharis halimifolia* (salt myrtle), *Iva frutescens* (marsh elder), *Spartina patens* (salt meadow hay), and *Spartina cynosuroides* (giant cordgrass) or scrub shrub. Where the spoil is deposited above the supratidal zone, vegetation includes *Myrica cerifera* (wax myrtle), *Ilex vomitoria* (yaupon holly), *Myrica pensylvanica* (northern bayberry), *Pinus* spp. (pine), *Juniper virginiana* (eastern red cedar), *Spartina patens* (salt meadow hay), *Smilax* spp. (cat brier), and *Toxicodendron radicans* (poison ivy).

Rock Jetty (AF_jetty)

A rock jetty is a structure that is built perpendicular or oblique to a shoreline. The Cape Lookout jetty was built of boulders. It caused accretion of sand that elongated Power Squadron Spit towards Shackleford Banks and increased the areal extent of Cape Lookout Bight.

Sound Features

Sound features include submarine sand bodies behind the barrier islands. The features are included in the Core Banks map because they are clear on the 1998 DOQQs used for that area, and because they are abundant and critically important features to barrier island evolution and to associated estuarine ecosystems (Ames and Riggs 2008); they are not included on other islands due to the poor resolution of aerial photographs from those areas.

Upper Shoals (SF_up_shoal)

Submarine shoals (fig. 50) supply width to the back sides of the barrier islands and interact with the lower overwash ramp habitats to form the underlying framework for expansion of the lower overwash ramp onto the back-barrier shoals over time (Ames and Riggs 2008).

Shallow, sub-tidal sand shoals range from 0 to 0.3 m (-1 ft) below mean sea level (MSL). Due to the dominance of wind tides within the NE North Carolina estuarine system, these upper shoals are frequently and irregularly exposed to sub-aerial conditions that extend over time periods that range from hours to many days.

The surficial sediments on the upper shoals are generally bound by algae (microbial organisms) that inhibit sediment transport under non-stormy weather conditions. However, during high energy storms, and particularly during the winter, the bound surface can be disturbed, allowing the sediment to be transported and producing strandplain beaches and fringing berms on adjacent platform marshes. This ecosystem also contains an extensive population of burrowing infauna.

Lower Shoals (SF_low_shoal)

Shallow, sub-tidal sand shoals (fig. 50) grade down slope from the upper shoals, range from -1 to -2 feet below mean sea level (MSL), and grade into deeper water. These shoals are exposed to sub-aerial conditions during some extreme storm events.

The surficial algae decrease on the lower shoals and diminish the binding of surficial sediments. Thus, the unbound sediments are readily transported forming ripple marks and other micro-topographic features. Submerged aquatic vegetation (SAV) is abundant.

Flood-Tide Delta Shoals (SF_fld_tide)

The flood-tide delta shoals are extensive back-barrier sand shoals and associated tidal channels that form on the estuarine side of active inlets though barrier islands. This broad fan-shaped geomorphic unit is cut by a network of tidal channels that exchange water between the ocean and estuary.

The flood-tide delta shoals are dynamic, responding to the regular astronomical tidal currents and storm tides that actively erode, transport, and deposit sediments throughout the shoal system. The surface morphology of the shoals is characterized by sedimentary structures that range from ripples to sand waves.

In general, these geomorphic units are so active that they are not dominated by inter-tidal marshes, algae (microbial mats), or submerged aquatic vegetation. As inlets migrate laterally, abandoned flood-tide deltas eventually develop marshes on the inter-tidal shoals, algal-bound surfaces on the submerged upper shoals, and submerged aquatic vegetation on the lower shoals.

Tidal Delta (SF_tidal_del)

Platform marshes are often cut with shore-perpendicular tidal channels to produce molar-tooth structures on the lower overwash ramp. Active tidal channels are flanked on the lower overwash ramp and on the estuarine side by tidal deltas. Each end of the tidal channel shallows, flattens, and broadens out into deltaic lobes. The tidal deltas are deposited by sound-side flooding through the tidal channels and may be inter-tidal or supra-tidal sand bodies.

Fine-grained sediments of the tidal deltas may be bound by algae (microbial organisms). Tidal deltas are sparsely to partly vegetated with *Spartina patens* (salt meadow hay).

Barrier Island System Units of Shackleford Banks (East Carolina University Field Survey and Archeological Data Map)

The Riggs et al. (2015) map relies in part on the same methods as the Core Banks map developed by Ames and Riggs (2008): classifying geomorphic units based on a model of barrier island evolution developed from process-response studies and modern field surveys of the North Carolina Outer Banks (Riggs and Ames 2006). The base map for Shackleford Banks is the National Agriculture Imagery Program (NAIP) 2012 digital orthoimagery, and the base map for Back Sound is the NAIP 2010 digital orthoimagery. Geomorphic features were delineated using heads-up digitizing in ArcGIS 10.1 to create a geodatabase and to interpret historical orthoimagery from 1954, NAIP imagery from 1998 to 2012, NAIP 2009 infra-red images, and 1883 and 1954 topographic maps. Lidar elevation data, 2013 oblique aerial photos, and ground-based surveys were also used to define geomorphic features. Dominant vegetation type was identified through the literature and ground-truth field surveys (Riggs et al. 2015).

To date the formations of various portions of Shackleford Banks, the island was also surveyed with ground-penetrating radar (GPR) along multiple cross-island and shore-parallel transects where the terrain, vegetation, and fresh groundwater supply allowed. NPS Southeast Archeological Center (SEAC) conducted archeological excavations at test sites; radiocarbon analysis was performed on shell samples, peat deposits, and pottery soot, all of which occurred in conjunction with prehistoric and historic deposits. Environmental data and radiocarbon age data from previous excavations (Prentice and Hellmann 2014, as cited in Riggs et al. 2015) were also incorporated into this study (Riggs et al. 2015, 2016).

The map identifies subgroups and units of the following regional geomorphic features (table 17): beach, overwash-plain, polydemic, and anthropogenic features. The unit descriptions are taken primarily from Ames and Riggs (2008), and supplemented by information from publications where cited. The dominant vegetation is included with the detailed geomorphic units because vegetation is a critical component of barrier island dynamics, but the level of detail is insufficient to utilize these maps as detailed vegetation maps. If the geomorphic unit is polydemic (occurs in many different parts of the barrier island) or if the vegetation has been severely modified, the vegetation type of the geomorphic unit is undifferentiated (Ames and Riggs 2008).

The geomorphologic features on Shackleford Banks are extremely different between the western and eastern portions of the island (fig. 13), so the maps subdivide the island into the western portion that extends from Beaufort Inlet eastward to about mile marker 51.6, and the eastern portion that extends from about mile marker 51.6 east to Barden Inlet (Riggs et al. 2016). Mile markers are illustrated in plate 1 (in pocket).

