National Park Service
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Natural Resource Stewardship and Science

Cape Hatteras National Seashore

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2015/964

ON THE COVER
Sea oats are a vital component to dune formation at Cape Hatteras National Seashore.
National Park Service photograph.

THIS PAGE
The sun rises over Cape Point at Cape Hatteras National Seashore.
National Park Service photograph.

Cape Hatteras National Seashore

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2015/964

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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) 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 for Cape Hatteras National Seashore (North Carolina) held on 3–5 April 2000 and convened by the Geologic Resources Division to determine geologic resources, the status of geologic mapping, and geologic resource management issues and needs. It is a companion document to previously completed GRI digital geologic map data.

Cape Hatteras National Seashore is part of the North Carolina Outer Banks, a barrier island chain within the Atlantic Coastal Plain physiographic province. It was established to preserve the wild and primitive character of the dynamic barrier islands, to protect diverse plant and animal communities, and to provide for recreation that is compatible with its natural and cultural resources.

Most of the barrier islands are long and narrow, separated from the mainland by wide, shallow sounds. The islands provide diverse barrier island habitats that are controlled and sustained by natural coastal geomorphological processes and human modifications. These habitats support native mammals, reptiles, amphibians, many types of marine invertebrate, and several species listed federally as threatened or endangered. The park provides important avian breeding, migratory, and wintering habitats. The rich and productive estuary includes large areas of marshland and submerged aquatic vegetation, and the inland forests protect freshwater aquifer recharge areas.

The Outer Banks of North Carolina are intimately associated with several key periods of US history. American Indians were the first inhabitants and Europeans arrived in 1584. In the early 1800s, lighthouses and US Lifesaving Service stations were established to support increased maritime traffic. In 1903, the Wright brothers made their first powered flights in Kitty Hawk. Increased road access to the islands during the 20th century led to the growth of residential and tourist populations on the Outer Banks.

The Outer Banks are geologically young. The geologic framework of Cape Hatteras was constructed by the cyclic rise and fall of 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. During multiple glacial episodes (ice ages) beginning 2.6 million years ago, sea level rose and fell many times, and rivers incised the previously deposited marine strata, leaving a paleotopography that controls the estuarine geometry and bathymetry and the location of the barrier islands. These paleoriver 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 of marine, coastal, estuarine, riverine, and other Coastal Plain deposits, ranging from compact peat and mud to unconsolidated to semi-consolidated sands, gravels, and shell beds.

Modern coastal processes (storms, waves, tides, sediment transport, inlet dynamics, and sea-level change) shape the landforms and rework the thick Quaternary sediments. Due to the reworking of these older sediments, much of the present Outer Banks is less than 3,000 years old, and some island segments are less than 500 years old. Storms, waves, and winds continue to shape the islands, along with anthropogenic activities such as dune construction, nearshore dredging, inlet and shoreline stabilization, and beach renourishment.

This report is supported by two digital maps of the surficial geology of Cape Hatteras National Seashore, each with unique sets of geomorphic units. The map developed by Ames and Riggs (2006a–j) and described by Riggs and Ames (2006) is based on a model of barrier island evolution developed from time-slice, process-response studies of sequential aerial photography, in concert with detailed field surveys. It describes four geomorphic groups: beach, overwash-plain, polydemic, and anthropogenic features. The map developed by Hoffman et al. (2007a–g) shows the classification of surficial features based on remotely sensed data. It describes four geomorphic groups: intertidal, supratidal, relict, and anthropogenic.

This GRI report was written for resource managers to support science-informed decision making. It may also be useful for interpretation. The report was prepared using available geologic information, and the NPS Geologic Resources Division conducted no new fieldwork in association with its preparation. Chapters of the report discuss distinctive geologic and environmental features and processes within Cape Hatteras National Seashore, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the GRI geologic map data. Posters (in pocket) illustrate these data. The Map Unit Properties Tables (in pocket) summarize report content for each map unit on the two maps.

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

- Oceanographic Conditions. The Outer Banks is a storm- and wave-dominated barrier island system with low tidal ranges.
- Sediment Transport Processes. Waves, wind, and storm surge move sediment through the inlets and along and across the islands. The longshore transport rate is very high. The framework geology controls sediment availability and type. New sediment comes from the eroding shoreface, updrift beaches, cape-associated shoals, and inlet deltas.
- Capes and Cape-Associated Shoals. Cape Hatteras and Diamond Shoals separate two major ocean currents and biological regimes. The cold-water Labrador Current flows southward to meet the warm-water Gulf Stream, which flows northward. Their interaction and the resulting oceanographic and atmospheric responses are controlled by the geography of the continental margin, Cape Hatteras and Diamond Shoals, and the underlying geology.
- Inlets. New inlets open during storms, when storm surge breaches the island from the ocean or estuarine side. Tidal currents deposit sediment, building flood and ebb tidal deltas, which are important for the island sediment budget, marsh building, and long-term island evolution. Inlets are dynamic and essential components of barrier islands and associated riverine and estuarine systems. Only three modern inlets are currently present, but up to 30 inlets have opened and closed along the Outer Banks in the last 400 years.
- Estuaries. Pamlico and Roanoke sounds provide fish nursery and foraging habitats, and support several seagrass species. Water quality is good in most areas, but is impacted by septic leachate and other riverine pollutant input. Estuarine sediments are derived from shoreline erosion, continental shelf, and ongoing biogenic production.
- Freshwater Aquifer. The shallow groundwater is recharged through rainfall, and is depleted through anthropogenic withdrawal, evapotranspiration through surface vegetation, and surface drainage from uplands. It can also be affected by impoundments and drought. These influences can, in turn, alter hydrologic processes, wetland function, and vegetation community distribution, composition, diversity, and structure.
- Barrier Island Evolution and Behavior. The modern coastal geomorphology results from interaction among the underlying geologic framework, fluctuating rates of relative sea-level change, coastal oceanographic processes, and anthropogenic modifications.
- Simple and Complex Barrier Island Model. The majority of islands at Cape Hatteras National Seashore are simple barrier islands, which are young, sediment poor, and narrow with low topography. They are particularly vulnerable to sea-level rise and anthropogenic modifications. Complex barriers are older, sediment rich, and wide with high elevations, numerous beach ridges, and large dune fields.
- Geologic Influences on Island Habitats. Barrier island habitats are controlled by elevation above mean sea level, cross-island location relative to the ocean beach, and the tidal and salinity characteristics of the adjacent ocean, estuarine waters, and shallow groundwater.
- Barrier Island System Units (Field Survey Map). This map, one of two maps supporting this GRI, relies on a model of barrier island evolution developed from time-slice, process-response studies based on aerial photography in concert with modern field surveys of Riggs and Ames (2006).
- Barrier Island System Units (Remote Sensing Map). This map, one of two maps supporting this GRI, relies on remotely sensed data and incorporates the field-survey map findings of Hoffman et al. (2007g).
- Paleontological Resources. Quaternary-age fossil marine invertebrates, marsh peat, and trees are abundant on the beaches of Cape Hatteras National Seashore. They are derived from the adjacent continental shelf and erosion of older beach and inlet sediments that constitute the shoreface seaward of the beach. Their ages vary from a few centuries to tens and hundreds of thousands of years old.

Geologic issues of particular significance for resource management at Cape Hatteras National Seashore were identified during a 2000 GRI scoping meeting and follow-up discussions. They include the following:

- Shoreline Erosion. Erosion of the ocean and estuarine shorelines threatens infrastructure and cultural resources. Natural overwash and inlet processes, if allowed to occur, would supply new sediment to the island interior and to the estuarine shoreline and shallow back-barrier shoals, which would in turn support development of marsh and seagrass habitat.
- Coastal Vulnerability and Sea-Level Rise. Global sea level is rising. Portions of the park are highly vulnerable due to their low topography and the high rate of relative (local) sea-level rise, which increase the rate of shoreline erosion and the potential for overwash, inlet formation, and wetland location 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 geomorphic stability of the barrier islands to reach a tipping point, resulting in increased landward migration and breaching, reduction in size, and possibly even submergence.
- 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. Storms erode protective dunes and damage Highway 12 through overwash, undermining, and inlet formation. In recent years, these impacts have been addressed by

immediate inlet infilling, dune restoration, and the relocation of overwash deposits back toward the ocean. These practices prevent natural increases in island elevation and width, as well as their landward migration as sea level rises.

- Inlet Modifications. The major inlets through the Outer Banks are actively maintained through dredging and stabilization to maintain navigability. However, new inlets are often closed artificially to protect infrastructure. Anthropogenic modifications of an inlet, such as dredging and coastal engineering structures, disrupt its ability to expand and shrink in response to storms, to bypass sediment between islands, to exchange sediment between flood and ebb tidal deltas, and to migrate laterally.
- Recreational and Watershed Land Use. Natural landscape and coastal processes have been disturbed by coastal settlement and development, dune construction and stabilization, off-road vehicle use, stormwater runoff, and nutrient inputs at the local and watershed levels.
- 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. Relocation and site selection are longer-term alternatives to protect infrastructure from erosion.
- Highway 12 Transportation Corridor. Highway 12, including Bonner Bridge over Oregon Inlet, provides the only road access to the park and adjacent island communities, but it is very vulnerable to shoreline erosion and storm overwash and has been damaged repeatedly in the last 50 years. Plans to replace the bridge and vulnerable portions of the highway are controversial. Longer-term development considerations would include new landward bridge routes or alternate transportation systems, such as ferries.
- Geomorphic Mapping. An understanding of geomorphic processes and landform evolution is critical to park manager's ability to prepare for the island's response to coastal processes and its evolution throughout the coming decades.
- Paleontological Resource Inventory, Monitoring, and Protection. A paleontological resource summary was produced for the park in 2009. 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, including terrestrial and aquatic habitat maps, septic system surveys, and assessment of estuarine benthic health. A resource stewardship strategy has been identified as a future management need.

Products and Acknowledgments

The NPS Geologic Resources Division partners with institutions such as Colorado State University, the US Geological Survey, state geological surveys, local museums, and universities to develop GRI products. This chapter describes those products and acknowledges contributors to this report.

GRI Products

The objective of the Geologic Resources Inventory is to provide 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. To realize this objective, the GRI team undertakes three tasks for each natural resource park: (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 digital geologic map 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 compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (section 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://www.nature.nps.gov/geology/inventory/. The current status and projected completion dates of products are available at: http://www.nature.nps.gov/geology/GRI_DB/Scoping/Quick_Status.aspx.

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Geologic Setting and Significance

This chapter describes the regional geologic setting of Cape Hatteras National Seashore and summarizes connections among geologic resources, other park resources, and park stories.

Park Setting

The Geologic Resource Inventory (GRI) maps created for the present report include three sites (plate 1) managed as part of the National Park Service (NPS) Outer Banks Group and located on the North Carolina Outer Banks and the Atlantic coast of North America (fig. 1). Wright Brothers National Memorial was originally designated on 2 March 1927 as Kill Devil Hill Monument National Memorial; it was transferred to the NPS from the War Department on 10 August 1933 and re-designated as Wright Brothers National Memorial on 1 December 1953 (NPS 2005). The park, which commemorates the first successful controlled power flight at the site where it occurred in 1903, is located in Kill Devil Hills, North Carolina, and comprises 173 ha (428 ac; plate 1) (NPS 2005). Fort Raleigh National Historic Site is located on 207 ha (513 ac) at the northern end of Roanoke Island, which is situated between Bodie Island and mainland North Carolina (plate 1). The park, authorized on 5 April 1941, preserves and interprets the first English colony in North America and the history of the many peoples who lived on Roanoke Island.

The present GRI report focuses on the third site, Cape Hatteras National Seashore, which was authorized on 17 August 1937 (Public Law 50 Stat. 669, as amended in 1940 by Public Law 54 Stat. 702). After several land acquisitions, its boundaries were established on 12 January 1953, making it the first designated national seashore. Its stated purpose is to permanently preserve the wild and primitive character of the ever-changing barrier islands, protect the diverse plant and animal communities sustained by coastal island processes, and provide for recreational use and enjoyment that are compatible with the preservation of the distinctive natural and cultural resources of the nation's first national seashore (NPS 2011).

Cape Hatteras National Seashore is a long and narrow park that comprises multiple barrier islands (fig. 1; plate 1). It includes 108 km (67 mi) of beach along the Dare and Hyde county coastlines, and composes a portion (14,326 ha [35,400 ac]) of the island chain known as the North Carolina Outer Banks. The national seashore includes portions of Bodie, Hatteras, and Ocracoke islands and is bounded by Ocracoke Inlet to the south, Whalebone Junction to the north, the Atlantic Ocean to the east, and Pamlico Sound to the west. Pamlico Sound is connected to Albemarle Sound by Roanoke and Croatan sounds, which bound Roanoke Island at Fort Raleigh National Historic Site (fig. 1). The boundary of Cape Hatteras National Seashore is the mean low tide line on the ocean side, and it extends 46 m (150 ft) from the shore into Pamlico Sound on the estuarine side (Mallin et al. 2006).

Figure 1. Regional map showing the location of Cape Hatteras National Seashore. The black box indicates the extent of plate 1 (in pocket), a detailed map of Cape Hatteras National Seashore (red area). Map by Trista Thornberry-Ehrlich (Colorado State University) with basemap by Tom Patterson (National Park Service), available at: http://www.shadedrelief.com/physical/index.html (accessed 26 March 2014).

The coastal plain of northeastern North Carolina has very low topography (less than 0.06 m elevation per horizontal kilometer [0.3 ft/mi]) (Corbett et al. 2008) and an average seaward gradient of approximately 0.01°, or 0.10 m per horizontal kilometer (5.3 ft/mi) (Mallinson et al. 2010a). As a result, shoreline recession related to sea-level rise has removed 130 km^2 (50 mi^2) of marsh and

Figure 2. Bathymetry (in meters) and dimensions of the Albemarle-Pamlico Estuarine System. Map by Trista Thornberry-Ehrlich (Colorado State University) after figure 1 in Wells and Kim (1989).

estuarine shoreline in northeastern North Carolina in the past 25 years (Riggs and Ames 2003). Seaward of the Outer Banks barrier islands, the base of the modern shoreface occurs at a depth of approximately 15 to 20 m (49 to 66 ft) below present sea level (Mallinson et al. 2010a). The shelf break occurs at a depth of approximately 50 m (164 ft) about 20 km (12 mi) east of Cape Hatteras (Mallinson et al. 2010a); the slope of the ocean floor deepens rapidly from this point to about 50 to 100 km (31 to 62 mi) offshore (Mallin et al. 2006).

Most islands in the park are less than 400 m (0.25 mi) wide (Pendleton et al. 2004), but widths vary from about 180 m (590 ft) near Hatteras Village to nearly 5 km (3.1 mi) at Cape Hatteras. Dune crests along Cape Hatteras National Seashore can reach elevations of 10 m (33 ft), whereas dune toe and winter storm berm elevations are fairly constant at about 3 m (10 ft) (Elko et al. 2002). Isolated points within inland dune fields reach heights of approximately 18 m (60 ft) above sea level (Harris and Wilder 1964). Westward, beyond the dune ridges, sand flats as wide as 300 m (1,000 ft) slope gently down to the sounds. The flats are generally less than 3 m (10 ft) above sea level. Immediately adjacent to the sounds, along the western shores of most of the barrier islands, are salt marshes and some isolated, irregular sand ridges. Migrating inlets separate the barrier islands and are subject to considerable change during major storms, when new inlets may form or old ones may close (Winner 1975).

The islands provide diverse barrier island habitats that support native mammals, reptiles, amphibians, and many types of marine invertebrate. Cape Hatteras National Seashore habitats also support several species listed federally as threatened or endangered: seabeach amaranth (*Amaranthus pumilus*), piping plover (*Charadrius melodus*), and loggerhead (*Caretta caretta*), green (*Chelonia mydas*), and leatherback (*Dermochelys coriacea*) sea turtles (NPS 2010). The American Bird Conservancy has designated the park as a Globally Important Bird Area because it contains important avian breeding, migratory, and wintering habitats (NPS 2012). It supports 360 documented bird species that use the islands' habitats for nesting, resting, or feeding (NPS 2011). These populations include species listed by the North Carolina Wildlife Resources Commission (NCWRC) as of special concern, such as colonial waterbirds (least tern [*Sterna antillarum*], common tern [*Sterna hirundo*], and black skimmer [*Rynchops niger*]), American oystercatcher (*Haematopus palliatus)*, and Wilson's plover (*Charadrius wilsonia*), and the gull-billed tern (*Sterna nilotica*), which is listed by the NCWRC as threatened (NPS 2010).

The Albemarle-Pamlico Estuarine System (fig. 2) is the second largest estuary in the United States, containing extensive marshes that support a rich and productive ecosystem (Corbett et al. 2008). Pamlico Sound is up to 45 km (28 mi) wide (Corbett et al. 2008). Croatan Sound, which connects the Roanoke/Albemarle drainage system to Pamlico Sound and the Atlantic Ocean, ranges in width from 4.2 km to 8 km (2.6 to 5 mi) and has an average depth of 5 m (16 ft), with depths of up to 7.5 m (25 ft) in the northwest–southeast-trending channel (Riggs et al. 1992; Parham et al. 2007).

Ocracoke, Oregon, and Hatteras inlets affect physical, hydrologic, and geomorphic processes within the park. Ocracoke Island has significant fresh and brackish water resources, including a vast brackish marsh near South Point Road, a freshwater marsh near the northern end of the island in the vicinity of the ferry terminal, and temporary ponds. Tidal creeks (fig. 3A, 3B) are present on Ocracoke, Hatteras, and Bodie islands (Mallin et al. 2006).

Wider and higher portions of the islands support maritime forests, such as Buxton Woods on Hatteras Island and near Ocracoke Village on Ocracoke Island. Approximately one-third of the 405-ha (1,000-ac) Buxton Woods is within park boundaries (NPS 2012). Buxton Woods contains many freshwater swales, or sedges, that serve as important wildlife habitat (fig. 3C) (Mallin et al. 2006). The mature broad-leaved evergreen forest and shrub (fig. 3D), freshwater marsh, and bog habitats of Buxton Woods support a diverse assemblage of aquatic, terrestrial, and avian species. Buxton Woods also overlies, protects, and provides for recharge of an important freshwater aquifer (NPS 2012). Small maritime forest is also found in the Bodie Island and Whalebone Junction areas.

The Outer Banks of North Carolina are intimately associated with several key periods of US history. Native Americans were the first inhabitants. Early European settlers tried to establish a colonial base on the northern end of Roanoke Island in 1584, a settlement now known as the Lost Colony; the next significant European settlement developed in 1663 on Colington Island (Dolan and Lins 1986). As settlement increased, inlets became vital transportation routes for maritime traffic, which struggled through rough surf and shoals to reach the North Carolina coast; the many shipwrecks inspired the coast's nickname, "the graveyard of the Atlantic." To aid coastal navigation, historic lighthouses were built in 1823 and 1870, and the US Lifesaving Service (forerunner to the US Coast Guard) set up a series of lifesaving stations on the Outer Banks (Stover 2008). In 1903, the Wright brothers made their first powered flights on the sandy flats of Kitty Hawk. Increased road access to the islands led to the growth of residential and tourist populations in the Outer Banks. Cape Hatteras National Seashore received nearly 2.2 million visitors in 2014 (National Park Service 2015).