West Shackleford Banks Units

Riggs et al. (2015) describe the following units occurring on West Shackleford Banks (Beaufort Inlet east to mile marker 51.6):

Inlet Berm (inlet_bm)

Inlet Berms (fig. 49) occur along the sound shore of Beaufort Inlet, where sand is deposited by wind and currents. They generally occur as arcuate features that are sub-parallel to the estuarine shoreline with lateral ends having a recurved geometry, concave on the landward side. The Inlet Berm progrades into the adjacent inlet along the active shoreline. The unit also occurs further inland as relict ridges. Inlet Berms tend to be 1 to 2 m (3 to 7 ft) high, less than 25 m (82 ft) wide, and are composed entirely of sand. The active Inlet Berm generally is unvegetated. Relict Inlet Berms are vegetated with shrub-scrub consisting mainly of *Juniper virginiana* (eastern red cedar) and *Spartina patens* (salt meadow hay), with large unvegetated areas of exposed sand. In addition, there may be abundant *Baccharis halimifola* (silverling), *Iva frutescens* (marsh elder), *Myrica cerifera* (wax myrtle), and *Ilex vomitoria (yaupon holly)*.

Inlet Flat (inlet_flat)

The Inlet Flat unit (fig. 49) is separated from Beaufort Inlet by the Inlet Berm. The Inlet Flat is a gently ramped surface that slopes gradually from the Ocean Beach berm towards the inlet and estuary. The Inlet Flat is a product of the interaction between the waves and tidal currents during high-water overflow conditions associated with spring tides and small storm tides. Active portions of the Inlet Flat contain abundant tidal creeks. The most active portions of the flat adjacent to Beaufort Inlet are unvegetated. Older portions are increasingly vegetated with mixed grasses that include *Spartina patens* (salt meadow hay). The vegetation grades upslope towards the south and east into *Borrichia frutescens* (sea oxeye), abundant *Juncus roemerianus* (black needlerush), and scattered *Myrica cerifera* (wax myrtle). Supra-tidal portions of the Inlet Flats with finer grained sediments will frequently be dominated by algal mats and *Salicornia* sp. (marsh glass wort).

Inlet Spit (inlet_spit)

The Inlet Spit unit (fig. 49) occurs on the ocean side of both Beaufort and Barden inlets and may consist of one or more shore parallel recurved ridges. At Beaufort Inlet, erosion has all but obliterated the curved feature. At Barden Inlet, several shore-parallel recurved ridges extend up to 1.6 km (1 mi) in length with height ranging from 1 to 5 meters. The active portions of these features result from regular overwash events, and the spit forms by the combined interaction of waves and tidal currents during high water overflow conditions associated with spring tides or small storm tides. Sometimes, the higher ridges formed by previous storm events will be subsequently truncated, breached, or even enlarged by the accretion of secondary spits. An older Inlet Spit often will contain active dunes that develop after the spit is formed. Active Inlet Spits will be either unvegetated or grassed with *Uniola paniculata* (sea oats) and *Spartina patens* (salt meadow hay), while vegetation on older Inlet Spits often consists of mixed grasses and shrub-scrub.

Inlet Tidal Sand Flat (inlet_tidal_sand_flat)

The Inlet Tidal Sand Flat occurs adjacent to Beaufort Inlet on the estuarine side of Shackleford Island. It forms as a semi-enclosed area behind the Inlet Berm that allows regular tidal flooding and ebbing. Generally there is no macro-vegetation, but has micro-flora and macro-fauna.

Foredune Ridge (fdune_ridge)

The size of the Foredune Ridge depends upon sand availability and coastal erosion rates. The Foredune Ridge in the western portion of Shackleford Banks is high (up to 5 m), steeply scarped, and fairly continuous from Shackleford Banks mile marker 51.6 west to mile marker 54.6. Foredune Ridges are unvegetated on the scarped ocean side, topped by Uniola paniculata (sea oats), and have increasing vegetation density and diversity landward as the impact of salt spray is diminished. Other plants that commonly occur on the north side of the Foredune Ridge include *Spartina patens* (salt meadow hay), *Cakile edentula* (sea rocket), *Solidago sempervirens* (golden rod), *Myrica cerifera* (wax myrtle), occasionally *Juniper virginiana* (eastern red cedar) and ground cover plants such as *Hydrocotyle bonariensis* (penny wort).

High Interior Dune Field (high_interior_dune_field)

The High Interior Dune Field unit (fig. 52) is generally coincident with and north of the high Foredune Ridge that runs from mile marker 51.6 westward to mile marker 54.6 to 55 where it curves NW and extends to Back Sound. This vast area of high dunes reaches up to 9 m (30 ft) in height and covers the southern portion of the island where the sand dunes migrated atop pre-existing maritime forest. The dune fields are generally complex in geomorphic character, having been modified and eroded over decades by storms with multiple wind directions. The High Interior Dune Field unit is relatively stable today and has an extensive cover of grass vegetation with localized areas of active blowouts and over-steepened slopes. The vegetation on the High Interior Dune Field is dominated by the grass *Uniola paniculata* (sea oats) and ground cover plant *Hydrocotyle bonariensis* (penny wort). Occasionally

Juniper virginiana (eastern red cedar) occurs in small damp areas between the dunes. Ghost trees from the buried forest often protrude through the sand.

Wet Vegetated Flat (wet_veg_flat)

The Wet Vegetated Flat is a former Inlet Flat that now occurs within the main body of the island surrounded by the High Interior Dune Field. This low flat geomorphic feature (<1 m [3 ft] above MSL) formed within a former inter-tidal zone, but was cut off by formation of a Strandplain Beach and is no longer connected to estuarine dynamics. Thus, this flat now occurs at the fresh ground-water table and is frequently dominated by shallow, black-water ponds, especially after heavy rains. Due to the shallow fresh water table, the shrub-scrub vegetation tends to be very thick and lush and includes the following species: *Baccharis halimifolia* (silverling), *Myrica cerifera* (wax myrtle), *Iva frutescens* (marsh-elder), *Myrica pensylvanica* (bayberry), *Juniper virginiana* (eastern red cedar), *Spartina patens* (salt meadow hay), *Smilax* sp. (cat brier), *Toxicodendron radicans* (poison ivy), and *Parthenocissus quinquefolia* (Virginia creeper).

Interior Flat (int_flat)

The Interior Flat comprises a slightly undulating and low surface (generally <1 m [3 ft] above MSL) within the High Interior Dune Field. Major portions of the Interior Flat are at or close to the ground water table, occasionally contain shallow ephemeral ponds, and are often characterized by dense growth of shrub-scrub as described in the Wet Vegetated Flat. These low Interior Flats have linear sections that may be the relict expressions of the swale features that occur on the northern portion of the island.

Interior Marsh (int_marsh)

Swales or interior flats that have been cut off from the estuarine dynamics long enough and surrounded by higher topography to prevent salt-water influx from storms can develop as Interior Marshes dominated by fresh, black-water. Historic maps show Mullet Pond connected to Back Sound. Today Mullet Pond is an inland pond dominated by fresh, black-water marsh containing abundant *Typha angustifolia* (cat tail) and surrounded by higher land and shrub-scrub vegetation.

Vegetated Ridge (veg_ridge)

Large-scale forested sand ridges (up to 6 m [20 ft] in height) are mapped as Vegetated Ridges and are oriented generally perpendicular to Back Sound. Maritime forest vegetation includes *Pinus* sp. (pine), *Quercus virginiana* (live oak), and *Juniper virginiana* (eastern red cedar) and *Ilex* (holly) community. The under-story of shrubs include *Myrica cerifera* (wax myrtle) and *Ilex vomitoria* (yaupon holly), along with various vines including *Smilax* sp. (cat brier), *Toxicodendron radicans* (poison ivy), and *Vitis rotundifolia* (muscadine grape). The shrubs and vines occur throughout the forest and are densest generally near the periphery.

Vegetated Ridge and Swale (veg_ridge_swale)

This unit occurs as multiple sets of sub-parallel couplets consisting of forested sand ridges (up to 2 m [7 ft] in height) interspersed with low inter-ridge swales dominated by wetland vegetation and that contain plant species that range from inter-tidal to supra-tidal in the up-slope directions. The sand ridges and associated swales tend to be linear to slightly curved features at various oblique angles to the estuarine shore where they are being truncated by sound-side erosion.

Tidal Swale (tidal_swale)

Where the swales have been inundated and drowned by sea level rise and sound-side dynamics, they are subjected to daily astronomical tides and mapped as Tidal Swales unit. The swales grade laterally inland to *Juncus roemerianus* (black needlerush) marsh and thick shrub-scrub zones onto the forested ridges.

Pond (pond)

Some ponds (fig. 50) occur within low depressions or swales and are non-tidal since they are not directly connected to the estuary. These ponds can still be irregularly flooded by storm tides and thus the water can range from fresh to brackish, and even occasionally may become highly saline waters due to post-storm evaporation. Consequently, these Ponds are generally dominated by *Juncus roemerianus* (black needlerush) that grades upslope to *Borrichia frutescens* (sea oxeye), and to the adjacent inland shrub-scrub.

Strandplain Beach (strandplain_beach)

Strandplain Beaches (fig. 52) form the Back Sound shoreline in areas where cross-barrier island sand features such as Vegetated Ridges, Ridge and Swales, or Vegetated Flats intersect the eroding estuarine shoreline. These beaches always have a high tide or storm beach along the eroding sediment scarp. If there is enough sand available, the Strandplain Beach can prograde away from the source and form sand spits across flooded swales or in front of marshes. Strandplain Beaches can also form adjacent to offshore sand shoals in the adjacent estuary. Generally there is no macro-vegetation on an active Strandplain Beach. However, wrack (dead marsh grass and submerged aquatic vegetation) is abundant on Strandplain Beaches and in adjacent marshes, deposited by storm tides.

Ocean Beach (oc_beach)

The Ocean Beach unit (fig. 49) extends from the mean wet-dry line to the base of either a natural or a scarped foredune ridge. If no dune ridge is present then the beach extends to the beach berm crest, which is the high crest of an overwash ramp that separates the surface water flow between the ocean and back-barrier estuary. The Ocean Beach west of mile 51.6 is backed by a high (up to 5 m) and mostly continuous Foredune Ridge, whereas on the east portion of Shackleford Island, from mile marker 51.6 to 48.6, the Ocean Beach is characterized by a wide and gentle beach backed by a low (2 to 3 m), steeply scarped Intermittent Foredune. This Intermittent Foredune is repeatedly broken by low (1 to 2 m) berm crests formed by recent overwash fans. The Ocean Beach through much of the east portion of Shackleford Banks, particularly at low tide between mile markers 48.5 and 5.0, expose an outcrop of in situ marsh peat. The peat commonly contains shrub-scrub roots and dates to 1470 CE to 1650 CE The Ocean Beach from mile marker 48.5 to Barden Inlet is characterized by a series of ocean shoreline beach ridges. The change (nodal point) from shoreline recession west of mile marker 48.5 to shoreline accretion east of mile marker 48.5 is due to the growth of the hook on Cape Lookout in concert with the ebb-tide delta dynamics of Barden Inlet.

Macro-vegetation is rare within the active Ocean Beach unit. Storm wrack often lies along the upper swash lines associated with the storm beaches, and may consist of offshore algae (*Sargassum* sp.), dune grasses, estuarine submerged aquatic vegetation, or estuarine marsh grasses.

East Shackleford Banks Units

Riggs et al. (2015) describe the following units occurring on East Shackleford Banks (mile marker 51.6 east to Barden Inlet):

Intermittent Foredune (intermit_fdune)

This unit occurs between mile marker 48.6 to 51.6, on the eastern portion of Shackleford Banks. It is characterized by low (2 to 3 m) steep scarps that are repeatedly broken by low (1 to 2 m) berm crests formed by recent overwash fans. It is unvegetated along the ocean side, where erosion is severe, but the tops and landward side are vegetated primarily by Uniola paniculata (sea oats). The density and diversity of the vegetation increases landward as the impact of salt spray is diminished. Other plants that commonly occur on the north (sound) side of the Intermittent Foredune include *Spartina patens* (salt meadow hay), *Cakile edentula* (sea rocket), *Solidago sempervirens* (golden rod), *Myrica cerifera* (wax myrtle), occasionally *Juniper virginiana* (eastern red cedar), and ground cover plants such as *Hydrocotyle bonariensis* (penny wort).

Low Interior Dune Field (low_int_dune_field)

The dunes in this unit rise up to 2 m (7 ft) in height. They occur north of and grade into the adjacent Intermittent Foredune unit in the region between Shackleford Banks mile marker 48.6 and 51.6. The dunes are generally complex in geomorphic character. The Low Interior Dune Field includes ramps that formed during overwash events and that slope gradually from the berm crest towards the Vegetated Flats unit along the estuarine shoreline. The ongoing overwash events supply new sand that is winnowed and blown to form scattered low dunes that are 1 to 2 m (3 to 7 ft) high. The Low Interior Dune Field is mostly vegetated, except in areas of recent overwash. Vegetation is dominated by the grass *Uniola paniculata* (sea oats), the ground cover plant *Hydrocotyle bonariensis* (penny wort), and *Gaillardia pulchella* (fire wheel). Occasionally *Juniper virginiana* (eastern red cedar) occurs in small damp areas between the dunes.

Vegetated Flat (veg_flat)

This unit (fig. 51) is dominated by shrub-scrub including *Ilex vomitoria* (Yaupon Holly), *Myrica pensylvanica* (bayberry), and *Juniper virginiana* (eastern red cedar). These are dense thickets that include vines such as *Toxicodendron radicans* (poison ivy) and *Vitis rotundifolia* (muscadine grape

Sparsely Vegetated Flat (sparse_veg_flat)

This unit is dominated by grasses including *Spartina patens* (salt meadow hay), *Uniola paniculata* (sea oats), as well as the ground cover plant *Hydrocotyle* *bonariensis* (penny wort), *Gaillardia pulchella* (fire wheel), and occasional patches of *Juncus roemerianus* (black needlerush), *Iva frutescens* (marsh elder), and *Baccharis halimifolia* (salt myrtle).

Isolated Dune (iso_dune)

This unit (fig. 51) occurs on the estuarine side and in the two wide sections in the eastern portion of the island. These dunes are situated within the Vegetated Flats unit and are generally surrounded by grassed areas that grade into very dense shrub-scrub. The sand dunes are irregularly shaped and rise up to 3.6 m (12 ft) high. The surface of the Isolated Dune may be covered by a shell lag.

Tidal Marsh (tidal_marsh)

This unit occurs on the eastern portion of Shackleford Banks. The salt marshes are connected to Back Sound by tidal channels that are fed by complex networks of smaller channels that sometimes connect to interior ponds. Tidal Marshes are regularly flooded by astronomical tides and display major vegetation zonations. Vegetation closest to Back Sound consists primarily of *Spartina alterniflora* (smooth cord grass) and *Salicornia* sp. (marsh glasswort) and grades upslope into the dominant *Juncus roemerianus* (black needlerush), then *Borrichia frutescens* (sea oxeye), and ultimately to shrub-scrub.