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) (fig. 4) initiated the formation and opening of the Atlantic Ocean. As rifting progressed, extensive marine, coastal, and riverine deposits infilled the western edge of the Atlantic Basin. A wedge-shaped deposit of sediments formed, thickening in a seaward direction and attaining a maximum

Figure 3. Water resources and habitat. A,B) Ocracoke, Hatteras, and Bodie islands have significant fresh and brackish water resources, including tidal creeks, marshes, and temporary ponds. C) Buxton Woods contains many wetlands and freshwater swales, or sedges, that serve as important wildlife habitat. D) Buxton Woods is a mature broad-leaved evergreen forest and shrub habitat. Photographs by Matthew McIver (A) and Michael Mallin (B, C, D) (University of North Carolina Wilmington) extracted from Mallin et al. (2006), plates 2, 4, 8, 9.

thickness of about 3,000 m (9,800 ft) at Cape Hatteras (Lawrence and Hoffman 1993); the sediment includes deposits of Cretaceous through Quaternary age (Brown et al. 1972).

The geologic framework of Cape Hatteras was constructed by the cyclic rise and fall of relative sea level (Colquhoun 1969; Richards et al. 1971). This framework controls the sediments available to the modern barrier island, and the ways in which the island responds to natural and anthropogenic processes. Island size and shape are largely dependent on sediment supply (Riggs and Ames 2006). Some of these earlier sediments have been reworked so recently that portions of the Outer Banks are less than 500 years old, and the oldest barrier island beach ridges on the Outer Banks date to about 3,000 years before present (Mallinson et al. 2007; Riggs et al. 2011).

The surface of the Atlantic Coastal Plain is predominantly characterized by a series of well-developed paleoshorelines and terraces that step down in elevation and decrease in age toward the Atlantic coast (fig. 5) (Wells and Kim 1989; Farrell et al. 2003; Tweet et al. 2009). Seven river basins dissect the coastal plain, so that its low-relief, flat, eastward-dipping coastwise terraces are separated by incised valleys with terraced borders (Colquhoun 1966). The Suffolk paleoshoreline has regional extent and is one of the youngest Pleistocene shorelines preserved on the North Carolina Coastal Plain.

Between the Cape Lookout High to the south and the Norfolk Arch to the north, thick Quaternary deposits fill a regional depositional basin called the Albemarle Embayment (Ward and Strickland 1985; Riggs et al. 1995, 2011; Foyle and Oertel 1997). This embayment is dissected by Pleistocene river valleys, which incised the underlying Pliocene erosion surface and subsequently filled with younger coastal and shelf sediments (Riggs et al. 1995). Croatan and Roanoke sounds are drowned lateral tributary creeks that flowed northward into the paleo–Roanoke River (now Albemarle Sound) (Riggs et al. 1992). Roanoke Island is a remnant of the interstream divide that separated the Roanoke River and Pamlico Creek drainages (Parham et al. 2007).

Sea-level cycles and the paleodrainage system deposited a complex assemblage of marine, coastal, estuarine, fluvial, and other Coastal Plain deposits (fig. 6) (Mallinson et al. 2008a). Relict Pleistocene inlets, which were infilled when sea level rose, may constitute up to 75% of Hatteras and Pea Islands (Mallinson et al. 2009). Relict flood-tidal delta deposits, which now underlie the narrowest portions of the islands, are generally overlain by marsh peat and storm overwash sediments; relict channel-fill sediments occur under the widest portions of the island (Mallinson et al. 2009).

Years before present	Cape Hatteras events
600–100	Little Ice Age; as many as 20 inlets open along Outer Banks due to nor'easter storms
1,100	Medieval Warm Period; large portions of Outer Banks collapse due to hurricanes
3,500	Nearly continuous barrier island system forms
5,000	Initial barrier islands form
21,000	Last Glacial Maximum; 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	Last interglacial warm period; most of Earth's glaciers melted; sea level approximately 6–8 m (20–26 ft) higher than present

Eon	Era	Period		Epoch	MYA	North Carolina events
Phanerozoic	Cenozoic	Quaternary		Holocene	0.01	Fluvial processes, erosion of Piedmont and Appalachian Mountains, sediment deposition in Coastal Plain
				Pleistocene	2.6	
		Tertiary	Neogene	Pliocene	5.3	
				Miocene	23.0	
			Paleogene	Oligocene	33.9	Limestone deposited in Coastal Plain, erosion, and weathering continue
				Eocene	56.0	
				Paleocene	66.0	
	Mesozoic	Cretaceous			145.0	Ongoing erosion and weathering in Piedmont and Appalachian Mountains, Cape Fear Arch begins to develop
		Jurassic			201.3	Rift basins form; brittle faulting and volcanism
		Triassic			252.2	Breakup of Pangaea begins; Atlantic Ocean opens

Figure 4. Geologic time scale. 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. Bold lines indicate major boundaries between eras. Graphic by Trista Thornberry-Ehrlich (Colorado State University), using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 27 April 2015).

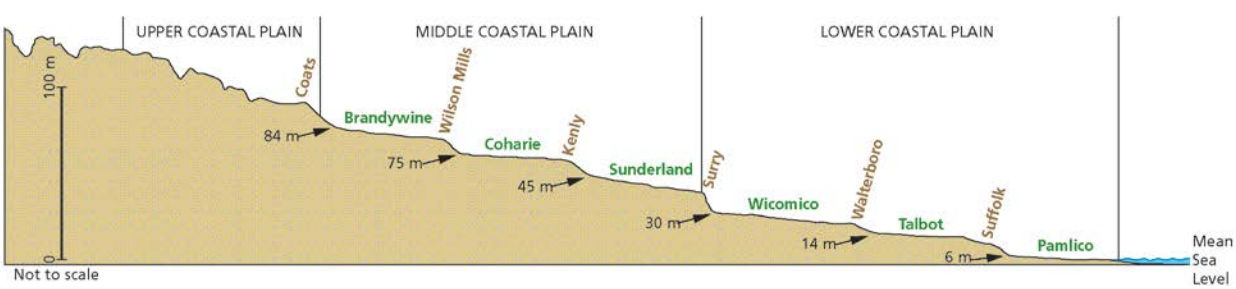

Figure 5. Cross-sectional topographic view of the marine terraces (green text) and paleoshorelines (brown text) of the North Carolina Coastal Plain. Graphic by Trista Thornberry-Ehrlich, modified after figure 3 in Daniels et al. (1984).

Era	Period	Epoch	Age*	Rock/Sediment Unit	Description
Cenozoic	Quaternary	Holocene	0.01–present	Barrier island facies (to 6 m below MSL**)	Fine to medium quartz sand with some gravel; peats associated with modern marshes and swamp forests.
				Estuarine bay facies (6 to 12 m below MSL)	Old fluvial (river) channels filled with coarse fluvial sand and gravel, overlain by thick accumulations of organic-rich, estuarine mud.
		Pleistocene	0.078–0.038	Barrier island sand facies (12 to 16 m below MSL).	Clean barrier-island sand, sandy open shelf, bay, inlet, and possibly fluvial-channel deposits. Outcrops on the lower portion of the lower foreshore and across the modern sea floor, and forms part of major bathymetrically high features known as the Albemarle and Platt shoals
				Estuarine bay facies (16 to 20 m below MSL).	Fossiliferous estuarine mud with oyster shells and other estuarine fauna. Outcrops on the lower portion of the lower foreshore and across the modern sea floor. Part of major bathymetrically high features known as the Albemarle and Platt shoals.
			0.18–0.08	Nearshore marine facies, underlain by marine deposits, underlain by marine erosion (ravinement) surface (21 to 35 m below present MSL).	Represents period of interglacial sea-level rise and transgression. Muddy quartz sand with mollusks and a major soil profile along the upper surface. Eroded and modified by overlying sediment sequence.
			0.55–0.22	Inner shelf facies (sand and shell), underlain by estuarine bay facies (silt and clay) (35 m to more than 50 m below present MSL).	Older sequences are separated by surfaces created during periods when no sediment was deposited, or sediment was deposited but later removed through erosion.
			0.8-0.55	Muddy, low-oxygen shelf deposits (40-43 m below present MSL)	Pleistocene interglacial
				Marine deposits (43-47 m below present MSL)	Pleistocene glacial
			1.2 – 0.8	Sandy open shelf, bay, and inlet deposits (47 – 55 m below present MSL)	Sequence boundary at about 55 m below present MSL
	Tertiary – Neogene	Pliocene	5.3–2.6	Yorktown Formation (or lateral equivalent) (more than 55 m below present MSL)	Muddy, fine-grained marine sediments deposited in reduced-oxygen, open-shelf conditions at midshelf depths. Paleotopography may control modern bathymetric features. Southward-thickening, steeply inclined, southward-prograding beds.
		Miocene	23–5.3	none	Inner to middle neritic (shallow marine) sand and silty clay beds. Parallel bedding with gently dipping beds.

Age is in millions of years before present 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.***

Figure 6. General stratigraphic column for Cape Hatteras National Seashore. The column is based on interpretations by Riggs et al. (1992), Parham et al. (2007), and Culver et al. (2008b) of multiple sediment cores obtained along the barrier island from Nags Head to Oregon Inlet, North Carolina. Colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps.

The modern barrier island system of North Carolina consists of a thin veneer of modern sands that covers marsh peats, tidal-flat muds, fluvial sands and gravels, bay-fill sands and muds, flood-tidal delta sands, and inlet-fill sands and gravels (Riggs et al. 1995). Coastal processes (storms, waves, tides, sediment transport, inlet dynamics, and sea-level rise) continue to shape the landform and rework the thick Pliocene and Quaternary sediments. The morphology of the islands can change quickly during major storms due to surge overwash, rapid erosion, and inundation (Winner 1975). Anthropogenic activities, such as dune construction, nearshore dredging, inlet and shoreline stabilization, and beach renourishment, also control the ways in which the barrier island system evolves.

The dominant sediment size on the barrier islands is sand, which is concentrated on beaches, in dunes and inlets, and on tidal bars. The sand is composed primarily of quartz, with minor amounts of heavy minerals, organic matter, and shell debris (Johnson et al. 1986; Tweet et al. 2009). Finer-grained, muddy deposits are associated with back-barrier environments. The present continental shelf consists of reworked surficial siliciclastic sands that form shelf sand ridges (Swift et al. 1978) interspersed with outcrops of Pleistocene calcareous sandstone and estuarine mud.

The subaqueous Diamond Shoals extend 15 km (9 mi) seaward from Cape Point, at the tip of Cape Hatteras. The cape separates two major ocean currents and biological regimes: the Labrador Current, which is north of the cape and moves cold water southward, and the tropical Gulf Stream, which is south of the cape and moves warm water northward (Mallinson et al. 2009). Alongshore sediment transport is currently directed toward the tips of capes (Swift 1976; McNinch and Wells 1999), and the shoals can move dramatically in response to changes in oceanographic conditions (Mallinson et al. 2009).

Geologic and Environmental Features and Processes

This chapter describes noteworthy natural features and processes in Cape Hatteras National Seashore.

Discussions during the scoping meeting (3–5 April 2000) for Cape Hatteras National Seashore provided opportunities to develop a list of geologic and environmental features and processes operating in the park, including the following:

- Oceanographic Conditions
- Sediment Transport Processes
- Capes and Cape-Associated Shoals
- Inlets
- Estuaries
- Freshwater Aquifers
- Barrier Island Behavior and Evolution
- Simple and Complex Barrier Island Model
- Geologic Influences on Island Habitats
- Barrier Island System Units (ECU Field Survey Map)
- Barrier Island System Units (NCGS Remote Sensing Map)
- Paleontological Resources

Significant features within Cape Hatteras National Seashore mentioned in this text are listed on table 1 and mapped on figure 7. See also plate 1 (park map; in pocket).

Coastal natural resources are located in a transition zone between terrestrial and marine environments, and as such, include resources and characteristics of both types of environments. 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 miles) of shoreline (Curdts 2011). Of that total, 444 km (276 miles) are within Cape Hatteras National Seashore, 1.6 km (1.0 miles) are within Fort Raleigh National Historic Site, and none are mapped within Wright Brothers National Memorial (Curdts 2011).

More than 120 parks are close to the coast, even though some do not manage a shoreline, and are vulnerable to sea-level rise, lower lake levels, salt water intrusion, and inundation during coastal storms (Beavers et al. in review; see "Resource Management Issues" chapter). The NPS Geologic Resources Division Coastal Geology website, http://nature.nps.gov/geology/coastal/index.cfm, provides additional information.

Coastal change in the Cape Hatteras region is a product of geologic and oceanographic factors in combination

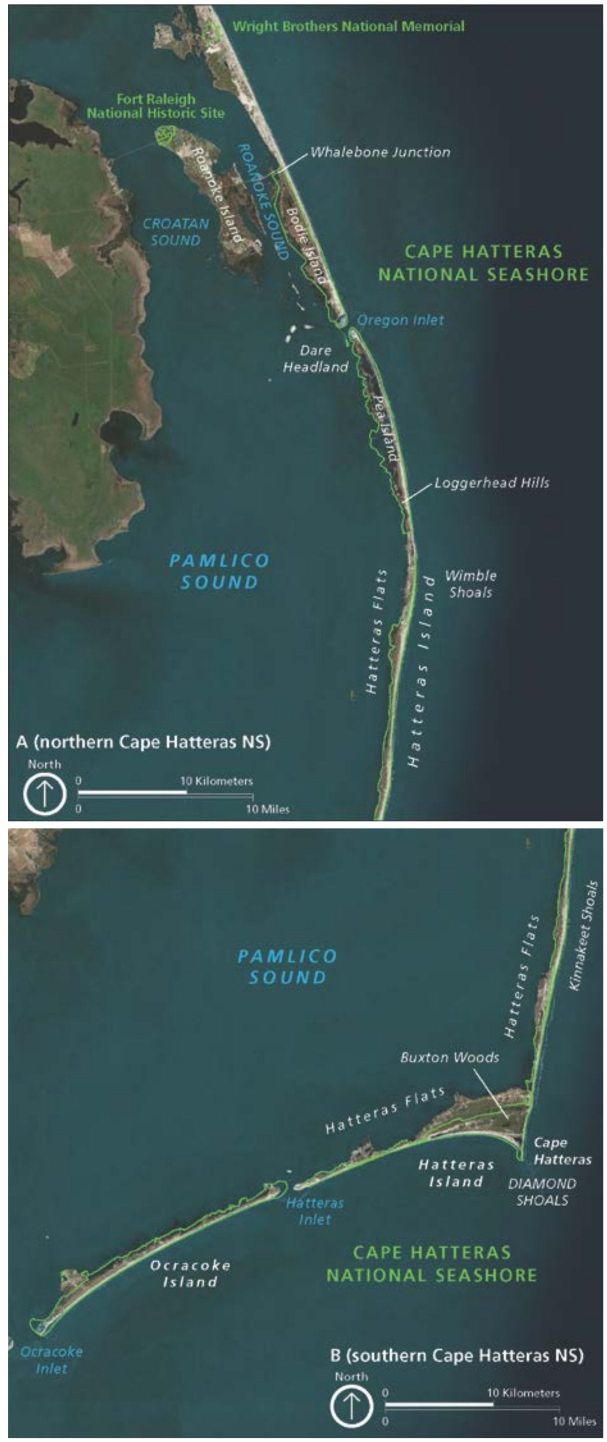

Figure 7. Location of significant features (table 1) in Cape Hatteras National Seashore. A) Northern portion. B) Southern portion. Map annotated by Jason Kenworthy (NPS Geologic Resources Division). Imagery from Esri World Imagery basemap layer using imagery Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Table 1. Significant features at Cape Hatteras National Seashore discussed in this report. Features are listed from north to south. Refer to figure 7 for location.

Significant Feature	Type of Feature	Notes
Croatan Sound	Estuary	Connects the Roanoke/Albemarle drainage system to Pamlico Sound and the Atlantic Ocean.
Roanoke Island	Island	A remnant of the interstream divide that separated the Roanoke River and Pamlico Creek drainages. Site of early (1584) European settlement now known as the Lost Colony.
Roanoke Sound	Estuary	Separates Roanoke Island from the barrier island chain.
Whalebone Junction	Island section	Former salt marsh islands that were part of the flood tidal delta for the paleo–Roanoke Inlet, which closed around 1817.
Bodie Island	Island section	Supports small maritime forest, elevated dune ridges, and freshwater aquifers.
Oregon Inlet	Inlet	Inlet stabilization (e.g., terminal groin construction) causes downdrift erosion, but provides some protection for the current configuration of Highway 12.
Hatteras Flats	Estuarine shoals	Broad and shallow platform composed of coalesced relict flood tidal deltas and overwash sand shoals. Extends along the west side of the barrier islands between Oregon Inlet and Ocracoke Island.
Dare Headland	Submarine headland	Controls morphology of the northern Pamlico Sound in the area between Oregon Inlet and Cape Hatteras.
Pea Island	Island section	Site of many former inlets, resulting in extensive flood-tidal delta deposits and overwash sediments. High shoreline erosion rate. Vulnerable to future inlet breaching despite continued dune construction and renourishment.
Loggerhead Hills	Overwash fan	This massive overwash fan on Pea Island covers the flood tidal delta of Loggerhead Inlet, which was frequently open between about 1650 and 1870.
Hatteras Island	Island section	Has accretionary shoreface, wide beaches, continuous dune ridges, and well-developed maritime forest.
Buxton Woods	Ridge and swale complex	Old section of complex Hatteras Island supports forests, freshwater swales, and aquifer.
Wimble Shoals and Kinnakeet Shoals	Submarine ridges	Offshore hardbottom features composed of carbonate-cemented sandstones and mudstones. Ridges influence wave refraction and wave setup. Oriented from the north-northeast to the south-southwest along Hatteras Island north of the cape.
Diamond Shoals at Cape Hatteras	Cape-associated shoals	Separates two ocean currents, biological regimes, and sediment transport directions.
Hatteras Inlet	Inlet	One of only three inlets along the northern Outer Banks. No bridge crosses it.
Ocracoke Island	Island	Supports some fresh- and brackish-water resources and limited maritime forest. Interior dunes are isolated single ridges. Frequently overwashed.
Ocracoke Inlet	Inlet	One of only three inlets along the northern Outer Banks. No bridge crosses it. Southern boundary of Cape Hatteras National Seashore.
Pamlico Sound	Estuary	Supports diverse plant and animal communities. Threatened by increased pollutant loading.

with human modifications and climate-driven changes. Major storms often cause changes that may persist for weeks to a decade or more (Zhang et al. 2002, 2004; List et al. 2006; Riggs and Ames 2007). Complex interactions between nearshore sand bodies and underlying geology influence beach morphology over time (Riggs et al. 1995; Honeycutt and Krantz 2003; McNinch 2004; Browder and McNinch 2006; Miselis and McNinch 2006; Schupp et al. 2006).

Oceanographic Conditions

The Outer Banks are wave-dominated barrier islands. Mean significant wave heights at Cape Hatteras are 1.2 to 1.3 m (3.9 to 4.3 ft), based on data from 1976 through 1995 (Pendleton et al. 2004). Mean wave period is 6 s, with a standard deviation of 2.4 s, and the predominant wave direction is from south to southeast (Wamsley et al. 2009). Astronomical tidal range is less than 1 m (3.3 ft), based on data from the National Oceanic and Atmospheric Administration/National Ocean Service (NOAA/NOS) ocean tide gauges at the Cape Hatteras fishing pier and the Field Research Facility at Duck, North Carolina (Pendleton et al. 2004). Storm waves and storm surges exceed these average magnitudes and drive significant physical changes on the island and in the estuary; these forcings are described in detail in the "Geologic Resource Management Issues" chapter.

The Gulf Stream off of North Carolina is located seaward of the continental shelf-slope break. It moves northward toward Cape Hatteras, and its dynamic current drives the predominantly counterclockwise circulation in Raleigh Bay through frictional forcing. Filaments of the Gulf Stream sometimes flow landward up onto the shelf, bringing nitrogen-enriched water within 10 km (6.2 mi) of the shoreline (Mallin et al. 2006). At the Cape, the Gulf Stream meets the southward-moving Labrador Current (see the "Capes and Cape-Associated Shoals" section).

Sediment Transport Processes

The barrier islands at Cape Hatteras National Seashore are continuously modified by natural processes and human activities (Ames and Riggs 2006j). They are reshaped by the constant movement of sand by wind, waves, and currents (Dolan and Lins 1986).

Shifting shorelines are recorded not only by historical maps, but also by the appearance on eroding ocean beaches of peat deposits and tree stumps in the surf zone. These deposits are remnants of back-barrier marshes and forests that grew on the landward side of the barrier islands (Dolan and Lins 1986). Steadily rising sea level is causing net beach recession, which results in increased wave energy on the dunes and subsequent overwash and build-up of the interior sand flats and tidal marshes on the sound sides of the islands. The net effect of this process in response to rising seas is upward and landward (westward) migration of the barrier islands (Dolan and Godfrey 1972).

Aeolian Transport

Average wind speeds are 15 km (9.3 mi)/h, but speeds can reach 48 km (30 mi)/h in every month of the year (Wells and Kim 1989). Winds blow primarily from the south to southwest between April and August and from the north to northwest between September and February. Annually, average strong winds blow most frequently from the north and northeast, resulting in overall average southward and southwestward aeolian sand transport (Havholm et al. 2004). A fetch of 100 km (62 mi) is possible when winds blow along the axis of Pamlico Sound (Wells and Kim 1989).

As detailed in the "Estuaries" section, wind drives circulation in Pamlico Sound (Wells and Kim 1989), and major wind-driven tides can cause sediment erosion and transport. Storm winds, described in the "Hurricane Impacts and Human Responses" section of the "Geologic Resource Management Issues" chapter, also move significant amounts of sand into the island interior and estuary, and help to build and shape dunes.

Wave Transport

Waves and wave-induced currents produce a very high net southerly sand transport, estimated to be 590,000 m^3 (772,000 yd^3) per year, along the northern Outer Banks toward Cape Hatteras (Inman and Dolan 1989). In comparison, net northerly sediment transport in southern Virginia, just north of the Outer Banks, is only 160,000 m^3 (209,000 yd^3) per year (Inman and Dolan 1989). The depth of closure, a measure used in coastal engineering models and defined as the depth beyond which sediment transport relative to beach dynamics does not occur, is estimated to be 18.6 m (61 ft) at Nags Head and 21.6 m (70.8 ft) off Cape Hatteras (Everts 1978, as cited in Moore et al. 2007).

Despite the high rate of alongshore sediment transport, some areas of the shoreface and inner shelf are devoid of sand. A thin layer of modern beach sand commonly overlies shoreface sediment, which consists of relict fluvial and estuarine sediments (muddy sands, mud, and sometimes rock), but these underlying sediments are sometimes exposed in the surf zone and nearshore areas (shoreline to 5 km [3.1 mi] offshore) from Wilmington to Nags Head (Pearson 1979; Snyder 1993; Riggs et al. 1995; Miselis and McNinch 2006).

Overwash

Overwash is an important process in building island elevation, expanding marsh platforms, and creating and maintaining early-succession habitat.

When small storm surges produce waves that overtop the island berm and erode the dune ridge, sediment is deposited in small overwash fans on the ocean side of the barrier. Large storm events 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. 8) (Riggs et al. 2009). These processes move sediment on top of and across the island, building island

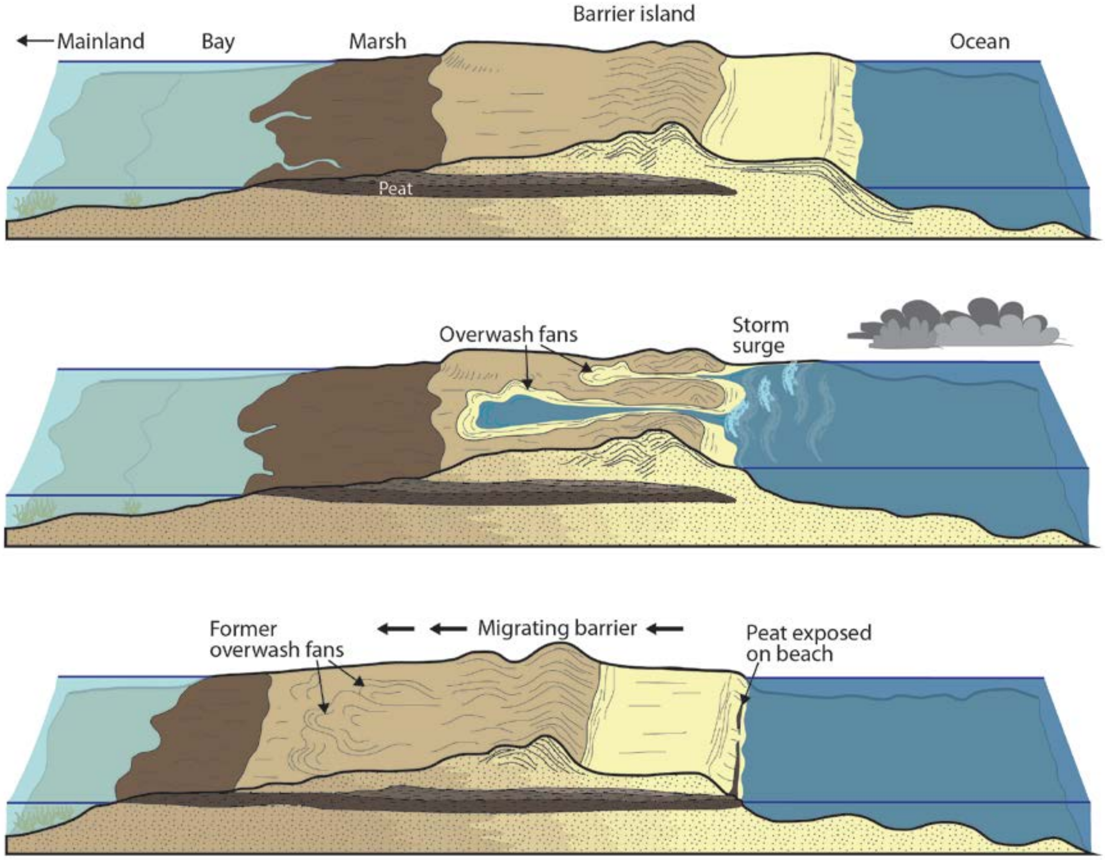

Figure 8. Schematic illustration of overwash fan development. When waves carry sand across the beach, sediment is deposited as small overwash fans on the ocean side of the barrier. Large storm events can drive meters of water across the island, resulting in large overwash ramps that bury the back-barrier platform marshes and may even build shallow shoals in the estuary. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after online figure by NPS and University of Maryland Center for Environmental Science (2012).

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 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. 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. 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 mat algae in the supratidal zone. 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 increased elevation of the island reduces the frequency and extent of overwash events. The ocean shoreline will then slowly recede, moving the island berm farther inland, narrowing the island, and ultimately eliminating the middle overwash zone. As the island narrows, overwash can again reach the back barrier; marsh platforms and associated tidal channels are buried by overwash sediment as the island berm and beach move landward over the molar-tooth structure (Riggs and Ames 2006).

Sediment Sources

New sediment for the northern Outer Banks ocean shoreline usually comes from four sources (Riggs and Ames 2006):

1) Fossil sands and gravels that were deposited as river deltas on the adjacent continental shelf during prior low sea-level conditions and that now occur on the shoreface;
2) Diamond Shoals, which extends from Cape Hatteras across the continental shelf and contains large amounts of sediment that can periodically supply volumes of new sand to the downstream beaches of Buxton Woods;
3) Erosion of shoreface sediments, including barrier island sand, estuarine valley-fill muddy sands, and mudstone;
4) Inlet ebb and flood tidal deltas, which can provide sediment to island segments adjacent to present-day or paleo-inlets.

The majority of beaches along the barrier island are composed of quartz sand, with small concentrations of black heavy mineral sand and river gravel in some areas. All three of these sediment types were ultimately derived from erosion of the Piedmont and Appalachian mountains and transported by rivers to the coast in past millennia (Riggs et al. 2008a). The black sands are composed of various types of very hard and chemically stable heavy mineral. The dominant minerals are illmenite and magnetite, with smaller proportions of red minerals (garnet and rutile) and the rare pale-green and -blue minerals (tourmaline, zircon, and apatite). These minerals are heavier and denser than quartz and calcite, and their grain sizes are usually fine to very fine sand. They often appear in the upper portions of a post-storm beach and are particularly concentrated around inlets and capes (Riggs et al. 2008a).

Shell fragments from organisms presently living in the surf zone, along the shoreface, and on the continental shelf are also present in varying amounts. Most of the shells on today's beaches are fossils. Fossil shells include oysters (*Ostrea virginica*) that lived in back-barrier estuaries; were buried in mud and peat, where they were stained gray or black; and were then exposed in the surf zone as the barrier island migrated westward over the earlier marsh deposits (Riggs et al. 2008a). These oysters are usually a few hundred to a few thousand years old. Fossil shells that have been stained orange with iron are usually tens to hundreds of thousands of years old. When sea level was more than 120 m (400 ft) below present sea level, these shells were subaerially exposed and stained with iron oxide within the surficial soil profile on what is now the continental shelf offshore of the modern barrier island (Riggs et al. 2008a).

Capes and Cape-Associated Shoals

Cape Point and the associated Diamond Shoals, which extend 15 km (9 mi) seaward from Cape Point, are part of a high-energy and mobile sand shoal system that responds dramatically to changes in oceanographic conditions (Mallinson et al. 2009). This cross-shelf shoal system creates dangerous boating conditions, but provides excellent fishing opportunities. The system separates two major ocean currents and biological regimes (fig. 9). North of the cape, the Labrador Current moves cold water southward; south of the cape, the Gulf Stream and its associated warm water move northward and host a different set of tropical fauna and flora. The two water masses meet at Diamond Shoals (Mallinson et al. 2009). Alongshore sediment transport is currently directed toward the tips of capes (e.g., it moves southward north of Cape Hatteras and northward south of the cape, so that the sediment loads meet and are deposited at Diamond Shoals) (Swift 1976; McNinch and Wells 1999).

Figure 9. Map of major currents. Cape Point and the associated Diamond Shoals, which extend 15 km seaward from Cape Point, are part of a high-energy system that is highly mobile and responds dramatically to changes in oceanographic conditions. The shoals separate two major ocean currents and biological regimes. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

The locations of Cape Hatteras and the other Carolina capes (Capes Lookout, Fear, and Romain) are all likely controlled by the underlying geologic framework (Swift et al. 1972; Moslow and Heron 1981; Popenoe 1985). The findings of a recent study (Thieler and Ashton 2011) suggest that the Carolina capes are dynamic, selforganized features in which the shoreline responds to high-angle waves (wave crests that approach the coast at a large angle), and that they continue to evolve.

Inlets

The number and size of inlets between barrier islands are in equilibrium with the volume of water discharged from the rivers and entering and exiting the estuaries due to tides. At Cape Hatteras National Seashore, new inlets open during powerful storms and old inlets may close due to rapid influxes of sediment (Dolan and Godfrey 1972). In areas with minimal tidal range, such as northern North Carolina and Cape Hatteras National Seashore, inlets act primarily as outlets for freshwater flowing from rivers to estuaries, resulting in fewer inlets and longer barrier islands than in southern North Carolina (Mallinson et al. 2008b). The formation and location of new inlets are difficult to predict, but the potential for inlet formation exists everywhere along the simple barrier islands of the Outer Banks (fig. 10), with likelihood depending on six major variables: storm event dynamics, physical geometry of coastal compartments, island geomorphology, framework geology, estuarine geometry and dynamics, and human modifications (fig. 11) (Riggs and Ames 2006).

An inlet through a barrier island is created when storms drive surges across and through the island from 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). Margin shoals are often formed immediately

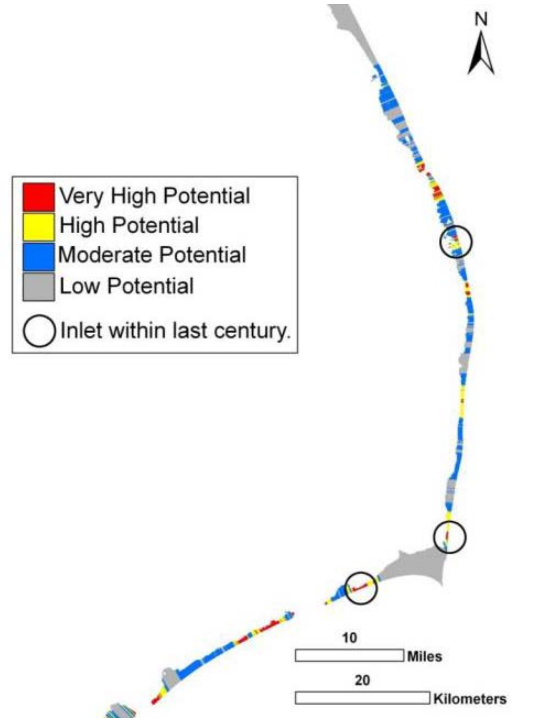

Figure 10. Map of potential for new inlet opening. The potential for a new inlet to open varies by location along the Outer Banks. Potentials illustrated in this figure are based on measurements of subaerial island volume. Categories are defined by quartiles of the total number of sample sites measured. Note that inlets opened in the last century are in areas mapped as "Very High Potential" (red). Figure 20 from Mallinson et al. (2008b).

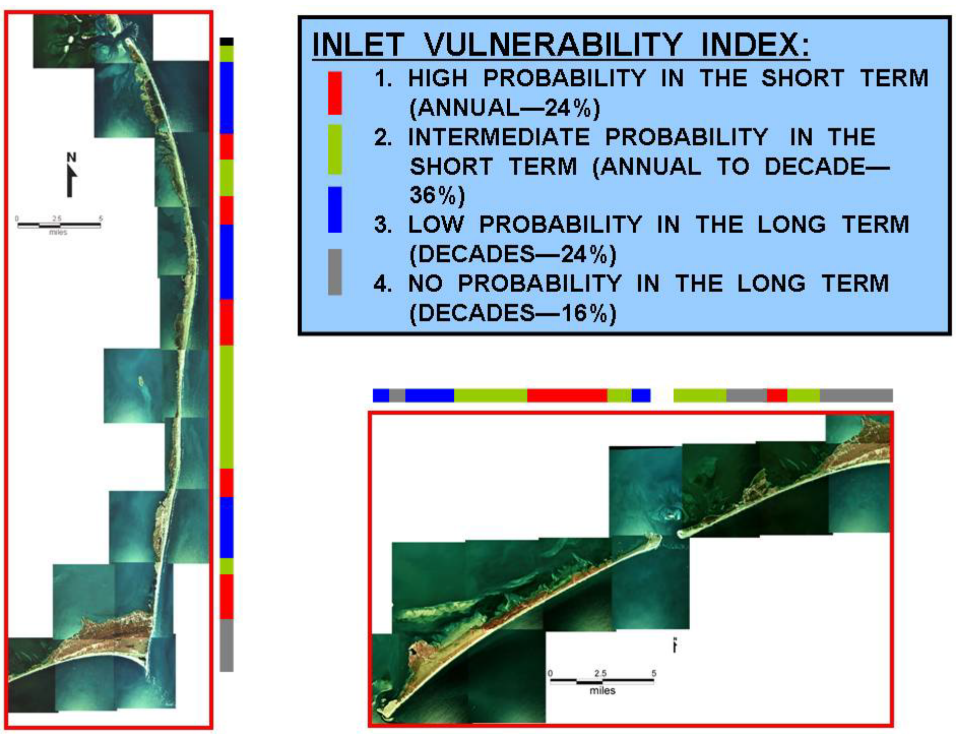

Figure 11. Map of inlet vulnerability index. The likelihood that an inlet will form at a given location along the Outer Banks depends on at least six major variables: storm event dynamics, physical geometry of coastal compartments, island geomorphology, framework geology, estuarine geometry and dynamics, and human modifications. Text and figure 12 from Riggs and Ames (2006).

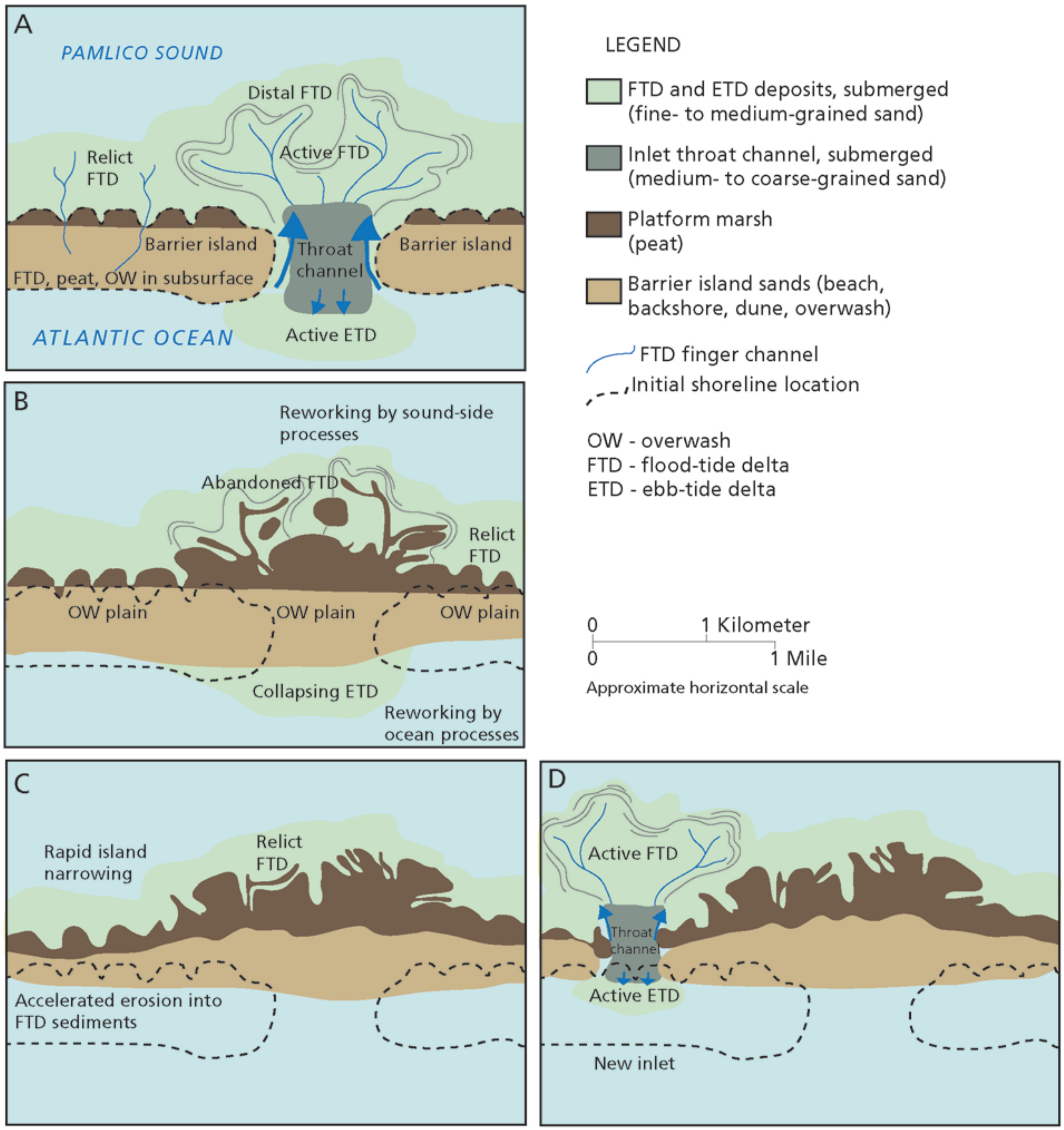

Figure 12. Schematic illustrations of inlet formation. Inlet formation and shoreline recession are important components of barrier island evolution. A) Active flood and ebb tidal deltas (FTDs and ETDs, respectively) form in association with an inlet. B) As the inlet closes, the ETD collapses, causing 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 shoreline 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)

after the inlet opens. Sufficient depth of scour in the inlet allows the interchange of freshwater and ocean water, even after the storm has subsided, and tidal flow continues to widen and deepen the channel. If the inlet flow is strong enough to flush littoral drift-derived sediments faster than they are introduced, the inlet is maintained (Wamsley et al. 2009). When water volume decreases, the channel begins to shoal (Mallinson et al. 2008b). Most inlets are temporary features of elevated water levels and last only a few days (Dolan and Lins 1986). Non-migrating inlets are usually ephemeral features, opening and closing on a time scale of months to years (Mallinson et al. 2010b).