Inlet Tidal Mud Flat (inlet_tidal_mud_flat)

The Inlet Tidal Mud Flat unit (fig. 51) occurs adjacent to Barden Inlet. Tides flow through a complex of tidal channels from Barden Inlet and Back Sound. The Inlet Tidal Mud Flat consists of organic-rich, fine sandy mud with micro-algae and the ubiquitous mud snail *Ilyanassa obsoleta*, Slight topographic elevations throughout the mud flat form small vegetated hummocks that include *Spartina alterniflora* (smooth cord grass) and *Juncus roemerianus* (black needlerush). These are highly productive habitats that are filled with micro-organisms, infauna, epifauna, and epiflora.

Back Sound Units

Riggs et al. (2015) describe the following units occurring in Back Sound.

Sand Flat

The Sand Flat unit (fig. 53) is composed of back-barrier features that are inter-tidal to sub-tidal flats and range from 0 to -0.3 m (-1 ft) below MSL. Due to both astronomical and frequent wind tides, sand flats are frequently and irregularly exposed to sub-aerial conditions. The fine-grained sand provides rich habitats for burrowing infauna, abundant oysters (*Crassostrea virginica*), and mud snails (*Ilyanassa obsoleta*).

Sand Shoal

The shallow subaqueous Sand Shoals unit is part of the flood-tide delta deposits within Barden Inlet.

Sand Shoal Marsh

The Sand Shoal Marshes unit (fig. 51, 53) consists of flood-tide delta sand shoals that are sub-aerial and vegetated primarily with *Spartina alterniflora* (smooth cord grass).

Subtidal Vegetated Flat

The Subtidal Vegetated Flats unit (fig. 53) is extensive in Back Sound and is dominated by submerged aquatic vegetation (SAV) that occurs in protected areas and adjacent to shallow, but subtidal Organic Banks.

Organic Bank

This unit is shallow but subtidal.

Shell Bank

This unit is composed primarily of oyster and clam shells.

Anthropogenic Features (Polydemic) Units

Riggs et al. (2015) describe the following Anthropogenic Features (Polydemic) units on Shackleford Banks. Of these, only the Dredge Spoil unit appears on the GRI map.

Dredge Spoil (dredge_spoil)

This unit composes sub-aerial islands in Back Sound on the east end of Shackleford Banks. The islands were built with material from the maintenance dredging of Barden Inlet. They are often vegetated with grasses or shrub-scrub and contain major bird rookeries.

Historic Telephone Line

Remnants of telephone poles run along the entire length of the island and are located in the shallows of Back Sound and on the estuarine and ocean beaches. The poles were probably emplaced in the first half of the 20th century and are plotted on the old topographic maps.

Figure 53. A 2010 aerial photograph of central Shackleford Banks with the Atlantic Ocean in the lower left corner and Back Sound in the upper right portion. Figure A34 from Riggs et al. (2015).

Fenced Area

Fenced Areas were developed to exclude horses in order to observe grazing impacts on vegetation growth and composition. The study plots were built in various habitats on Shackleford Banks.

Pen Chute

Corrals, pens, chutes, and associated dock were built with fences to round up and manage the wild horse population on Shackleford Banks

Docks and Buildings

The park has several public toilets, equipment sheds, and docks.

Cemetery

Only one cemetery is known to be preserved on Shackleford Banks. It occurs on a Vegetated Ridge on the estuarine side of the west portion of the island. The gravestones date from 1881 to 1919. Other cemeteries have been buried by subsequent depositional processes, eroded by receding shorelines, or eliminated by storm impacts.

Remnant Sea Wall and Rock Jetty

A concrete and rock sea wall, and a series of rock jetties, were built on the western tip of Shackleford Banks and along the estuarine shoreline of Back Sound in the late

1800s to stop the eastward migration of Beaufort Inlet into the western portion of Shackleford Island. A 1,460 m (4,800 ft) long rock jetty was built in 1914 on the hook of Cape Lookout to stabilize Cape Lookout Bight for economic development. The northernmost rock jetty is still functional on the Back Sound shoreline; the others are no longer functional due to westward migration of the island.

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Additional References

This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are valid as of February 2017. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

- NPS Geologic Resources Division—*Energy and Minerals, Active Processes and Hazards, and Geologic Heritage*: http://go.nps.gov/geology/
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://go.nps.gov/gip
- NPS Views program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks): http://go.nps.gov/views

NPS Resource Management Guidance and Documents

- 1998 National Parks Omnibus Management Act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- Geologic monitoring manual: http://go.nps.gov/geomonitoring
- Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html
- NPS-75: Natural resource inventory and monitoring guideline: http://www.nature.nps.gov/nps75/nps75.pdf
- NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://www.nps.gov/dsc/technicalinfocenter.htm http://etic.nps.gov/

Climate Change Resources

- NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm
- US Global Change Research Program: http://globalchange.gov/home
- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Geological Surveys and Societies

- North Carolina Geological Survey: https://deq.nc.gov/about/divisions/energy-mineral-land-resources/north-carolina-geological-survey/
- US Geological Survey: http://www.usgs.gov/
- USGS Publications: http://pubs.er.usgs.gov/
- Geological Society of America: http://www.geosociety.org/
- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

- Geologic glossary (simplified definitions): http://geomaps.wr.usgs.gov/parks/misc/glossarya.html
- Geologic names lexicon (Geolex; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html
- Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")
- National geologic map database (NGMDB): http://ngmdb.usgs.gov/
- Publications warehouse (many publications available online): http://pubs.er.usgs.gov

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Cape Lookout National Seashore, held on 3-5 April 2000, or the follow-up report writing conference call, held on 16 June 2015. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: https://go.nps.gov/gripubs..

2000 Scoping Meeting Participants

Name	Affiliation	Position
Tim Connors	NPS Geologic Resources Division	Geologist
Stephen Culver	East Carolina University	Professor of Geology
Nikki Ernst	NPS Cape Hatteras National Seashore	Cartographic Technician
Kathleen Farrell	North Carolina Geological Survey	Senior Geologist
Steve Harrison	NPS Cape Hatteras National Seashore	Resource Management Chief
Bruce Heise	NPS Geologic Resources Division	Geologist
Bill Hoffman	North Carolina Geological Survey	Chief Scientist
Stanley Riggs	East Carolina University	Professor of Geology
Michael Rikard	NPS Cape Lookout National Seashore	Resource Management Chief
Rob Thieler	U.S Geological Survey	Research Geologist
Keith Watson	NPS Cape Hatteras National Seashore	Resource Management Specialist

2015 Conference Call Participants

Name	Affiliation	Position
Lisa Baron	NPS Southeast Coast I&M Network	Coastal Ecologist
Rebecca Beavers	NPS Geologic Resources Division	Coastal Geologist
Linda Bell	NPS Water Resources Division	Sea Level Specialist
Maria Caffrey	NPS Geologic Resources Division	NPS Partner
Janet Cakir	NPS Southeast Regional Office	Climate Change, Socioeconomics, and Adaptation Coordinator
Jeri DeYoung	Cape Lookout National Seashore	Resources Management Chief
Brian Gregory	NPS Southeast Coast I&M Network	Program Manager
Cat Hawkins-Hoffman	NPS Climate Change Response Program	National Climate Change Adaptation Coordinator
Pat Kenney	Cape Lookout National Seashore	Superintendent
Hal Pranger	NPS Geologic Resources Division	Geologic Systems Branch Chief
Courtney Schupp	NPS Geologic Resources Division	Coastal Geologist, GRI Report Author
Anna Toline	NPS Southeast Regional Office	Marine Scientist
Linda York	NPS Southeast Regional Office	Coastal Geologist