Tidal currents construct a flood tidal delta on the estuarine side of the barrier island and an ebb tidal delta

Figure 13. Location and duration of historic 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).

on the ocean side, where sediment is deposited as the swiftly moving tide dissipates into larger water bodies (fig. 12A) (Riggs et al. 2009). These delta shoals are important components of the coastal sediment budget and the long-term evolution of the barrier islands, allowing a platform for marsh development (Dolan and Lins 1986) and for island migration as sea level rises (Riggs et al. 2009; Mallinson et al. 2010b). Flood-tidal delta deposits provide the major volume of sediments beneath the Outer Banks (Mallinson et al. 2010b). Migrating inlets provide sediment to the back-barrier system through the growth of spits and the longevity of the inlet's existence. The deltaic deposits widen the island in back-barrier areas adjacent to the inlet throat (Mallinson et al. 2010b).

After an inlet closes, sand from the flood tidal deltas is incorporated into the island as intertidal marsh flats known as molar-tooth platform marshes (fig. 12B), which may be segmented by the old delta channel system. As overwash buries the marsh, the channels are filled with sand (fig. 12C). The barrier migrates over this 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 are easily eroded, producing new inlet channels (fig. 12D) (Mallinson et al. 2008b; Riggs et al. 2009).

Ebb tidal deltas also 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). 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).

Historic Inlets

As many as 30 inlets have opened and closed along the Outer Banks since the first European presence in this area 400 years ago (fig. 13) (Dolan and Lins 1986), and approximately 70% to 85% of the Outer Banks have had at least one inlet in the past 500 years (Riggs et al. 2009). On Pea Island, North Carolina, New Inlet was open numerous times between 1650 and 1945, and Chicinacommock Inlet was open irregularly between about 1650 and 1775. Loggerhead Hills (a massive overwash fan) covers the flood tidal delta of Loggerhead Inlet, which was frequently open between about 1650 and 1870 (Riggs et al. 2009). Whalebone Junction, at the foot of the causeway to Roanoke Island, is located on former salt marsh islands that were part of the flood tidal delta of the paleo–Roanoke Inlet, which closed around 1817 (Mallinson et al. 2008b).

Only three major inlet systems now connect the entire Albemarle-Pamlico Estuarine System to the ocean. Ocracoke Inlet, open since at least 1584, has undergone maintenance dredging at various times, including 1828–1835, 1895–1905, and 1942–1961 (Riggs and Ames 2007). Oregon Inlet, which was opened by a hurricane in 1846, has a history of dredging and stabilization that is described in detail in the “Geologic Resource Management Issues” chapter. Hatteras Inlet, which also opened during a hurricane in 1846, has typical inlet features, including a small, well-developed ebb tidal delta on the ocean side, an extensive flood tidal delta of shallow sand flats on the estuarine side, and a long prograding spit on the northeastern (updrift) side of the inlet (Mallinson et al. 2009). Vegetation on this accretionary spit increases with distance from the inlet, indicating decades of inlet migration to the southwest.

Estuaries

Pamlico Sound is an important fishing resource, and provides nursery and foraging habitats for mid-Atlantic fish species (Paerl et al. 2006). Three seagrass species are present along the eastern sides of Pamlico and Roanoke sounds: *Zostera marina* (eelgrass), *Halodule wrightii* (shoalgrass), and lesser abundances of *Ruppia maritima* (widgeongrass) (Ferguson et al. 1988, as cited in Mallin et al. 2006).

Roanoke Sound, west of Bodie Island, and Pamlico Sound, west of the rest of the park, are both polyhaline with salinities of 18 to 29 practical salinity units (psu) (Mallin et al. 2006). Tide range within the Albemarle-Pamlico lagoonal system is low (10 cm [3.9 in] or less; more around the inlets) (Wells and Kim 1989). Coves and tidal creeks have variable estuarine salinities, depending on local rainfall, which averages about 143 cm (56 in)/year (Mallin et al. 2006).

Pamlico Sound receives freshwater from five major watersheds and has a surface area of 435,000 ha (110,000 ac) (Giese et al. 1985). Recent estimates indicate that the sound contains 16.9×10^9 m^3 (2.2×10^{10} yds^3) of water, 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, shallow inlets (Paerl et al. 2006). Circulation is dominated 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).

Estuarine water-quality data for Cape Hatteras National Seashore are collected monthly at one continuous-monitoring station located near the Ocracoke Lighthouse, at the southern end of Ocracoke Island. In 2011, the monthly data recorded consistently good conditions for water quality, dissolved oxygen, and chlorophyll *a*, and fair conditions for dissolved nitrogen and phosphorus (see table 2 for condition definitions) (NPS 2012; Wright et al. 2012). Benthic conditions in the estuary and ocean were rated as good (healthy) (NPS 2012).

Table 2. Coastal water-quality monitoring criteria used by the NPS Southeast Coast Network, based on thresholds set by the US Environmental Protection Agency (2005).

Rating	Water Clarity (k)[1]	Chlorophyll *a* (ug/L)	Total Dissolved Nitrogen[2] (mg/L)	Total Dissolved Phosphorus[2] (mg/L)	Dissolved Oxygen (mg/L)
Good	<2.3	<5	<0.1	<0.01	>5
Fair	2.30–2.99	5–20	0.1–0.5	0.01–0.05	2–5
Poor	>2.99	>20	>0.5	>0.05	<2

Table and notes reproduced from table 3 in Wright et al. (2012).

[1]Light attenuation coefficients (k) were used to assess water clarity conditions using criteria categories in Smith et al. (2006), which are comparable to the US Environmental Protection Agency (2005) criteria for the assessed water bodies.

[2]US Environmental Protection Agency nutrient criteria use dissolved inorganic nitrogen and dissolved inorganic phosphorus, which are close approximations of total dissolved nitrogen and total dissolved phosphorous.

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, shoreline erosion, continental shelf, and autochthonous biogenic production of fauna and flora. Minor contributions are derived from silt and sand transported by storm wind and water from the barrier islands and from periodically unvegetated agricultural fields on the mainland. Riverine input is mostly silt and clay with high organic content. Biogenic material in the form of shell fragments (fig. 14) represents less than 2% of bottom sediments throughout much of Pamlico Sound, but more than 16% of sediments at Ocracoke, Hatteras and Oregon inlets, where shell 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. Shoreline erosion by direct wave attack provides the major source of coarse sediment, mainly from high banks and bluffs that are undercut during storms, then collapse as slump blocks onto the beach (fig. 15). Erosion rates of 1 to 3 m (3.3 to 10 ft)/year are sufficient to create beaches along the estuarine shorelines. Most of the sand in Core Sound and central and eastern Pamlico Sound is derived from barrier islands and offshore sediments carried through inlets and overwash fans, as evidenced by the similarity in texture between sound and barrier-island sediments and the decreasing landward percentage of garnet and yellow quartz. The three inlets influencing Cape Hatteras National Seashore are high-energy, wave-dominated features with flood tidal deltas that account for approximately half of the medium-grained sand in the estuarine system. Extensive washover fans and former inlets have also contributed sand to nearly all of Core Sound.

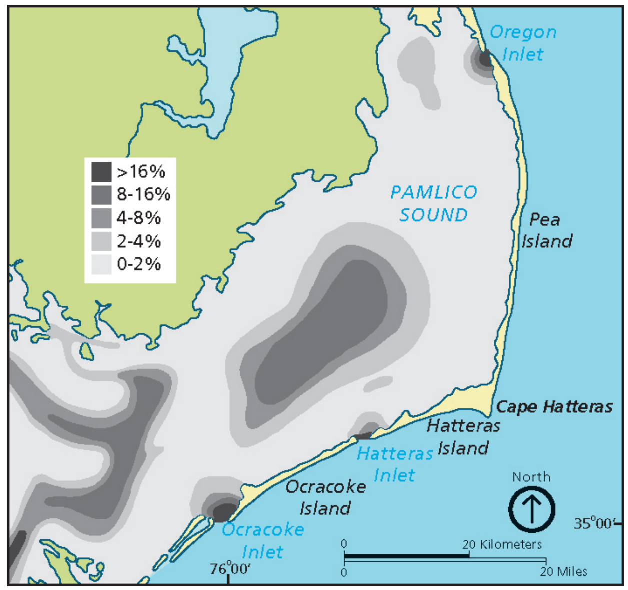

Figure 14. Distribution (wt%) of calcium carbonate content in Pamlico Sound. Highest concentrations occur at inlets where shell fragments are transported from the oceanside surf zone. Figure redrafted by Trista Thornberry-Ehrlich (Colorado State University) after figure 5 in Wells and Kim (1989), as modified from Pickett (1965).

Grain size in Pamlico Sound decreases away from cross-estuarine finger shoals, toward the center of the sound and quiet-water environments near drowned tributary mouths and protected mainland embayments (fig. 16). Along the mainland side of Pamlico Sound are areas of sandy mud characterized by sediment mottled by burrowing organisms. The deeper central part of the sound has homogeneous sediment that lacks sand and burrowing organisms (Wells and Kim 1989).

Freshwater Aquifer

The popularity of Cape Hatteras National Seashore has placed increasing demands on natural resources and visitor use facilities. An understanding of the potable

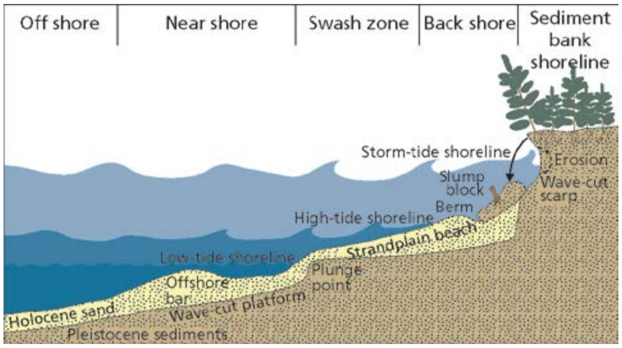

Figure 15. Schematic cross section of a strandplain beach. Strandplain beaches are common shoreline shapes on the estuarine sides of complex barrier islands in Cape Hatteras National Seashore, and are the dominant forms of sediment-bank estuarine shorelines along the mainland. Shoreline erosion occurs 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).

Figure 16. 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).

groundwater supply is critical to protect and ensure the optimal use of this resource.

Surficial water aquifers consist of porous and permeable sediments capable of storing and transmitting useable quantities of water. These aquifers extend from a water table at or below the land surface down to an underlying confining layer of silt and clay. On barrier islands, surficial fresh groundwater may occur as a lens-shaped mass floating atop denser salty water, with an intervening mixing zone (Harris and Wilder 1964; Winner 1975). Below the confining layer of the surficial aquifer, other confined or semi-confined aquifers may occur between additional confining silt and clay beds (Brown 1960; Harris and Wilder 1964; Winner 1975). The depth of freshwater below the land surface and the thickness of the aquifers vary along the Outer Banks.

On Hatteras Island, the Buxton Woods surficial aquifer consists of an upper permeable layer up to 12 m (39 ft) thick, with a semi-confining layer of silts and fine sands below it. A lower aquifer ranges from 12 to 24 m (39 to 79 ft) in thickness. It is generally a layer of shell and shell hash underlain by a 13-m- (43-ft-) thick confining layer of silty to clayey sand. This deep aquifer continues to supply a portion of local drinking water, although most freshwater is currently derived from brackish water in deeper (70 m [230 ft]) wells that is treated by reverse osmosis (Anderson et al. 2000, as cited in Mallin et al. 2006). On Ocracoke Island, drinking water is sourced from brackish water obtained from a 189-m- (620-ft-) deep aquifer that is purified by a reverse osmosis treatment system located on Cape Hatteras National Seashore property in Ocracoke Village.

Brown (1960) reported the presence of two fresh groundwater aquifers at the southern end of Bodie Island. The upper aquifer lies 0 to 6 m (20 ft) below the surface and is composed of medium- to fine-grained quartz sand with shell fragments. The water level varies with rainfall, evapotranspiration, and tides. The lower aquifer, at a depth of 9 to 13 m (29 to 42 ft), is composed of coarse- to medium-grained quartz sand with shell fragments. It is separated from the upper aquifer by a layer of sandy silt and clay that is 3 m (9 ft) thick. Underlying the lower aquifer is a silty clay layer that is 5 m (18 ft) thick and prevents intrusion of the underlying saline water.

The Outer Banks fresh groundwater supply is recharged through rainfall and depleted through residential use, evapotranspiration from the surface and vegetation, and surface drainage from wetlands (Mallin et al. 2006). Annual average rainfall ranges from 114 to 140 cm (45 to 55 in) and is greatest between July and October (Brown 1960; Kimrey 1960). Most rainwater enters the aquifer directly, with little to no surface runoff; the amount of groundwater available is thus related directly to the amount and frequency of precipitation (Brown 1960; Harris and Wilder 1964; Winner 1975). Runoff typically occurs only when significant rainfall saturates the ground. Some freshwater ponds exist, but they are often ephemeral (Winner 1975; Ames and Riggs 2006a–i).

Fresh surficial groundwater tends to move away from the central part of the island, toward the ocean and sound, at an average of about 0.3 m (1 ft) per day (Harris and Wilder 1964; Winner 1975). Test drilling and water sampling have indicated that subsurface lateral permeability is greater than vertical permeability (Brown 1960). The downward and outward movement of freshwater recharge maintains the freshwater lens atop the saline water until storm overwash events add saltwater to the freshwater, creating a brackish resource that persists for some period of time.

Groundwater systems and aquifers can be affected by impoundments, weather conditions (e.g., drought), and water withdrawal for anthropogenic needs. The combination of these influences can, in turn, alter hydrologic processes, wetland function, and the distribution, composition, diversity, and structure of vegetation communities (NPS 2012). Water levels have declined in two of the three wells, located on the Coastal Plain, that the NPS Southeast Coast Network monitors as indicators of park resource conditions (NPS 2012): a surficial aquifer well just south of Plymouth, North Carolina (130 km [80 mi] northwest of Cape Hatteras) with a 25-year quarterly record, and a deeper well in the Castle Hayne aquifer just north of Washington, North Carolina (150 km [90 mi] northwest of Cape Hatteras) with an 8-year daily record (Wright 2012). Withdrawal of freshwater will change the balance between the freshwater lens and underlying saltwater, due to the resulting encroachment of adjacent saltwater bodies (Brown 1960; Harris and Wilder 1964; Winner 1975).

Areas favorable for fresh groundwater development are not likely to be inundated by saltwater and subject to only rare overwash from the largest storms (Winner 1975). Areas such as the high and wide island mass at Buxton Woods and a smaller area at the southern end of Bodie Island (dunes near Theoff Point) fit these criteria (Brown 1960; Winner 1975). Higher areas in the central parts of the narrower islands (e.g., Ocracoke Island) have more frequent saltwater overwash. Overwash from Hurricane Emily in 1993 caused an increase in chloride levels in the Buxton Woods Aquifer from the normal level of 40 mg/L (milligrams per liter, equal to parts per million) to 280 mg/L; this level remained above 100 mg/L for eight months (Anderson 2002, as cited in Mallin et al. 2006). The Environmental Protection Agency has set a secondary standard of 250 mg/L chloride in drinking water due to effects related to taste and corrosion.

Barrier Island Evolution and Behavior

The modern coastal geomorphology of the Cape Hatteras region results from interaction among the antecedent topography, varying magnitudes of relative sea-level change, variable fluvial input, and coastal oceanographic processes (Mallinson et al. 2010a). Thus, to understand large-scale barrier behavior along the Outer Banks, the geologic framework must be considered.

Geologic Framework

At the broadest scale, Coastal Plain sediments sit atop bedrock basement characterized by broad structural highs (the Carolina Platform High, underlying the region

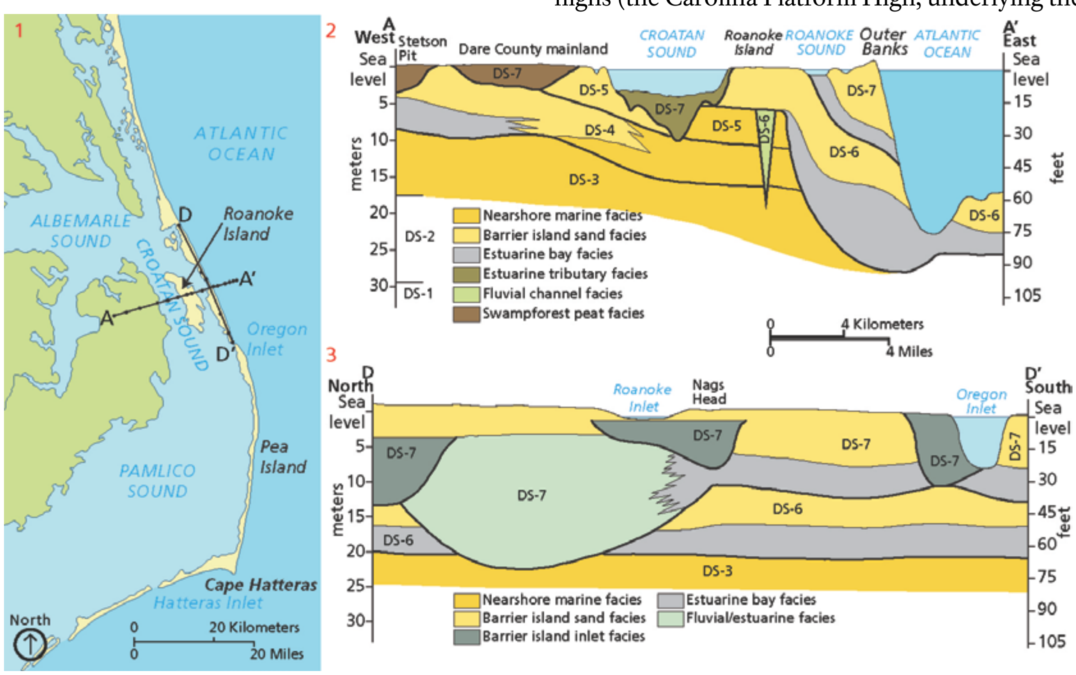

Figure 17. Schematic cross sections illustrating the diversity of strata underlying the Outer Banks. 1) Location of cross-island (A–A′) and along-island (D–D′) geologic sections along the Outer Banks. 2) West–east geologic cross section extending from Stetson Pit (A) eastward into the Atlantic Ocean (A′), showing seven stacked Quaternary depositional sequences (labeled DS-1 through DS-7), and major sediment facies of each depositional sequence. DS-7 is the Holocene depositional sequence. 3) North–south geologic cross section extending from the north side of Kitty Hawk Bay (D) southward through Nags Head and to the south side of Oregon Inlet (D′), showing portions of at least three stacked Quaternary depositional sequences and major sediment facies of each. Graphic redrafted by Trista Thornberry-Ehrlich (Colorado State University) after figures 1, 2, and 5 in Riggs et al. (1992).

between Myrtle Beach, South Carolina, and Cape Fear, North Carolina) and lows (the Albemarle Embayment, which is the shallow flank of the Salisbury Embayment and is slowly subsiding in the northern coastal zone from Cape Lookout, North Carolina, to the Virginia state line) (Riggs et al. 2011). Cape Hatteras beaches are perched atop pre-existing Pleistocene, Tertiary, and Cretaceous sediments. Locally, a Quaternary sequence (50 to 70 m [160 to 230 ft] thick) of soft sediments (slightly indurated to unconsolidated mud, muddy sand, sand, and peat) fills the Albemarle Embayment depositional basin (Riggs et al. 1995).

Superimposed on the regional stratigraphy between southeastern Virginia and Cape Hatteras is a flooded, ancient drainage system consisting of a series of Pleistocene paleofluvial channels (Riggs et al. 1995, 1996; Thieler et al. 2001; Boss et al. 2002; Schwartz and Birkemeier 2004; Mallinson et al. 2005; Miselis and McNinch 2006) that incised the Quaternary strata across the regional shoreface. When sea level rose following the lowstands of the Last Glacial Maximum, these channels filled with Pleistocene and Holocene coastal sediments, including bedded sequences of muddy estuarine sediments, fine to medium sands, and, where inlets or rivers were present, coarse sands and gravel that now outcrop in the shoreface (fig. 17) (Boss et al. 2002; McNinch 2004; Mallinson et al. 2005; Browder and McNinch 2006; Miselis and McNinch 2006; Culver et al. 2008b; Mallinson et al. 2010a, 2010b). Large interstream areas of older sediments separate the paleovalleys (Riggs et al. 1995).

The modern estuaries behind the barrier islands occur within the flooded paleovalleys of the Roanoke, Pamlico/Tar, and Neuse rivers (Mallinson et al. 2010a). Ocracoke Inlet, the southern boundary of Cape Hatteras National Seashore, has historically been relatively stable, appearing on maps as far back as 1590, likely because it occurs within the fluvial paleovalley of Pamlico Creek (Riggs and Ames 2003; Mallinson et al. 2010a). A major erosional hotspot presently occurs north of the Wright Brothers National Memorial in Kitty Hawk, where the paleo–Roanoke River Valley passes beneath the northern Outer Banks (Mallinson et al. 2010a).

Mallinson et al. (2009) estimated that paleo-inlet channels constitute up to 75% of Hatteras and Pea islands, resulting from the cutting of inlets into older flood tidal deltas that formed when barrier islands existed farther seaward. These flood-tidal delta deposits are generally overlain by marsh peat and storm overwash sediments. Channel-fill sediments occur under the widest portions of the island. Narrow portions of the island are underlain by flood-tidal delta and overwash sediments (Mallinson et al. 2009).

The Hatteras Flats (fig. 18) occur on the western side of the barrier islands between Oregon Inlet and Ocracoke Island. This broad and shallow platform, which is composed of coalesced relict flood tidal deltas and overwash sand shoals, extends up to 8 km (5 mi) into Pamlico Sound and is in water depths of less than 1 to 2 m (3 to 6 ft) (Mallinson et al. 2011). From Oregon Inlet south to Rodanthe, the flats slope gradually into Pamlico Sound. From Rodanthe southward to Avon, the western side of these flats has a high-angle slope that drops from 0.5 m (1.6 ft) or less into 3 to 4 m (9.8 to 13 ft) water depth (Mallinson et al. 2009).

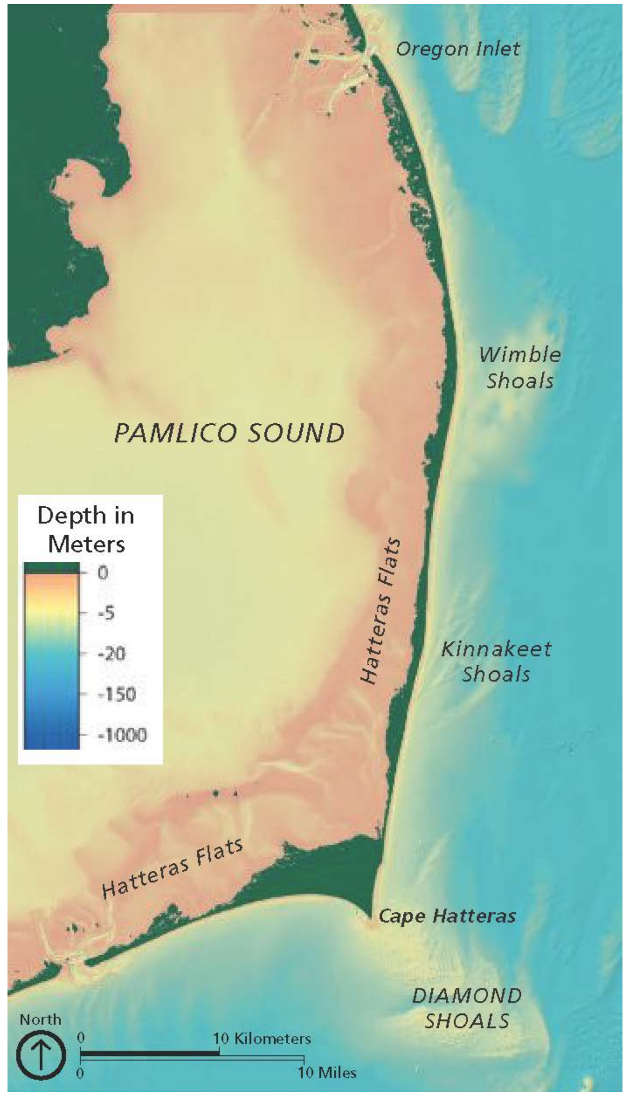

Figure 18. Bathymetric map of Cape Hatteras National Seashore from Oregon Inlet to Hatteras Village. Hatteras Flats is an extensive shallow shoal system that occurs on the west side of the barrier islands between Nags Head and Ocracoke Inlet. The shoals are composed of relict flood tidal deltas and overwash sand shoals. Wimble and Kinnakeet shoals are offshore hardbottom features composed of Pleistocene carbonate-cemented sandstones and mudstones. The green feature is the modern barrier island. Map annotated by Jason Kenworthy (NPS Geologic Resources Division) using the National Oceanic and Atmospheric Administration National Geophysical Data Center's Bathymetry and Digital Elevation Models viewer (DEM Hillshades layer), available online: http://maps.ngdc.noaa.gov/viewers/bathymetry/?layers=nos_hydro&minx=-200&maxx=-50&miny=10&maxy=70 (accessed 19 May 2014).

Influence of the Geologic Framework on Modern Processes

Sediment availability for the North Carolina barrier islands is significantly influenced by the geologic framework of older stratigraphic units occurring beneath and seaward of the shoreface. The variability in age, origin, and composition of units within the geologic framework interacts with coastal processes to determine the three-dimensional shoreface morphology, composition and texture of beach sediments, and shoreline recession rates (Riggs et al. 1995).

Perched barrier islands such as the Outer Banks do not develop a classic shoreface profile of equilibrium because they consist of thin and variable layers of surficial beach sand on top of older eroding stratigraphic units characterized by a variety of lithologies, compositions, and geometries (Riggs et al. 1995). A shoreface composed of compact muds, limestones, or sandstones is more resistant to erosion than are unconsolidated sands or soft muds, and thus exerts a greater effect on the island and nearshore morphology. Also, along many parts of the Cape Hatteras National Seashore coastal system, bathymetric shoal features occur on the inner shelf and modify incoming wave and current energy, which in turn affects the patterns of sediment erosion, transport, and deposition on adjacent beach faces (Riggs et al. 1995).

Older sediments cropping out on the eroding shoreface characterize submarine headlands or submerged morphological features upon which the barrier-estuarine system is perched. Submarine headlands commonly occur on the inner shelf as bathymetric highs seaward of the modern shoreface. These bathymetric high areas modify incoming waves between Kill Devil Hills and Cape Hatteras. Erosional remnants (submarine headlands) control changes in the orientation of the barrier islands, occurrence of minor cape structures on the barrier beach, and a series of offshore ridge and shoal structures (Riggs et al. 1995).

Between Oregon Inlet and Cape Hatteras, the barrier system is perched on a major submarine headland (the Dare Headland), which controls the morphology of the northern Pamlico Sound in this area (fig. 17). This area is characterized by four distinctive coastal features (fig. 18) (Riggs et al. 1995):

1) a major change in barrier island orientation at Rodanthe;
2) a series of bathymetric highs (Wimble and Kinnakeet shoals) on the inner shelf associated with each of several minor capes that intersect the lower beachface at acute angles;
3) minor cape structures (associated with Wimble and Kinnakeet shoals) on the barrier beach in Rodanthe and Avon, with rapidly receding beach segments occurring between the structures; and
4) Hatteras Flats, a broad, shallow platform bound on the west by a vertical scarp up to 3 m (9 ft) high, located on the back side of the barrier island in Pamlico Sound south of Rodanthe.

Transgressive (erosional) shorefaces occur along a large portion of the barrier islands at Cape Hatteras National Seashore, between Nags Head and Ocracoke (Riggs et al. 1995). These areas of pronounced erosion are generally characterized by irregular and steep beach geometry with discontinuous, highly scarped dune ridges and abundant overwash fans. Estuarine peat and mud deposits are characteristic and were overrun by barrier island systems as they migrated inland (westward) in response to ongoing sea-level rise. Storms often expose these deposits within the surf zone and upper shoreface following significant beach sand removal.

Regressive (accretionary) shorefaces (fig. 19) occur on Hatteras Island, southwest of Cape Hatteras. These features are characterized by progradational geometries, beach ridge accretion, and dune development with wide beaches and continuous dune ridges. They occur along barrier island stretches with adequate sediment supplies, often in association with headlands, cape structures, and inlets, which are the sources of new sediment (Riggs et al. 1995).

Channel-dominated inlet-fill shorefaces exist at Bodie Island and numerous beach segments of Pea, Hatteras, and Ocracoke islands. These features form when historic, ephemeral inlets close and their channels fill with beach sand from prograding spits. As sea level rises, the shoreface recedes and the upper portion, underlain by inlet fill, rapidly erodes and produces relatively steeper beach slopes. This erosion produces a sediment supply for adjacent beach segments that tend to have slightly wider beaches with much slower erosion rates (Riggs et al. 1995).

A major portion of the Kitty Hawk area, north of the Wright Brothers National Memorial, is underlain by a channel-dominated valley-fill shoreface. Historically, this area was dominated by the paleodrainage of the Roanoke River/Albemarle Sound estuarine system. With initial drowning of the river system and development of the barrier islands, the channel complex was backfilled with estuarine mud sediments, which can be fairly cohesive. As the barrier island continues to recede over the backfilled channel deposits due to ongoing sea-level rise, the mud-filled channel erodes more slowly, producing relatively shallower slopes. The eroded sediments are fine grained and tend to be transported offshore, instead of supplying adjacent beaches. The net result for adjacent beaches is relatively higher rates of shoreline recession (Riggs et al. 1995).

Wimble and Kinnakeet shoals occur in the nearshore area of the Hatteras Island portion that has a north–south orientation. The shoals are ridges with north/northeast–south/southwest orientations at angles of about 25° to 30° to the shoreline and up to 6 m (20 ft) relief (fig. 18) (Mallinson et al. 2009). These offshore hardbottom features are relict erosional Pleistocene features composed of carbonate-cemented sandstones and mudstones (Boss and Hoffman 2001). These shoals influence wave refraction and wave setup (Cox 1996), thereby affecting the large-scale behavior of this coastal

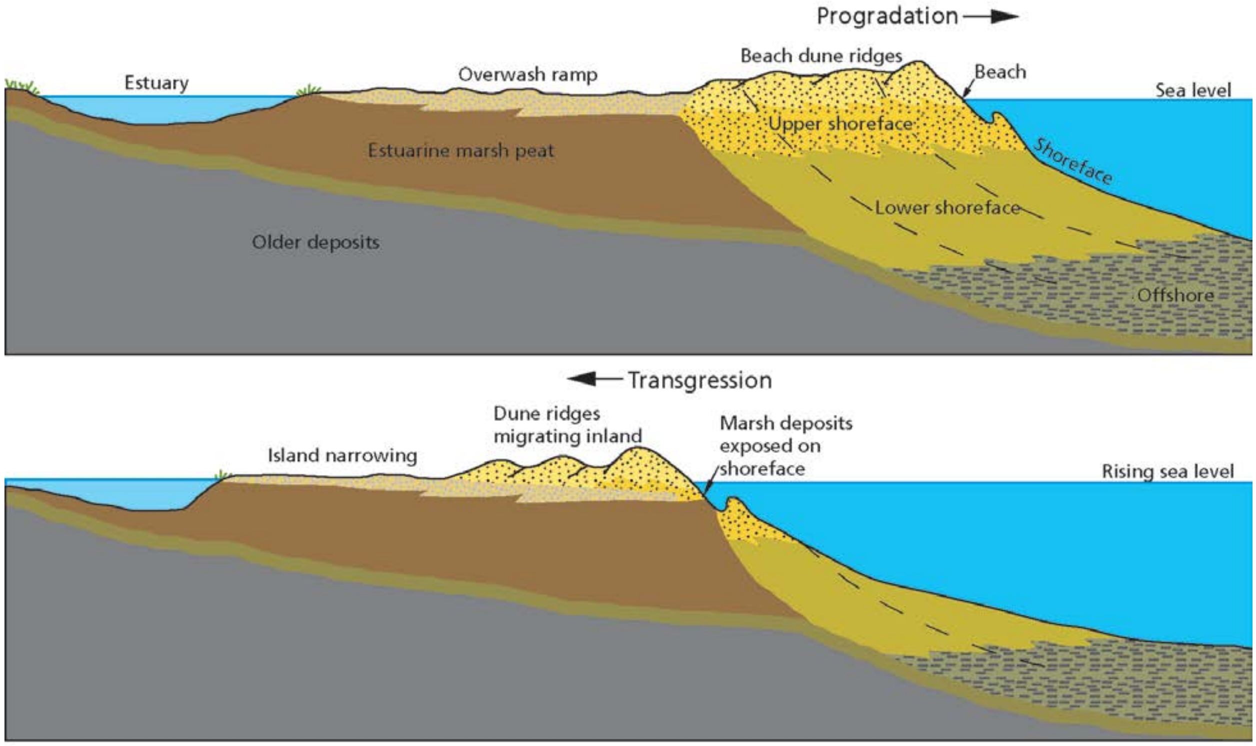

Figure 19. Schematic cross section showing a regressive shoreface during progradation (sea-level fall) and a progressive shoreline during transgression (sea-level rise). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after information provided by Kathleen Farrell (North Carolina Geological Survey, senior geologist, written communication, 13 August 2010) and Stanley Riggs (East Carolina University, professor, written communication, 30 December 2013).

segment. The shoreface profile directly off the two shoal features is steep, but the shoreface and adjacent beach are broad and shallow with relatively low erosion rates where these shoal features intersect the barrier island (Mallinson et al. 2009).

Broad fields of nearshore, shore-oblique, unconsolidated sandbars that are 200 to 1,000 m (660 to 3,280 ft) wide and up to 1 km (0.6 mi) long occur in the nearshore area of the northern Outer Banks (north of Oregon Inlet). A gravel layer outcrops in the troughs between these bars. These persistent features coincide with the locations of paleochannels in the shoreface (McNinch 2004; Browder and McNinch 2006; Miselis and McNinch 2006) and are spatially correlated with onshore hotspots of shoreline variability and, in some places, zones of long-term (decadal-scale) erosion (List et al. 2006; Schupp et al. 2006). The bar morphology is similar to others documented in the surf zone and nearshore areas along the northern Atlantic coast (Niedoroda and Tanner 1970; Swift et al. 1972; Stubblefield and Swift 1976; Swift and Field 1981; Wright and Short 1984; Lippman and Holman 1990; McBride and Moslow 1991; Konicki and Holman 2000).

These bars occur as bands of coarse and fine sediment that are oriented perpendicular or oblique to the shoreline. Studies of these sorted bedforms, known as rippled scour depressions, suggest that these features are self-reinforcing and repeating, responding to alongshore and cross-shore flows, and associated with long-shore sediment transport (Murray and Thieler 2004). These rippled scour depressions are believed to control the distribution, texture, and composition of surficial sediments and inner-shelf bathymetry (Thieler et al. 2001), while underlying geology may control the shoreface profile shape (Thieler et al. 1995).

Despite the tendency for shorelines to smooth out over time, the northern Outer Banks has persistent large-scale curvatures (Lazarus and Murray 2011). The greater availability of coarse paleochannel substrate may hold the large-scale curvature of the shoreline in place through interactions with patterns of alongshore sediment flux, allowing shore-oblique bars and gravel-lined troughs to persist despite a wave climate that tends to focus erosion at such promontories. In that case, the large-scale shoreline curvature could change the wave-driven alongshore sediment transport, which, in turn, affects shoreline change over long spatial and temporal scales (Lazarus and Murray 2011).

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 to evaluate the responses of geomorphic-ecologic systems to sea-level rise, storms, and human modification. The model describes two basic types of barrier island (simple and complex) in the area between Kitty Hawk and Cape Lookout, North Carolina (fig. 20).