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of August 2016. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. Regulations in association with 2009 PRPA are being finalized (August 2017).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.
Rocks and Minerals	**NPS Organic Act, 16 USC § 1 et seq.** directs the NPS to conserve all resources in parks (including rock and mineral resources), unless otherwise authorized by law.	**36 CFR § 2.1** prohibits possessing, destroying, disturbing mineral resources… in park units. **Exception: 36 CFR § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, or Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: -only for park administrative uses; -after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; -after finding the use is park's most reasonable alternative based on environment and economics; -parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; -spoil areas must comply with Part 6 standards; and -NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC § 403** prohibits the construction of any obstruction on the waters of the United States not authorized by Congress or approved by the USACE. **Clean Water Act 33 USC § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US [including streams]). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also **D.O. 77-2**) **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also **D.O. 77-1**)	None applicable.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks, unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding. **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams. **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Soils	**Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC § 4201 et. seq**. requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. Part 610 governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. Part 611 governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to -prevent unnatural erosion, removal, and contamination; -conduct soil surveys; -minimize unavoidable excavation; and -develop/follow written prescriptions (instructions).

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Coastal Features and Processes	**NPS Organic Act, 16 USC § 1 et. seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). **Coastal Zone Management Act, 16 USC § 1451 et. seq.** requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone. **Executive Order 11644** (use of off-road vehicles on public lands) (1972) establishes policies to control and direct ORV use on public lands so as to protect land resources, promote safety of land users, and to minimize conflicts among land uses. **Executive Order 11989** (off-road vehicles on public lands) (1974) closes off-road areas to ORV use that will impact soil, vegetation, wildlife, wildlife habitat, or cultural or historic resources until adverse effects have been eliminated and measures have been implemented to prevent future recurrence. Also includes authority to close public lands to ORVs where their use is not specifically authorized. **North Carolina Coastal Area Management Act** program was federally approved in 1978 and is the state's CZMP under the CZMA. Localities are responsible for planning while the state establishes areas of environmental concern **Clean Water Act, 33 USC § 1342/Rivers and Harbors Act, 33 USC 403** require that dredge and fill actions comply with a Corps of Engineers Section 404 permit. **Executive Order 13158 (marine protected areas) (2000)** requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas. **Executive Order 13690** (Establishing a Federal Flood Risk Management Standard) (2014) incorporates the Federal Flood Risk Management Standard to ensure that agencies expand management from the current base flood level to a higher vertical elevation and corresponding horizontal floodplain to address current and future flood risk and ensure that projects funded by taxpayers last as long as intended	**36 CFR § 1.2(a)(3)** applies NPS regulations to activities occurring within waters subject to the jurisdiction of the US located within the boundaries of a unit, including navigable water and areas within their ordinary reach, below the mean high water mark (or OHW line) without regard to ownership of submerged lands, tidelands, or lowlands. **36 CFR § 5.7** requires NPS authorization prior to constructing a building or other structure (including boat docks) upon, across, over, through, or under any park area. **36 CFR §4.10** prohibits motor vehicle use except on park roads, in parking areas and on routes and areas designated for off-road motor vehicle use; and requires that designated ORV routes and areas be promulgated as special regulations, with designations complying with Executive Order 11644.	**Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.8.1** requires NPS to allow natural geologic processes to proceed unimpeded. NPS can intervene in these processes only when required by Congress, when necessary for saving human lives, or when there is no other feasible way to protect other natural resources/ park facilities/ historic properties. **Section 4.8.1.1** requires NPS to: -Allow natural processes to continue without interference, -Investigate alternatives for mitigating the effects of human alterations of natural processes and restoring natural conditions, -Study impacts of cultural resource protection proposals on natural resources, -Use the most effective and natural-looking erosion control methods available, and -Avoid putting new developments in areas subject to natural shoreline processes unless certain factors are present.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Climate Change	**Secretarial Order 3289** (Addressing the Impacts of Climate Change on America's Water, Land, and Other Natural and Cultural Resources) (2009) requires DOI bureaus and offices to incorporate climate change impacts into long-range planning; and establishes DOI regional climate change response centers and Landscape Conservation Cooperatives to better integrate science and management to address climate change and other landscape scale issues. **Executive Order 13693** (Planning for Federal Sustainability in the Next Decade) (2015) established to maintain Federal leadership in sustainability and greenhouse gas emission reductions.	**No specific regulations, although applicable NPS policy memos include the following:** **Policy Memo 12-02** (Applying National Park Service Management Policies in the Context of Climate Change) (2012) applies considerations of climate change to the impairment prohibition and to maintaining "natural conditions". **Policy Memo 14-02** (Climate Change and Stewardship of Cultural Resources) (2014) provides guidance and direction regarding the stewardship of cultural resources in relation to climate change. **Policy Memo 15-01** (Climate Change and Natural Hazards for Facilities) (2015) provides guidance on the design of facilities to incorporate impacts of climate change adaptation and natural hazards when making decisions in national parks.	**Section 4.1** requires NPS to investigate the possibility to restore natural ecosystem functioning that has been disrupted by past or ongoing human activities. This would include climate change, as put forth in the NPS Coastal Adaptation Strategies Handbook (Beavers et al. 2016). **DO-100 "Resource Stewardship for the 21st Century"** (2016) requires parks to incorporate the Precautionary Principle and adaptive management into resource stewardship, and affirms that park resources and values take precedence over park uses. **NPS Coastal Adaptation Strategies Handbook** (Beavers et al. 2016) provides strategies and decision-making frameworks to support adaptation of natural and cultural resources to climate change. **NPS Climate Change Response Strategy** (2010) describes goals and objectives to guide NPS actions under four integrated components: science, adaptation, mitigation, and communication. **DOI Manual Part 523, Chapter 1** establishes policy and provides guidance for addressing climate change impacts upon the Department's mission, programs, operations, and personnel. **Revisiting Leopold: Resource Stewardship in the National Parks** (2012) will guide US National Park natural and cultural resource management into a second century of continuous change, including climate change. **Climate Change Action Plan** (2012) articulates a set of high-priority no-regrets actions the NPS will undertake over the next few years **Green Parks Plan** (2013) is a long-term strategic plan for sustainable management of NPS operations.

NPS 623/139595, August 2017

National Park Service
U.S. Department of the Interior

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Plate 1. Map of Cape Lookout National Seashore with mile markers added. National Park Service map available (without mile markers) at: https://nps.gov/hfc/cfm/carto-detail.cfm?Alpha=CALO.