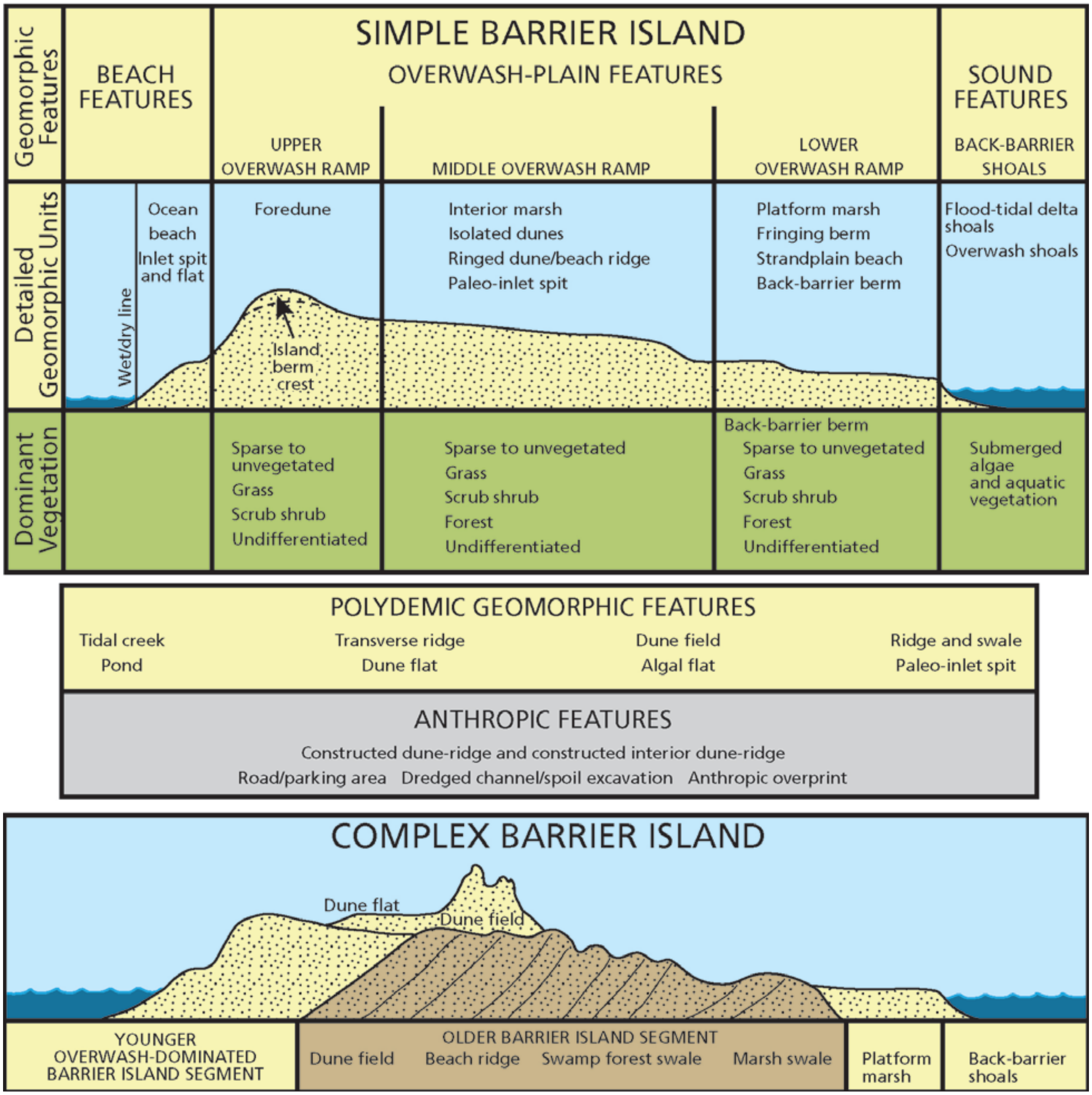

Figure 20. Diagram showing cross-section profiles and dominant vegetation of the model forming the basic framework of the geomorphic mapping presented in this report. A) Simple barrier islands are young, with active barrier components dominated by inlet and overwash processes, and are generally transgressive, with landward migration. B) A complex barrier island forms when a simple barrier island migrates into and accretes onto an older barrier island segment. When the 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).

Simple Barrier Islands

Simple barrier islands constitute about 70% of North Carolina's ocean shoreline (Riggs et al. 2011). This type of barrier island is sediment poor and narrow, with low elevations and surface morphology that is generally young (less than 500 years old). These islands are presently active and have developed in response to a fairly recent set of environmental conditions and processes (Riggs and Ames 2006). They are actively transgressing upward and landward in response to storm events. They are dominated by storm-surge overwash, in which much of the sand is incorporated into overwash fans, building island elevation; 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. 20) (Ames and Riggs 2006j). The morphology of each simple barrier island varies due to differences in storm patterns, sand supplies, shoreline erosion rates, underlying geologic structure, and anthropogenic impacts.

The ocean and estuarine shorelines of a simple barrier island erode due to poor sediment supply in combination with rising sea level. Eventually the island becomes so narrow that a major storm overwashes it or forms a new inlet and tidal delta. These processes build island elevation and width. Where human modifications, such as constructed dune ridges, 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 vegetative cover breaks the hydraulic flow; this process causes the rapid dumping of overwash sediment, building elevation on the ocean side of the island. Over time, this process steepens the upper overwash ramp and minimizes the middle overwash ramp. As the ocean 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 (Riggs and Ames 2006).

Simple barrier islands in the Outer Banks include most of Cape Hatteras National Seashore and Pea Island National Wildlife Refuge, including most of Ocracoke Island and the island segments between the villages of Hatteras and Frisco, Buxton and Avon, Avon and Salvo, Rodanthe and Oregon Inlet, and Oregon Inlet and Nags Head (Riggs et al. 2009).

Complex Barrier Islands

Complex barrier islands constitute about 25% of North Carolina's ocean shoreline (Riggs et al. 2011). This type of barrier island is older, more sediment rich, and wider than simple barrier islands, with higher elevations. Complex islands are generally composed of beach ridge and swale morphology, with extensive dune fields spanning them from the oceanfront toward the sound. These accretionary beach ridges are generally not forming under modern processes. Older portions of these islands represent multiple stages of formation dating back to 3,000 years before present; they are remnants of a previous set of climatic and environmental conditions and processes. 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 (Riggs and Ames 2006).

Kitty Hawk, Nags Head Woods, and Buxton Woods are examples of well-developed complex islands; they formed when a major sand source was available and as a result are sand rich and very wide and high, with extensive multidirectional and truncated sets of beach ridges, associated wetland swales, and often extensive dune fields. The southern shore of Buxton Woods continues to accrete new beach ridges composed of sand derived from Diamond Shoals during specific storm events (Riggs and Ames 2006).

Poorly developed complex barrier islands form when no major sand source is available. They are sand poor, 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. Hatteras Village is located on moderately developed complex islands, and the villages of Rodanthe, Waves, Salvo, and Avon are on poorly developed complex islands (Riggs et al. 2009). Ocracoke Village is on a complex barrier island that was still being formed until recently, when human modifications intensified (e.g., following the 1962 Ash Wednesday storm) (Riggs and Ames 2006).

Geologic Influences on Island Habitats

Island habitats are controlled by elevation above mean sea level (MSL), cross-island location on the barrier, and the tidal and salinity characteristics of shallow groundwater and associated estuarine water. The minimal vegetation on a low, overwash-dominated barrier island must be salt tolerant. Wider, higher islands with infrequent saltwater inundation allow for the establishment of mixed and freshwater-dominated plant species (Riggs and Ames 2006).

Twenty-four terrestrial mammal species are present in the region extending from Nags Head to Ocracoke, including the non-native feral pig. Ocracoke Island has much lower mammalian diversity than Hatteras Island, with only six species represented. This relative lack of diversity has been attributed to the lack of maritime forest, fewer freshwater wetlands, and frequent overwash from hurricanes and nor'easters (Webster and Reese 1992, as cited in Mallin et al. 2006). Mammals utilizing fresh and salt marshes as habitat include the *Cryptotis parva parva* (least shrew), *Sylvilagus palustris palustris* (marsh rabbit), *Oryzomys palustris palustris* (marsh rice rat), *Microtus pennsylvanicus nigricans* (meadow vole), *Ondatra zibethicus macrudon*, (muskrat), *Myocastor coypus bonariensis* (nutria, an invasive species), *Mustela vison mink* (mink), and *Lutra canadensis lataxina* (river otter). The park also provides important habitat for neotropical migrant landbirds, waterbirds, shorebirds, and marsh birds throughout the year.

Barrier Island System Unit Mapping

This report is supported by two digital maps of Cape Hatteras National Seashore surficial geology, each developed using a distinct methodology and resulting in a unique set of geomorphic units and different area of coverage.

The first map, developed by Riggs and Ames (2006; table 3), 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). This detailed map covers portions, but not all, of the northern Outer Banks and Cape Hatteras National Seashore.

Products of the Riggs and Ames mapping informed the North Carolina Geological Survey's development of a second map, which classifies surficial features using remotely sensed data (Hoffman et al. 2007g; table 4). The map includes complete areal coverage of Cape Hatteras National Seashore. In locations where anthropogenic development has occurred atop natural features, this map depicts the natural underlying unit, rather than the more recent anthropogenic feature. For example, the Fore-island Dune Complex, which has been significantly modified, was not differentiated as an anthropogenic feature (Hoffman et al. 2007g). Preliminary mapping for this second map was completed prior to Hurricane Isabel (September 2003), and thus does not incorporate the impacts of that storm to the Cape Hatteras National Seashore shoreline (Hoffman et al. 2007g).

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

The field-based map developed by Riggs and Ames (2006) identifies subgroups and units of the following regional geomorphic features: beach, overwash-plain, polydemic, and anthropogenic features (table 3). Each feature description includes detailed descriptions of geomorphic units and dominant vegetation. The unit descriptions provided below are taken primarily from Riggs and Ames (2006), and supplemented by information from publications where cited.

In predominantly urban areas, where severe modification of the landscape has occurred, the regional geomorphic features (beach, overwash-plain, and polydemic features) are drawn within the urban boundary, but the detailed geomorphic units are included only to the extent possible and where they remain obvious.

Submarine sand bodies in the sound behind the barrier islands were not mapped, although these features are abundant and critically important to barrier island evolution and associated estuarine ecosystems. They 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. The back-barrier shoals should be incorporated into future maps of the barrier islands.

Beach Features

Ocean Beach Unit

The ocean beach 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), which is listed federally as threatened, and *Chelonis mydas* (green sea turtle), but also by *Lepidochelys kempii* (Kemp's Ridley sea turtle) and *Dermochelys coriacea* (leatherback sea turtle), which is listed federally as endangered (Mallin et al. 2006). On average, 75 sea turtle nests were found on park lands annually between 1992 and 2004 (Mallin et al. 2006).

Inlet Flat Unit

Inlet flats 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 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

An inlet spit consists of one or more subparallel and curved ridges that occur adjacent to a modern inlet or a paleo-inlet. It is dominated by curved ridge structures 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 no longer occur as beach features, but occur in several locations on the barrier and are now classified as polydemic features.

Table 3. Summary of barrier island system units as mapped by East Carolina University.

<table>
<tr><th>Group</th><th colspan="2">Subgroup or Map Unit (symbol)</th></tr>
<tr><td rowspan="2">Beach Features</td><td colspan="2">Ocean Beach (BF_ocbeach)</td></tr>
<tr><td colspan="2">Inlet Spit and Flat (BF_spit_flt)</td></tr>
<tr><td rowspan="18">Overwash-Plain Features</td><td rowspan="5">Upper Overwash Ramp</td><td>Sparse to unvegetated (UO_unveg)</td></tr>
<tr><td>Grass (UO_grass)</td></tr>
<tr><td>Scrub Shrub (UO_scrb_shrb)</td></tr>
<tr><td>Foredune (UO_fdune)</td></tr>
<tr><td>Urban (UO_urbdune)</td></tr>
<tr><td rowspan="9">Middle Overwash Ramp</td><td>Sparse to Unvegetated (MO_unveg)</td></tr>
<tr><td>Grass (MO_grass)</td></tr>
<tr><td>Scrub Shrub (MO_scrb_shrb)</td></tr>
<tr><td>Forest (MO_forest)</td></tr>
<tr><td>Interior Marsh (MO_intmarsh)</td></tr>
<tr><td>Isolated Dunes (MO_isodune)</td></tr>
<tr><td>Ringed Dunes and Beach Ridges (MO_rdune_br)</td></tr>
<tr><td>Urban Dune (MO_urbandune)</td></tr>
<tr><td>Paleo-Inlet Spit (MO_p_inl_spt)</td></tr>
<tr><td rowspan="4">Lower Overwash Ramp</td><td>Platform Marsh (LO_pf_marsh)</td></tr>
<tr><td>Fringing Berm (LO_fring_brm)</td></tr>
<tr><td>Standplain Beach (LO_spln_bch)</td></tr>
<tr><td>Back-Barrier Berm (LO_bk_br_bm)</td></tr>
<tr><td rowspan="13">Polydemic Features</td><td colspan="2">Tidal Creeks and Tidal Channels (PF_tidal)</td></tr>
<tr><td colspan="2">Pond (PF_pond)</td></tr>
<tr><td colspan="2">Transverse Ridges (PF_trnv_dune)</td></tr>
<tr><td colspan="2">Dune Flat (PF_dune_flat)</td></tr>
<tr><td colspan="2">Dune Field (PF_dunef)</td></tr>
<tr><td colspan="2">Sparse to Unvegetated Dune Field (PF_dune_unvg)</td></tr>
<tr><td colspan="2">Grass Dune Field (PF_dune_grss)</td></tr>
<tr><td colspan="2">Forested Dune Field (PF_dune_fors)</td></tr>
<tr><td colspan="2">Urbanized Dune Field (PF_dune_urb)</td></tr>
<tr><td colspan="2">Algal Flat (PF_algal_flt)</td></tr>
<tr><td colspan="2">Ridge and Swale (PF_rdg_swl)</td></tr>
<tr><td colspan="2">Swale Marsh (PF_swl_marsh)</td></tr>
<tr><td colspan="2">Paleo-Inlet Spit (PF_p_inl_spt)</td></tr>
<tr><td rowspan="6">Anthropic Features</td><td colspan="2">Constructed Dune-Ridges (AF_cn_dune_r)</td></tr>
<tr><td colspan="2">Constructed Interior Dune-Ridges (AF_cn_idune)</td></tr>
<tr><td colspan="2">Road/parking Areas (AF_rd_prk)</td></tr>
<tr><td colspan="2">Dredge Channels/Spoils(AF_drdge)</td></tr>
<tr><td colspan="2">Excavations (AF_excavate)</td></tr>
<tr><td colspan="2">Anthropic Overprint (AF_an_overpr)</td></tr>
</table>

New and active inlet spits are unvegetated or grassed with *Spartina patens*. The vegetation on older inlet spits often consists of mixed grasses that include *Spartina patens* and a small growth of scrub shrub.

Overwash-Plain Features

Upper Overwash Ramp Unit

The upper overwash ramp begins at an 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 are superimposed on the uppermost portion of the upper overwash ramp.

Upper Overwash Ramp: Sparse to Unvegetated

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

This unit 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)
- *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)
- irregular and splotchy growth of lichens and moss on the sand surface

Upper Overwash Ramp: Scrub Shrub

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 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)
- *Parthenocissus quinquefolia* (Virginia creeper)

Upper Overwash Ramp: Foredune

Natural foredunes are frequently absent, particularly in regions where constructed dune ridges have been built and maintained by human efforts. In areas where such dune ridges have not been built or regularly maintained, natural foredunes 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)
- *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

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. However, 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

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 the following:

- *Spartina patens* (salt meadow hay)
- *Andropogon scoparius* (broom straw)

Middle Overwash Ramp: Scrub Shrub

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)
- *Parthenocissus quinquefolia* (Virginia creeper)

Middle Overwash Ramp: 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 the following:

- *Pinus* sp. (pine)
- *Quercus virginiana* (live oak)
- *Juniper virginiana* (eastern red cedar)

Almost all forested flats contain a major understory of shrubs, including the following:

- *Myrica cerifera* (wax myrtle)
- *Ilex vomitoria* (yaupon holly)
- *Smilax* sp. (cat brier)
- *Toxicodendron radicans* (poison ivy)
- *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

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 the following:

- *Spartina alterniflora* (smooth cordgrass)
- *Spartina patens* (salt meadow hay)
- *Juncus roemerianus* (black needlerush)
- *Distichlis spicata* (saltgrass)
- *Borrichia frutescens* (sea oxeye)

Dominant plants in areas characterized by lower-salinity to freshwater conditions include the following:

- *Scirpus robustus* (soft-stemmed bulrush)
- *Cladium jamaicense* (sawgrass)
- *Phragmites australis* (common reed)
- *Spartina cynosuroides* (giant cordgrass)
- *Typha angustiflora* (cattail)

Middle Overwash Ramp: Isolated Dunes

Small-scale isolated dunes 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: Ringed Dunes and Beach Ridges

An isolated dune that becomes stabilized by grasses on a sparse to unvegetated or algal flat–dominated middle overwash ramp increases in size over time by ringed accretion around a portion or the entirety of the dune. Grasses around the nucleus dune trap sand during the dry seasons, forming smaller dunes. The flats then become flooded during subsequent stormy seasons that rework the new perimeter dune sands, forming beach ridges that ring all or part of the nucleus dune. The isolated ringed dunes can become quite large, with numerous ringed structures around their perimeters. Flowing currents resulting from a major overwash event can truncate the dunes and cause blowouts within the nucleus dune, resulting in complicated dune geometries. A major flood event may severely truncate or destroy a ringed dune.

The same process occurs when the middle overwash ramp encroaches on an older component of the barrier island, such as Ocracoke and Portsmouth villages. During dry periods, windblown sands are trapped against the stabilized land mass; during stormy periods, these sands are reworked into a beach ridge by water that floods the middle overwash ramp. These beach ridges run subparallel to the portion of the land mass that has trapped the sands.

Isolated ringed dunes 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.

Middle Overwash Ramp: Paleo-inlet Spit

When an inlet opens through a barrier island segment, the upper overwash ramp is generally eliminated and the existing middle overwash ramp becomes the location of inlet spit formation. An inlet spit consists of one or more subparallel ridges that occur adjacent to an existing inlet or paleo-inlet. The spits are slightly curved ridge structures occurring at oblique angles to the ocean shoreline. The spit geometry results from two forces: the flow dynamics of regular, high spring tide, and small storm-tide overwash events that rework windblown sands deposited along the inlet during dry periods. During a tidal event, a higher inlet spit ridge that formed in response to a previous storm event may be truncated or breached, or may develop an accreted secondary ridge. Older inlet spits may contain small active dune fields, particularly after vegetation has been established. When an inlet closes and an upper overwash ramp reforms in front of the inlet spit, the spit becomes a paleo-inlet spit preserved on the middle overwash ramp.

Vegetation is absent on an active inlet spit. However, an inlet spit may be abandoned with the development of a younger spit as the inlet migrates. The older, abandoned inlet spit becomes grassed and, over time, may even become vegetated with 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 by strong vegetation zonation across the flat, 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

The platform marsh 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 are often cut with shore-perpendicular tidal channels to produce molar-tooth structures on the lower overwash ramp. Both ends of the tidal channels shallow, flatten, and broaden out into deltaic lobes. The tidal deltas are deposited by flooding through the tidal channels and may be intertidal or supratidal sand bodies. Fine-grained sediments of the tidal deltas are frequently bound by algae (microbial organisms) and occasionally sparsely vegetated with *Spartina patens* (salt meadow hay).

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 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 below MSL pond 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 northern Outer Banks 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), with 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

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 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

Small strandplain beaches 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

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 tidal channels have a recurved geometry that 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.

Examples of polydemic features include overwash channels (described in the "Upper Overwash Ramp" section), paleo-inlet spits (described in the Middle "Overwash Ramp Unit" section), and tidal deltas (described in the "Lower Overwash Ramp" section). Other major polydemic features are described below.

Tidal Channel Unit

Tidal channels, also known as tidal creeks, 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, particularly in areas adjacent to major inlets where astronomical tides are prevalent. The channels are often truncated by the overwash ramp as it migrates onto the platform marsh. However, 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 flow 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 angustiflora* (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 Unit

Ponds 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.

1) 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.
2) 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.
3) 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.
4) 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.
   a) 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.
   b) 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.
   c) 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.
5) 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.

Ponds vary in size, substrate composition, pH, vegetation, and water color; water chemistry is similar to that of local groundwater (Mallin et al. 2006). Ephemeral ponds, which may contain water for a few weeks or years, are polydemic; a survey of several on northern Ocracoke Island in August 2004 found that they had dimensions of 100 m^2 (1,076 ft^2) and about 0.5 m (1.6 ft) mean depth, with temperatures ranging from 31° to 33°C, salinities of 5 to 14 psu, and dissolved oxygen concentrations of 5.3 to 10.5 mg/L (72% to 140% saturation) (Mallin et al. 2006).

Ephemeral ponds provide important breeding habitat for amphibians and reptiles and support vertebrates, crustaceans, insects, mollusks, annelids, rotifers, and other species (Mallin et al. 2006). Fish living in the ponds came from overwash and intentional stocking. Species include *Lepomis gibbosus* (pumpkinseed), *Cyprinodon variegatus* (variegated minnow), *Gambusia a. holbrooki* (mosquitofish), *Fundulus confluentus* (marsh killifish), *Micropterus salmoides* (largemouth bass), *Lucania parva* (rainwater killifish), *Anguilla rostrata* (American eel), *Fundulus heteroclitus* (mummichog), *Lepomis machrochirus* (bluegill), *Cyprinus carpio* (carp), and *Menidia beryllina* (inland silversides) (Mallin et al. 2006). Mammals utilizing freshwater ponds include muskrats, otter, *Procyon lotor lotor* (raccoon), and *Odocoilus virginianus virginianus* (white-tailed deer) (Mallin et al. 2006).

Transverse Ridge Unit

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 *Vitus rotundifolia* (muscadine grape). The shrubs and vines occur throughout the forest, but their densest growth is generally near the periphery.

Dune Flat Unit

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.

When sufficient sediment is available, an aeolian dune field may form on top of a far more extensive aeolian dune flat. In this situation, the dune flat forms a broad platform that generally encircles the perimeter of the dune field. Such features are very important in the region extending from Kitty Hawk to Whalebone Junction, where aeolian dune flats have helped to build a barrier segment that is higher than most segments dominated by inlets and overwash. This difference has attracted development, resulting in almost total urbanization of this island segment.

Dominant vegetation on the pre-1930s aeolian dune flats differed markedly from that found after the 1930s between Kitty Hawk and Whalebone Junction. Frost (2000) described the dominant vegetation in the early 1900s based on regional photographs taken by the Wright Brothers between 1900 and 1912 in the area extending from Kill Devil Hills to Kitty Hawk. Because the aeolian dune flats have clean, well-sorted dune sands and higher elevations than overwash plains, a major freshwater aquifer frequently rises to the land surface. This process creates broad damp areas and shallow ponds dominated by algae and freshwater marsh plants, respectively. The small dunes rose above the water table and were dominated by *Spartina patens* (salt meadow hay) during non-stormy periods. Aeolian dune flats farthest from the ocean were usually stabilized by scrub shrub species and ultimately became forested with *Pinus* spp. (pine), *Ilex vomitoria* (yaupon holly), and *Quercus virginiana* (live oak).

In the 1930s, barrier island modification and urbanization began in earnest. Following bridge construction from the mainland to the barrier islands and paving of Highway 12 in the Kitty Hawk to Nags Head area in the early 1930s, initial construction of barrier-dune ridges in the late 1930s, and extensive construction of oceanfront motels and houses, the character of vegetation on the aeolian dune flats changed dramatically. The beach, which had been the major source of sand for aeolian and overwash transport processes, was cut off from the dune flats, decreasing the effects of wind and associated salt spray. In response, the aeolian dune flats were successively vegetated by an extensive growth of scrub shrub, followed by pine and live oak forests. Today, most dune flats in this area are fully developed, with lots, homes, and a highly urbanized understory of lawns and gardens, as well as the occasional occurrence of an upperstory of pine and live oak woods.

Dune Field Unit

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. In the region extending from Kitty Hawk to Whalebone Junction, sediments are provided by paleo–Roanoke River delta deposits associated with previous climatic conditions and sea-level stands. Consequently, much of this barrier segment is dominated by the extensive development of dune fields.

Before urban development in the 1930s, large individual dunes (e.g., Jockey's Ridge) with elevations of up to 45 m (148 ft) formed. The 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, which further complicates 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).

Dominant vegetation on the natural dune fields before the 1930s differed markedly from that occurring post-1930s. From 1900 through 1912, many natural dune fields, including those in front of Kitty Hawk Woods and Kitty Hawk Bay (e.g., Kill Devil Hill), on the front side of Nags Head Woods (e.g., Run Hill and Jockey's Ridge), and the Seven Sisters dune field in Nags Head Cove and the village of Nags Head, were active and essentially barren of vegetation (Frost 2000). The minor vegetation that did exist on these active dunes consisted of scattered grasses, including *Spartina patens* (salt meadow hay). Swales between many of the dunes contained shallow, freshwater ephemeral ponds dominated by algae and freshwater wetland vegetation.

After the establishment of Kill Devil Hill Monument National Memorial in 1927, work began in 1929 to stabilize with grass the Kill Devil Hill active dune utilized by the Wright Brothers. Construction of the first flight monument on top of Kill Devil Hill was completed in 1932, before this land was transferred to the NPS in 1933 (NPS 2002).

In the past (pre-1970s), dune fields occurring closest to the ocean front (e.g., Seven Sisters) tended to be most active, whereas those furthest from the ocean (e.g., Nags Head Woods) tended to be heavily forested. By the early 1970s, the ocean front had been completely developed and urbanization moved rapidly soundward and into the natural dune fields. The remaining Kill Devil Hills were quickly developed, followed by Nags Head Cove, the north end of Jockey's Ridge, and the Kitty Hawk dune field. Lastly, the village at Nags Head developed the southern half of the Seven Sisters dune field. Urban development in front of the dune fields cut off the sand source from the beach and modified and raised the wind field; the construction of houses and pavement and establishment of grass, urban gardens, and trees quickly stabilized the active dune fields.

Grass Dune Field Unit

Grass was planted in 1929 to stabilize the Kill Devil Hill active dune, which was utilized by the Wright Brothers and newly designated as the Kill Devil Hill National Memorial.

Forested Dune Field Unit

The major portion of Nags Head Woods dune field, which is situated on the back side of a wide island segment, has historically been heavily forested. Today, the high dunes generally contain a mature stand of mixed hardwood and pine forest with a perimeter zone of scrub shrub on the low dune flank along the estuarine side. Scrub shrub vegetation generally constitutes a transitional zone that occurs within the storm tide zone and grades downslope to the intertidal platform marsh of the lower overwash ramp.

Algal Flat Unit

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 Unit

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.

The most extensive and best developed sets of ridge and swale structures form Buxton Woods and Kitty Hawk Woods. Buxton Woods (located between Frisco and Buxton) is the largest maritime forest on the Outer Banks and is approximately 1,630 ± 200 years old (Mallinson et al. 2009). It is composed of multiple sets of ridge and swale structures occurring at slightly different angles, with each set bounded by a major erosional truncation, suggesting oscillating sets of events at several different time scales. The first set of ridges was built along the present Pamlico Sound shoreline and trends northeast–southwest. The formation of younger east–west-trending ridges built the island southward (Mallinson et al. 2009).

The Buxton Woods unit contains many freshwater ponds and marshes (locally known as sedges) that support wildlife. This area was impacted in 1994 by Hurricane Emily, which damaged pine forests; the resulting breakage allowed for subsequent insect infestation. Opening of the pine canopy enabled the establishment of hardwood forests in competition with the pines, returning this forest habitat to conditions like those preceding heavy logging for ship timbers in the 1800s and early 1900s (Mallinson et al. 2009).

Ridge and swale structures are dominant geomorphic units on complex barrier islands and are not products of overwash-dominated barrier island dynamics. No such structure is currently forming on the northern Outer Banks. Rather, the ridge and swale island segments 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, 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, as exemplified by the Kitty Hawk Woods island segment.

Similar ridge and swale features occur on the land masses occupied by Ocracoke and Hatteras villages. However, these ridge structures are rarely 2 m (6.5 ft) high and are spaced much farther apart compared to those in Kitty Hawk. They have wide marsh-filled swales. Many of the sand ridges have already been buried by the vertical growth of peat in response to the ongoing rise of sea level.

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.

Swale Marsh Unit

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.

Anthropic Features

Constructed Dune Ridge Unit

Constructed dune ridges are linear, ocean shoreline–parallel ridges that are built by sand transportation and bulldozing, then vegetated by the planting of grass. The size of these features is highly variable. In general, they are built over long beach segments and are up to 15 m (49 ft) wide at the base and up to 5 m (16 ft) tall. The purposes of these structures are to prevent the disruption of barrier island infrastructure by storm overwash and inlets, and to protect building superstructures and associated roads. They are built on the normal beach-overwash plain profile, which is in equilibrium with normal ocean dynamics. However, newly constructed dune ridges tend to be severely out of equilibrium and are rapidly scarped on the ocean side and readily eroded by storm surges.

The initial construction of dune ridges began in the late 1930s with the establishment of Works Progress Administration and Civilian Conservation Corps work camps. Ridges were initially built over the entire distance from the Virginia state line and Ocracoke Inlet utilizing many different sand-trapping methods, but they have not been maintained throughout this entire coastal stretch. Thus, some island segments contain only partial or terminated ridges. The constructed dune ridges have been rebuilt frequently in urbanized areas and in narrow island segments where Highway 12 occurs close to the ocean shoreline. Many island segments have multiple constructed dune ridges along with remnants of "going-to-sea" highways. In a few areas with sufficient sediment supply, the beaches tend to be very wide and shallow with low net erosion rates. Some dune ridges built within these wide beach segments have been naturally modified over time into natural dune fields, which are usually quite wide and high and comprise many irregularly shaped and scoured dunes with numerous small overflow channels.

Sand fencing has historically been used to stop and trap moving sand, creating long, linear constructed dune ridges that are up to 1 m (3.3 ft) high and hundreds of meters long. In the early 20th century, this method was also used routinely on unvegetated and algal flats within middle overwash ramps to preventing the sanding over of roads, ponds, and other features. Many of these constructed oceanfront dune ridges persist today because ongoing maintenance has minimized overwash and fostered the expansion of stable vegetation on the island.

Immediately after constructed dune ridges are built or rebuilt, they are planted with grass or implanted with sand fencing in an effort to stabilize the structure. The preferred vegetation along the oceanfront tends to be *Uniola paniculata* (sea oats) or *Ammophila breviligulata* (American beachgrass). In the island interior, the preferred stabilization vegetation tends to be *Spartina patens* (salt meadow hay). Old constructed dune ridges or sequences of two or three inner ridges frequently become vegetated 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).

Road/Parking Area Unit

Major highways in urban areas and paved roads and parking areas outside of the major urban areas have been mapped. Paved roads and parking lots within urban areas are not included on the map.

Dredged Channel/Spoils Unit

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 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).

The drainage ditches contain abundant periphyton, particularly during warmer months, and (in an August 2005 sample) consisted largely of floating mats of the blue-green alga *Microcoleus lyngbyaceus* intermixed with pennate diatoms (Mallin et al. 2006). Harpacticoid copepods, rotifers, protozoans, and nematodes graze on smaller algae and bacteria in the mat (Mallin et al. 2006). These ditches may be loci of intense microbial food web interactions, and may be important resources to small or young fish utilizing the marsh (Mallin et al. 2006).

Excavation Unit

Sand was commonly mined from portions of the barrier islands for construction of dune ridges or as fill material for roads or buildings elsewhere on the islands. The resulting holes have filled with water, becoming lakes or ponds that range from large, irregularly shaped structures to smaller square or rectangular structures. This unit also includes dredged harbors and marinas.

Where spoil is placed around an excavation as road bed within the supratidal zone, the dominant vegetation includes transitional-zone species, such as *Baccharis halimifolia* (salt myrtle), *Iva frutescens* (marsh elder), *Spartina patens* (salt meadow hay), and *Spartina cynosuroides* (giant cordgrass) or scrub shrub. Where the spoil rises 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).

Anthropic Overprint Unit

This category includes all major urban areas with dense patterns of buildings and roads. All urban areas, as well as campgrounds, Coast Guard stations, marinas, and cemeteries within Cape Hatteras National Seashore, the Pea Island Wildlife Refuge, Jockey's Ridge State Park, and Wright Brothers Historical Monument are mapped as an anthropic overprint. This unit includes paved roads and parking lots, but does not include dirt roads, power lines, or buildings. In predominantly urban areas, this unit includes only major state highways. Geomorphic features were mapped only where they remained in a recognizable and partially natural state within these highly modified areas.

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

Hoffman et al. (2007g) developed a geomorphic map of Cape Hatteras National Seashore using remotely sensed data. Descriptions of the processes and timing of unit formation are based on interpretation, rather than field-based studies. The map identifies the following geomorphic units in the intertidal, supratidal, relict, and anthropogenic groups (table 4). The unit descriptions provided below are taken primarily from Hoffman et al. (2007g), and supplemented by information from publications where cited.

Intertidal Group

Beach Unit

The beach is defined as the area between the 1998 wet/dry ocean shoreline (North Carolina Division of Coastal Management [NCDCM] 2003) and the toe of the Fore-island Dune Complex (delineated using a combination of slope and aerial imagery). Storms and high lunar tides subject the beach area to periodic flooding, particularly near inlets, where the beach merges laterally with sand flats of the Spit Complex Subgroup.

Sand Flat Unit

Sand flats are part of the Spit Complex Subgroup. They occur adjacent to the three active inlets in the mapped area. They are unvegetated and have low (<1.2 m [4 ft]) elevations and relief. They are subject to regular tidal flooding and overwash. Sand flats may contain areas of episodically ponded water and small isolated dunes, and seasonally may become encrusted with algae. Sand flats merge with the beach where the Fore-island Dune Complex first develops behind the beach.

Table 4. Summary of barrier island system units as mapped by the North Carolina Geological Survey.

Group	Subgroup or Map Unit (symbol)		
Intertidal	Beach (beach)		
	Spit Complex	Sand Flat (sand_flat)	
		Ridge and Swale (ridge_swale)	
	Marsh Platform (pf_marsh)		
Intertidal and Supratidal	Beach and Fore-Island Dune Complex	Dune Saddle (dnesadl_bch)	
Supratidal	Fore-Island Dune Complex Subgroup	Dune Ridges (dunerdge)	Interdune Swale and Dune Ridge (intswale_dr)
			Dune Saddle and Dune Ridge (dnesadl_dr)
	Overwash Complex Subgroup	Overwash Flat (owflat)	
		Overwash Flat and Overwash Channel (owflt_owchn)	
		Overwash Fan (owfan)	
		Isolated Dune (isodune)	
	Interior Dune (intdune)		
	Interior Marsh (intmarsh)		
	Back-Barrier Berm (bk_br_brm)		
Relict	Relict Beach Ridge Complex (rel_bch_rdge)		
	Relict Spit Complex (rel_splt)		
	Water Body (water)		
Anthropogenic	Airport/Landing Strip (airport_land)		
	Commercial/Industrial Facility (comm_indust)		
	Dredge/Spoil (drdge)		
	Filled (filled)		
	Erosion Control Structure (ersn_ctrl_st)		
	Excavation (excavate)		
	Dike (dike)		
	Waterfowl Impoundment (wtrfwl_impnd)		

Sand flats support tens of thousands of shorebirds representing at least 21 species annually. These areas are critical foraging sites for piping plovers breeding in the park, as well as migrating and wintering piping plovers from the Atlantic Coast and Great Lakes populations, currently listed federally as threatened and endangered, respectively (Mallin et al. 2006).

Ridge and Swale Unit

The arcuate ridge and swale unit, part of the Spit Complex Subgroup, occurs adjacent to the three active inlets. Where present, this unit is situated lateral to the sand flat and merges toward the island interior with the Fore-island Dune and Overwash complexes. Ridges and swales typically trend subparallel to the axis of a barrier and then curve toward the back of the island as they approach an inlet. Ridges range from incipient features to well-formed continuous structures to heavily dissected remnants. These units represent older, more stable portions of spit complexes.

Marsh Platform Unit

Marsh platforms are extensive on the back sides of barrier islands and along tidal creeks that cut into them. These areas are low lying (generally <0.6 to 0.9 m [2 to 3 ft] in elevation) and subject to regular tidal flooding. They are located along the sound-side shoreline. When they are located significantly inland of back-island tidal creeks, they are often found in depressions associated with relict features, such as the swales between relict beach ridges in the Buxton area or mid-island lows behind former sand flats.

Marsh platforms are relatively stable features and are quite extensive in parts of the barrier system. *Juncus* and *Spartina patens* are the dominant grass species inhabiting these platforms. A peat layer up to several feet thick has developed in concert with rising sea level and the associated increase in marsh elevation. Where sediment supply is insufficient for marsh aggradation into the sound, wave energy may undercut the peat and cause local shoreline recession. Updip (island-ward) areas are prone to storm overwash, which supplies sand to the marsh platforms' interior margins and raises their elevations above tidal influence. As this process continues, the Overwash Complex builds onto the marsh platform area.

Supratidal Group

Dune Ridge Unit

Dune ridges are part of the Fore-island Dune Complex Subgroup, which is a shoreparallel unit of higher elevation that occurs between the beach and island interior units. Dune ridges are the most prominent and extensive portions of the Fore-island Dune Complex. They are linear and shoreparallel. Dune heights vary, but generally are less than 6 m (20 ft). Dune toe elevations are typically 1.8 to 2.4 m (6 to 8 ft) on the front (ocean) side and 1.2 to 2.4 m (4 to 8 ft) on the back (island interior) side.

Intradune Swale Unit

Intradune swales are part of the Fore-island Dune Complex Subgroup. They are closed, relatively low-lying areas within dune complexes. These linear troughs are less than 3 m (10 ft) in elevation and occur between dune ridges.

Dune Saddle Unit

Dune saddles are part of the Fore-island Dune Complex Subgroup. They are gaps or breaks along dune ridge lines of the fore-island dune system, with elevations of less than 3 m (10 ft). Elevations are even lower in more extensive low-lying island segments, such as in the central Rodanthe map area. Saddles are important features of the dune complex in that they represent potential high-water flow pathways along ridge lines that are vulnerable to coastal flooding during major storms.

Overwash Flat and Overwash Channel Unit

Overwash flat is the dominant unit of the Overwash Complex Subgroup. This complex occurs behind the Fore-island Dune Complex and in front of the marsh platform. This area is elevated relative to the marsh platform and tends to have low to moderate relief; elevations typically range from 0.61 to 2.4 m (2 to 8 ft) and decrease gradually toward the sound side of the island. The Overwash Complex is a depositional feature receiving sand that is blown or washed over and through the Fore-island Dune Complex, most notably by storm events. Locally, the Overwash Complex extends into the sound.

Overwash flats represent the long-term accumulation of sand overwash behind the Fore-island Dune Complex. Discrete events deposit sand in lobate forms, which then coalesce into a single geomorphic unit through reworking by wind, water, and humans. In the southeastern part of Ocracoke Island and a few other localities, individual overwash fans and linear overwash channels that cut through the fore-island dune during storm events were sufficiently preserved to permit mapping.

Overwash Fan Unit

The overwash fan unit is part of the Overwash Complex Subgroup.

Isolated Dune Unit

The isolated dune unit is part of the Overwash Complex Subgroup. These features occur within or soundward of the overwash flat area. They appear to have a variety of origins, including: 1) as remnants of former fore-island dune ridges or large overwash fans, or 2) as constructional features caused by the trapping of sand by vegetation or anthropogenic features, such as sand fencing.

Interior Dune Unit

Interior dunes occur in several areas soundward of the Fore-island Dune Complex. They are larger than isolated dunes of the Overwash Complex. Interior dunes are significant geomorphic features of sizable areal extent, and are often the highest point on an island, with elevations of 3 to 27 m (10 to 90 ft). Most are vegetated.