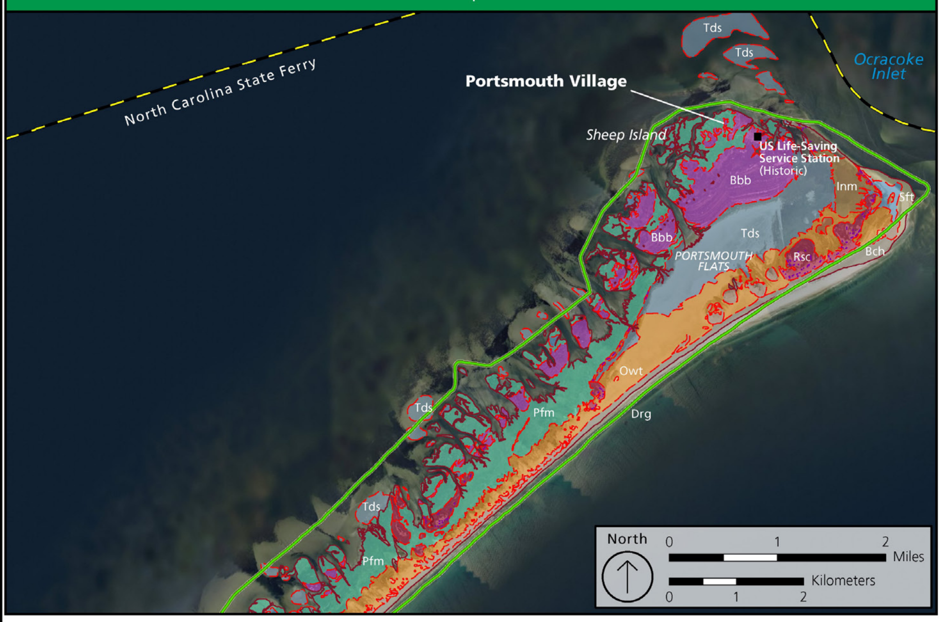
Geologic Map of Cape Lookout National Seashore

North Carolina

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

Map 1

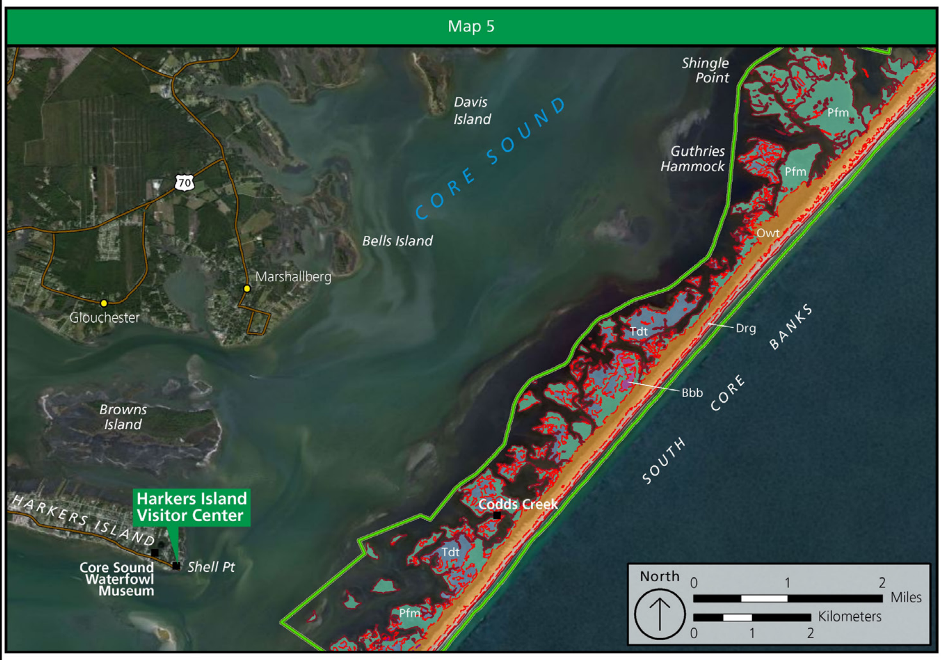


Map 2

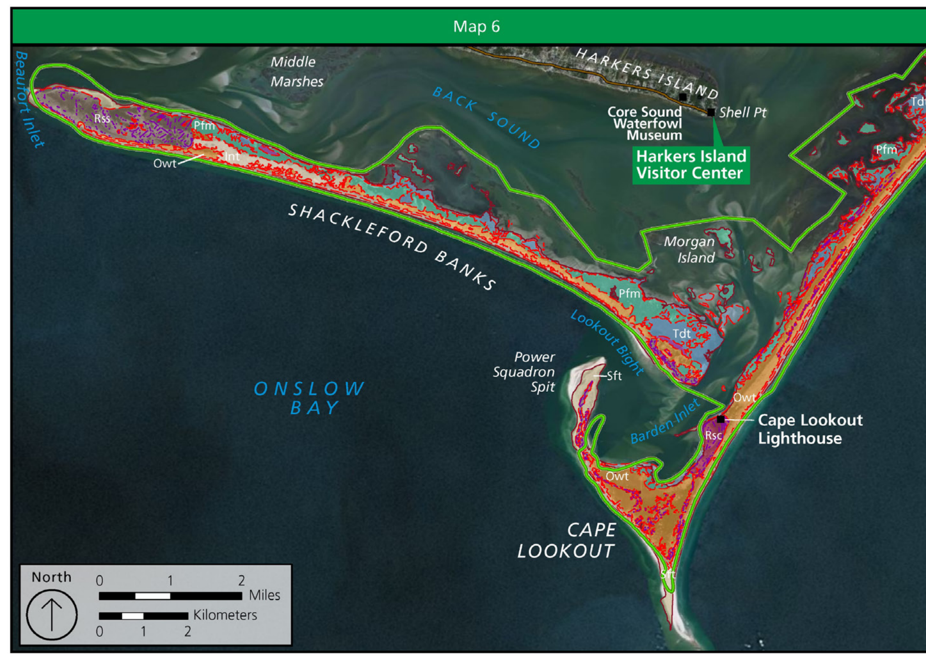
Map 3

Map 4

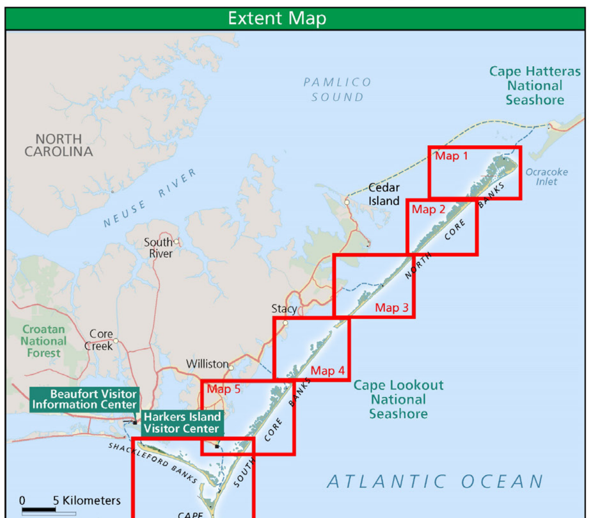
Map 5



Map 6



Extent Map



This map displays geologic map data compiled by the National Park Service Geologic Resources Inventory. It is not a substitute for site-specific investigations.

Source Map

The source maps used in the creation of this geologic data product include digital North Carolina Geological Survey publications (see references section for specific sources).

Source Scale

As per source map scale and U.S National Map Accuracy Standards, geologic features represented here are within 12 m (24 ft) (1:24,000 scale data) or 63m (203 ft) (1:125,000 scale data) of their true location.

Poster Layout

Dalton Meyer and Georgia Hybels (Colorado State University)

Poster Date

August 2017

GRI Data Date

June 2010

Source Map Date

2008

All Geologic Resources Inventory geologic map data and publications are available at http://go.nps.gov/gripubs.

NPS Boundary

Infrastructure

- Cities
- Points of Interest

Transportation

- Roads
- NC State Ferry

Geomorphic Contacts

- approximate
- map boundary
- water or shoreline

Geomorphic Ridge Lines

- ridge line, approximate

Geomorphic Units

Als	Airport/landing strip
Bch	Beach
Sft	Sand flat
Rss	Ridge and swale
Tdt	Tidal flat
Tds	Sand flat
Ilt	Inlet
Pfm	Marsh Platform
Pff	Marsh Platform, fringing berm
Drg	Dune ridge
Owt	Overwash flat
Own	Overwash fan
Isd	Isolated dune
Int	Interior dune
Inm	Interior marsh
Bbb	Back barrier berm
Rbr	Relict beach ridge complex
Rsc	Relict spit complex

These unit symbols are only used on this poster. Refer to the Geologic Map Data section for unit descriptions and data symbols.

National Park Service Photograph. Paul Terry

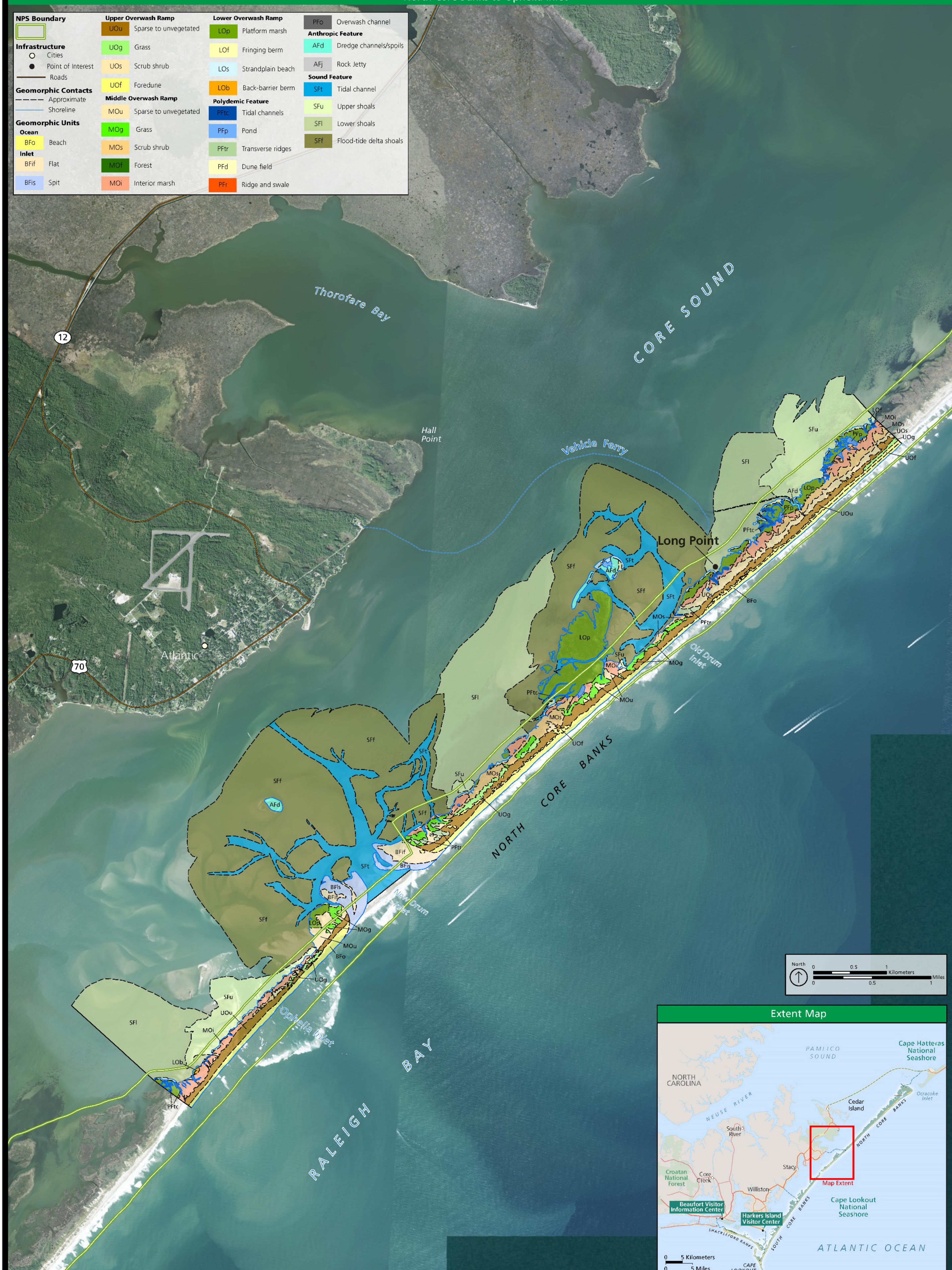
Geomorphic Map of Cape Lookout National Seashore

East Carolina University

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

North Core Banks to Ophelia Inlet



This map displays geologic map data compiled by the National Park Service Geologic Resources Inventory. It is not a substitute for site-specific investigations.

Source Map
Ames, D.V and S.R. Riggs. 2008. Geomorphic Framework of the North Carolina Outer Banks (scale 1:10000). Digital data. East Carolina University.

Source Scale 1:10,000
According to US National Map accuracy standards, features are within 5 m (16 ft) of their true location.

Poster Layout
Dalton Meyer and Georgia Hybels (Colorado State University)

Poster Date
August 2017

GRI Data Date
August 2009

Source Map Date
2008

All Geologic Resources Inventory geologic map data and publications are available at http://go.nps.gov/gripubs

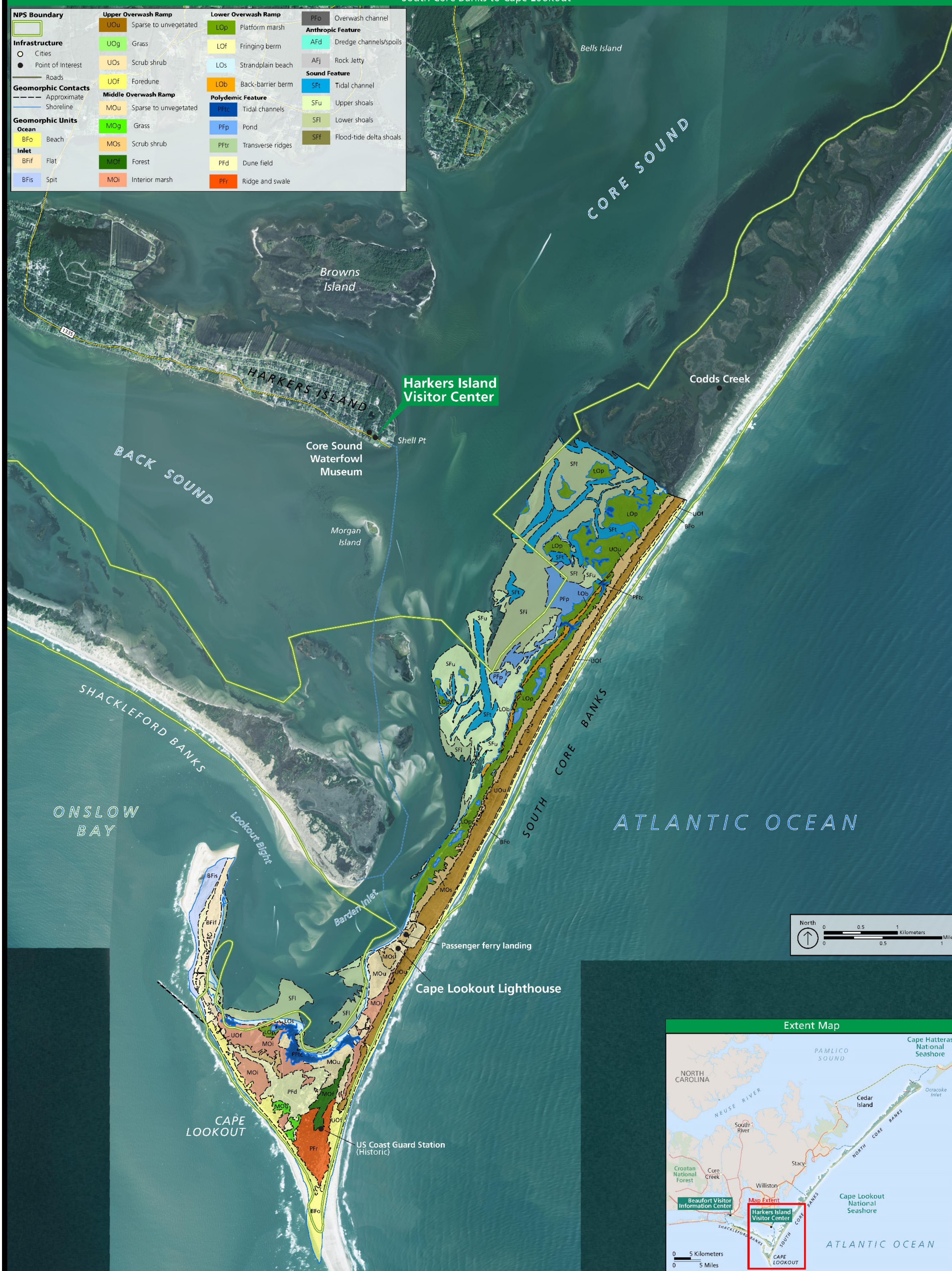
Geomorphic Map of Cape Lookout National Seashore

East Carolina University

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

South Core Banks to Cape Lookout



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Source Map
Ames, D.V and S.R. Riggs. 2008. Geomorphic Framework of the North Carolina Outer Banks (scale 1:10,000). Digital data. East Carolina University.

Source Scale 1:10,000
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Poster Date
August 2017
GRI Data Date
August 2009
Source Map Date
2008

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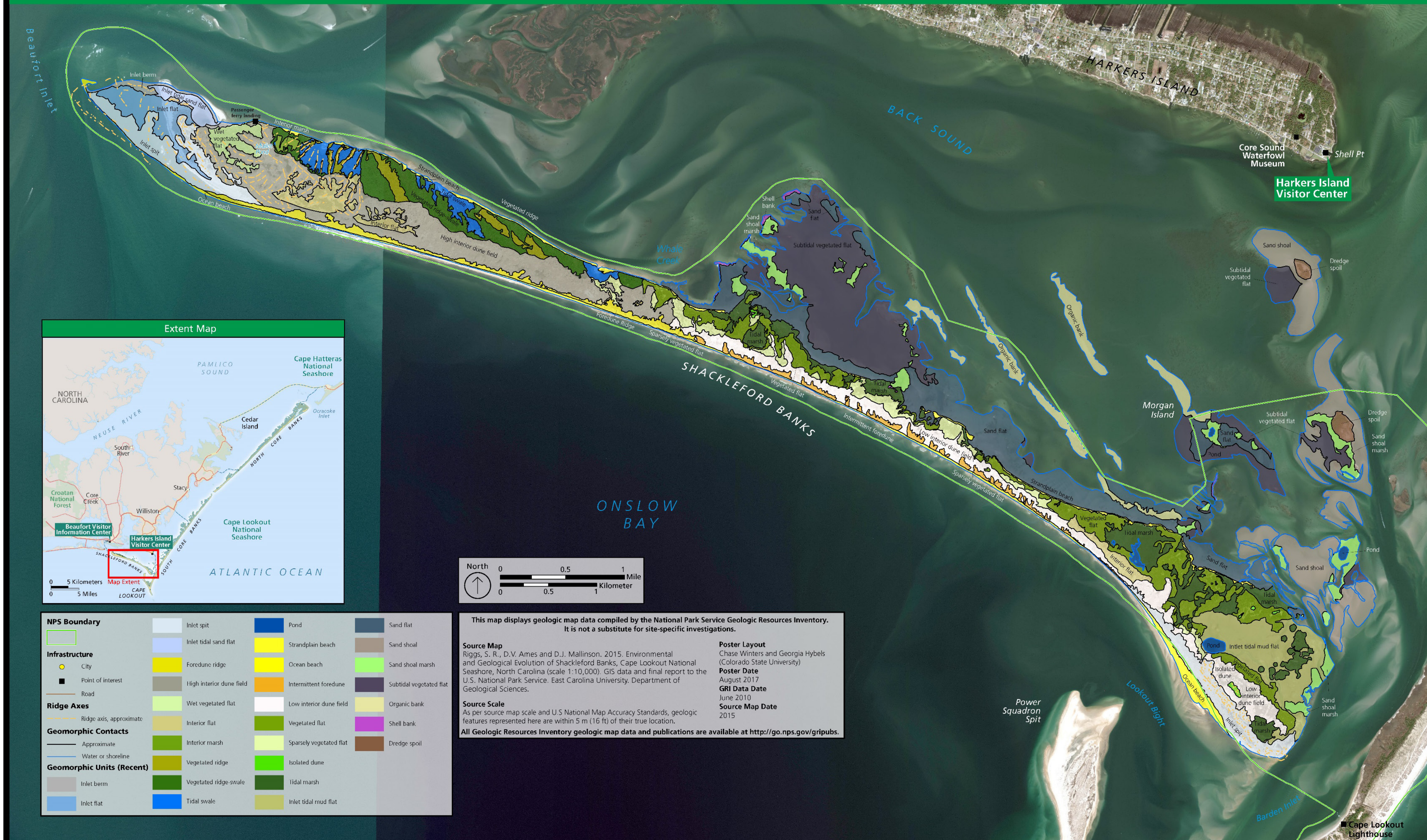
Geomorphic Map of Cape Lookout National Seashore

North Carolina

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

Shackleford Banks



This map displays geologic map data compiled by the National Park Service Geologic Resources Inventory. It is not a substitute for site-specific investigations.

Source Map
Riggs, S. R., D.V. Ames and D.J. Mallinson. 2015. Environmental and Geological Evolution of Shackleford Banks, Cape Lookout National Seashore, North Carolina (scale 1:10,000). GIS data and final report to the U.S. National Park Service. East Carolina University. Department of Geological Sciences.

Source Scale
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Poster Layout
Chase Winters and Georgia Hybels (Colorado State University)

Poster Date
August 2017

GRI Data Date
June 2010

Source Map Date
2015

All Geologic Resources Inventory geologic map data and publications are available at http://go.nps.gov/gripubs.