Interior dunes range from isolated single ridges, as seen on Ocracoke Island, to more laterally extensive elevated features, such as on central Bodie Island.

Interior Marsh Unit

Interior marshes are not connected to ocean or sound waters, but often are located adjacent to water bodies such as ponds. Interior marshes usually occur 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 Unit

Back-barrier berms occur in the back portions of the barrier island system throughout much of Cape Hatteras National Seashore. They vary from very subtle linear features lying just slightly higher than the surrounding marsh platform to elevated (>3 m [10 ft]) features. Many berms form broad arcs in areas of apparent relict flood tidal deltas, suggesting that wave reworking of delta sand bodies facilitated berm development. Other berms are of less intuitive origin.

Relict Group

Relict Beach Ridge Unit

The relict beach ridge unit occurs as sets of parallel ridges and swales in island-interior portions of the Buxton area, just west of Cape Hatteras. Most elevations are 3 to 4.6 m (10 to 15 ft) or less, but rise to 9 m (30 ft) in the Buxton complex. Swales between ridges often contain interior marsh and isolated water bodies.

Fisher (1967) originally mapped these ridges using aerial photographs. Truncation of parallel dune sets by later dune sets oriented at slightly different angles allows delineation of individual sets of relict beach ridges and determination of relative age relationships. Fisher (1967) identified 13 sequences of ridge development in this area and termed this complex the "Hatteras group of relict beach ridges." His analysis included dune ridges classified in this report as part of the modern Fore-island Dune Complex.

A large, very complex interior dune dominates the Buxton-area landscape. Its morphology differs considerably from that of the Relict Beach Ridge Complex. It has a boxwork-like pattern of spurs and connecting transverse ridges, with elevations approaching 18 m (60 ft).

Less-pronounced ridge and swale topography forms a portion of the complex barrier island in the Hatteras Village area. Despite considerable human modification of the landscape in this area, two sets of ridges can be recognized. Ridges in this area are less than 2.4 m (8 ft) in elevation, with some barely rising above the enveloping marsh platform in the soundward portion of the island.

Relict Spit Unit

Relict spits are subtle arcuate-shaped ridge and swale features located in mid- to back-island areas. They exhibit topography and geomorphic attributes characteristic of modern spit complexes, but lack connection to an active inlet. These areas have been interpreted as older, inactive spit complexes that developed adjacent to former inlets. Relict spit complexes are notable in the vicinity of Avon and south of Buxton.

Water Body Unit

Water bodies that appeared to be ephemeral features, such as those occurring on sand flats or in intradune swales, were not mapped.

Anthropogenic Group

Airport/Landing Strip Unit

Airport landing strips occur in the Buxton, Ocracoke, and Wright Brothers Memorial map areas.

Commercial/Industrial Facility Unit

Facilities such as marinas, ferry terminals, and other large developments were mapped in this category.

Dredge Spoil Unit

Dredging is a very common practice for construction and modification of landforms throughout the map area. This map unit is reserved for specific positive-relief features that can be confidently identified, with a dredged waterway as the source of each spoil deposit. Older spoil islands may not have been recognized due to subsequent wave modification and vegetation.

Filled Unit

Filling of low-lying areas for development purposes has been and continues to be a common practice, especially in wetland areas. Evidence of artificial fill includes linear boundaries, odd juxtapositions with or within the marsh platform, or atypically high elevations in comparison with surrounding areas.

Erosion Control Structure Unit

Where the shoreline has been stabilized through hardening, structures sufficiently large to map at 1:24,000 scale were included. The terminal groin at the north end of Pea Island is an example.

Excavation Unit

A limited number of low areas were recognized as artificially excavated, based on personal communication or inferred from imagery and elevation data.

Dike Unit

This map unit applies to dikes built for waterfowl impoundment areas in Pea Island National Wildlife Refuge.

Waterfowl Impoundment Unit

Several large water-filled impoundments occur in Pea Island National Wildlife Refuge.

Paleontological Resources

Cape Hatteras National Seashore is one of 258 NPS areas with documented paleontological resources as of April 2015. 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 the actual organism such as bones, teeth, shells, or leaves. Trace fossils are evidence of biological activity; examples include burrows, tracks, or coprolites (fossil dung). Fossils in NPS areas occur in rocks or unconsolidated deposits, museum collections, and cultural contexts such as building stones or archeological resources. The NPS Geologic Resources Division Paleontology website, http://www.nature.nps.gov/geology/paleontology/index.cfm, provides more information.

Paleontological resources present opportunities for education, interpretation, and scientific research at Cape Hatteras National Seashore. They contain valuable information about the geologic history and recent evolution of the area. Documented fossils collected from the park are archived at the NPS Museum Resource Center (Suitland, Maryland) and the Southeast Archeological Center (Atlanta, Georgia) (Tweet et al. 2009).

Mixed assemblages of Quaternary marine fossils are abundant on North Carolina beaches and can locally constitute up to 75% of beach shells (Riggs et al. 1995). Landward migration of the barrier islands exposes remnants of forests and swamps that once grew on their back sides. These remnant trees and organic peat deposits are generally hundreds to hundreds of thousands of years old (Dolan and Lins 1986; Tweet et al. 2009). Sediments eroded from relict inlet deposits provide another source of shell fragments and other fossils of pre-Holocene age (Herbert and Heron 1978; Tweet et al. 2009).

Although the geologic units at Cape Hatteras are young, older fossils are accessible by dredging and drilling operations and via offshore sources that are washed onshore. Culver et al. (2008a) drilled deep cores along the length of the northern Outer Banks and found Pliocene microfossils as deep as 60 m (200 ft) (between Nags Head and Whalebone Junction). Microfossils as old as Oligocene age have been recovered from deep cores at Cape Hatteras (Richards 1968; Tweet et al. 2009), and even older fossils were found in the deep (3,061 m [10,044 ft]) exploratory well that Esso drilled near the Cape Hatteras Lighthouse more than 60 years ago (Coffey 1977). Other local subsurface and offshore remains include sponges, scaphopods, barnacles, bivalves, and gastropods (Tweet et al. 2009).

The offshore continental shelf produces a variety of fossils that may wash ashore, including those of algae, foraminifera, corals, bryozoans, mollusks, ostracodes, barnacles, and echinoids, as well as polychaete worm tubes (Macintyre and Milliman 1970; Cleary and Thayer 1973; Culver et al. 2008b; Tweet et al. 2009). Vertebrate remains also wash ashore, including an *Odobenus rosmarus* (walrus) skull, radiocarbon dated to 36,760 ± 570 years before present, that washed up on the beach at Salvo in 1990 (Stover 2002; Tweet et al. 2009). Other vertebrate remains known from the area include a nearly complete skull of a female *Bootherium bombifrons* (Harlan's muskox or woodland muskox), fragments of whale vertebrae, and a group of three auditory bullae (hollow structures enclosing part of the ear) from whales (McDonald and Ray 1993; Tweet et al. 2009).

Fossils in the park may also be associated with cultural resources, such as fossils altered or modified by humans (Kenworthy and Santucci 2006; Tweet et al. 2009). According to the archeological record, humans were not present on the Outer Banks before about 3,000 years ago; at least 29 archeological sites predate European contact. Twenty of these sites have shell middens (refuse piles created by humans) or other shell relicts. Excavations at Fort Raleigh National Historic Site yielded artifacts from the late 16th century, including oyster shells associated with copper plates that may have been strung together for ornamental use (Thompson 1977; Tweet et al. 2009).

There are a variety of management issues associated with paleontological resources in Cape Hatteras National Seashore. They are summarized in the "Paleontological Resource Inventory, Monitoring, and Protection" section.

Geologic Resource Management Issues

This chapter describes geologic features, processes, or human activities that may require management for visitor safety, protection of infrastructure, and preservation of natural and cultural resources in Cape Hatteras National Seashore. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

Geologic issues facing Cape Hatteras National Seashore include natural processes, anthropogenic influences, and natural processes exacerbated by anthropogenic influences. The GRI scoping meeting (NPS 2000) and subsequent discussions identified 11 major issues that are related to the park's geology and that shape the park's resources:

- Shoreline Erosion
- Coastal Vulnerability and Sea-Level Rise
- Hurricane Impacts and Human Responses
- Inlet Modifications
- Recreational and Watershed Land Use
- Coastal Engineering and Shoreline Armoring
- Highway 12 Transportation Corridor
- Geomorphic Mapping Needs
- Paleontological Resource Inventory, Monitoring, and Protection
- Additional Information Needs

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.

Parks developing monitoring protocols can contact their NPS Inventory & Monitoring Network. They 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) shoreline 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.

The NPS Water Resources Division, Ocean and Coastal Resources Branch website (http://www.nature.nps.gov/water/oceancoastal/) has additional information 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://nature.nps.gov/water/oceancoastal/shorelinemaps.cfm.

Shoreline Erosion

Barrier islands recede when erosive forces exceed the ability of the sediment supply to replenish the beach system. Wave energy, sediment availability, sea-level change, and human activities vary and influence the balance between erosion and deposition (Dolan and Godfrey 1972).

Ocean shoreline change rates along Cape Hatteras National Seashore range from more than 2 m (6.5 ft) accretion to more than 2 m (6.5 ft) erosion per year (fig. 21), based on shoreline datasets from NOS T-Sheets and LiDAR data spanning 150 years (Pendleton et al. 2004). Erosional response and the post-storm shape of the shoreface profile are controlled by the degree of consolidation of sediments underlying the modern sand sheet (Riggs et al. 1995).

Estuarine shoreline shape and recession rates are controlled by variables including fetch, offshore depth and slope, shoreline geometry, height and composition of sediment bank (e.g., low peat banks are more erodible than high clay banks), presence of fringing vegetation, presence of boat wakes, water level, size and shape of the associated water body, and storm frequency and intensity (Riggs and Ames 2003; Corbett et al. 2008). Estuarine shoreline change in the Albemarle-Pamlico Estuarine System ranges from 0.2 m (0.6 ft) accretion (back-barrier beaches) to 1 m (3.3 ft) erosion (mainland marshes) per year (Riggs and Ames 2003). Mainland marsh and low sediment banks, which are the most abundant estuarine shoreline types (85% of such features in northeastern North Carolina), tend to have the highest average erosion rates. Bluffs and high sediment banks, which are less abundant (8%), erode more slowly (approximately 0.8 m [2.6 ft]/year). Swamp forest shorelines are the least abundant shoreline type (7%) and have the lowest erosion rates (0.7 m [2.3 ft]/year) due to their low offshore gradients and the presence of trees that abate wave energy.

In some cases, erosion rates of ocean and estuarine shorelines are greater than rates of sediment replenishment, causing an island to narrow and potentially disappear as its cross-sectional profile steepens. This process may be reversed by a significant overwash event or the development of a flood tidal delta that supplies sediment in an inlet (Ames and Riggs 2006j).

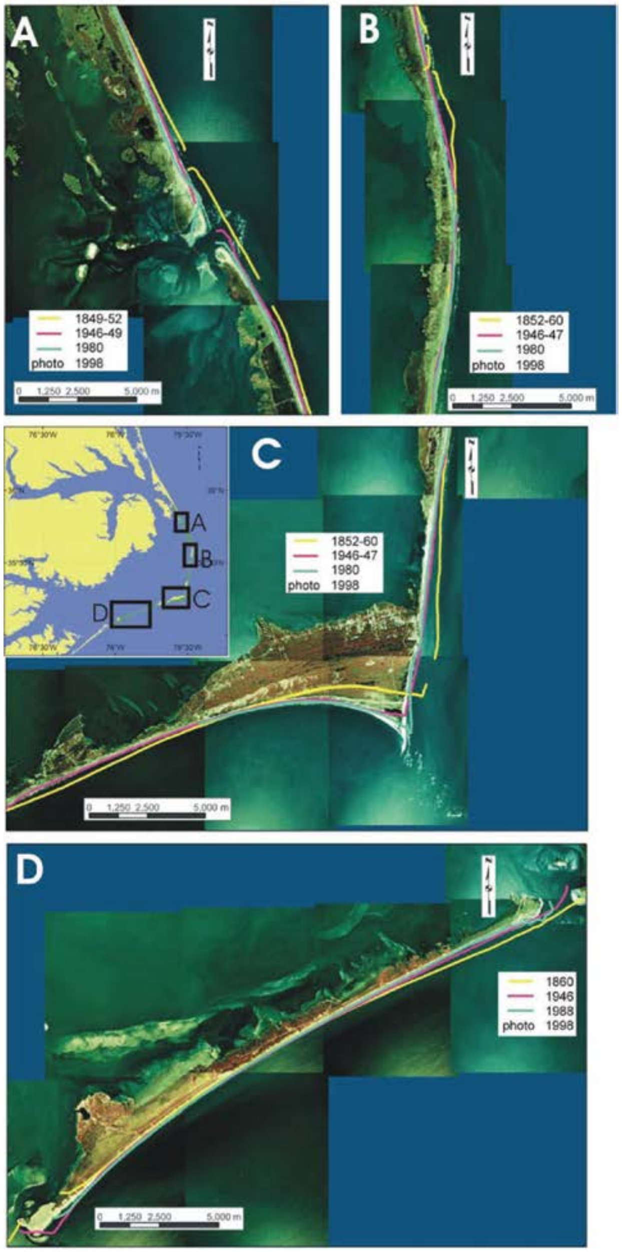

Figure 21. Historic shoreline positions. These maps span the past 150 years along Cape Hatteras National Seashore, collated from NOAA T-Sheets, NCDCM (2003) and LiDAR data (Morton and Miller 2005). Ocean shoreline change rates range from more than 2 m (6.5 ft)/year accretion to more than 2 m (6.5 ft)/year erosion. Figure 12 from Pendleton et al. (2004).

Examples of narrow, low, oversteepened barrier segments, where erosion rates are highest and the likelihood of inlet breaching in the future is high, include the island segment immediately north of Rodanthe, the southern portion of Pea Island, the Buxton and Isabel inlet areas, and northeastern Ocracoke Island (Ames and Riggs 2006j; Mallinson et al. 2008b). Within the estuary, shoreline erosion at Fort Raleigh National Historic Site threatens visitor infrastructure (theatre), cultural resources (cemetery), and likely also unknown and unexcavated archeological resources (NPS 2007).

Coastal Vulnerability and 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 (fig. 22) (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 uptake and the addition of meltwater from ice sheets and glaciers. Relative local sea-level rise, as measured by the growth of salt-marsh peat, tide gauge records, and the submergence of human structures, refers to the combination of global rise with regional and local factors, such as sediment compaction and changes in ocean circulation patterns and wind patterns.

Historic Sea-Level Rise

Sea level has fluctuated over geologic time and over the past millennia (table 5). 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 comparison, sea-level rise in the 1,000-km (600-mi) stretch of the coastal zone from Cape Hatteras, North Carolina, to north of Boston, Massachusetts, has increased 2 to 3.7 mm (0.08 to 0.14 in)/year. The authors expect this rate of increase to continue if global temperatures continue to increase. This sea-level-rise hotspot is consistent with the slowing of Atlantic Ocean circulation, which in turn may be related to changes in water temperature, salinity, and density in the subpolar North Atlantic.

Over the past 12,000 years, relative sea-level change along the North Carolina coast has varied as a function of latitude, with higher rates of rise in the north and lesser rates of rise in the south. This pattern is a function of the local geology as well as differential crustal subsidence and uplift (North Carolina Coastal Resources Commission [NCCRC] 2010). The rate of sea-level rise, based on microfossils from coastal marsh sites along the northern Outer Banks, was stable from 100 BCE (Before Common Era, preferred to “BC”) to 950 CE (Common Era, preferred to “AD”), then rose at a rate of 0.6 mm (0.02 in)/year until 1400 CE. It then stabilized again until the end of the 19th century before increasing again to a mean rate of 2.1 mm (0.08 in)/year beginning around 1880–1920 (Kemp et al. 2011). Since 1963, sea level has been rising at an estimated rate of 4.5 ± 1.5 mm (0.18 ± 0.06 in) per year (Kemp et al. 2009). At Duck, North Carolina, short-term (1980–2000) tide gauge data indicate that sea level is rising about 4.5 mm (0.18 in)/year (Zervas 2004, as cited in Riggs et al. 2008b). The rate of sea-level rise at Oregon Inlet Marina is 2.82 ± 0.44 mm (0.11 ± 0.02 in) per year, based on tide gauge data from 1977–2006. In Beaufort, North Carolina (about 75 km [47 mi] southwest of Ocracoke Island), the rate is 2.57 ± 0.44 mm (0.10 ± 0.02 in)/year, based on tide gauge

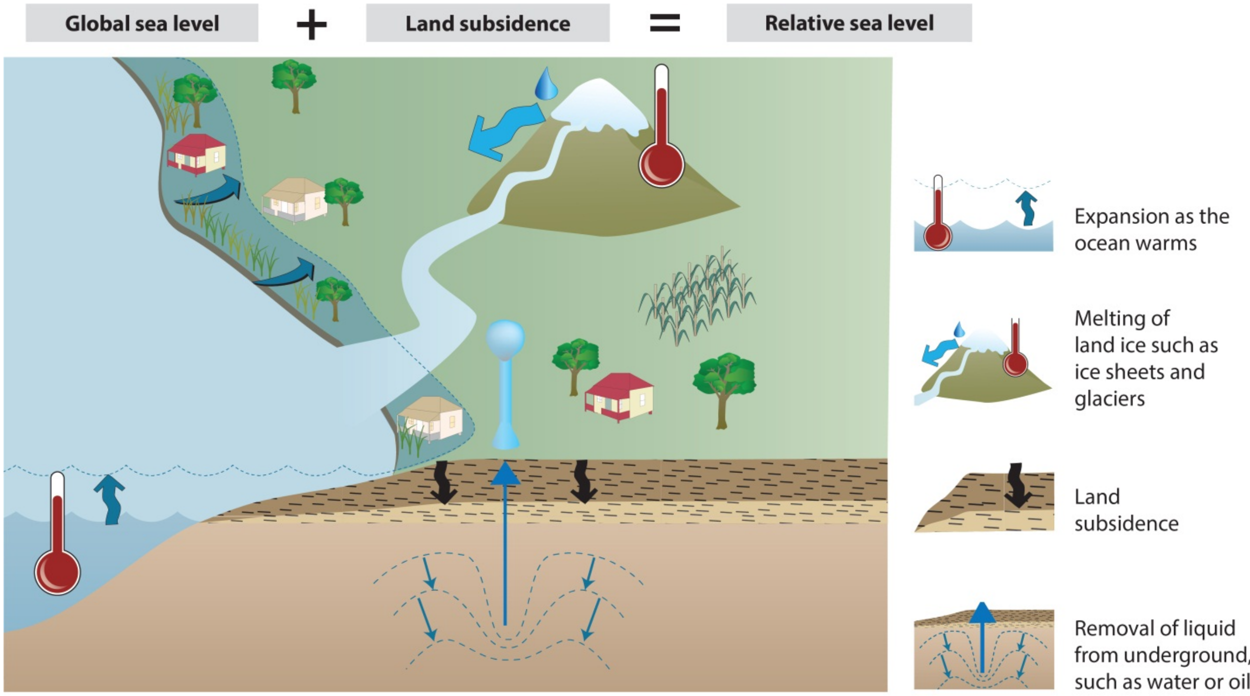

Figure 22. Schematic graphic illustrating major causes of sea-level change. Sea-level rise is caused by global climate warming in combination with regional and local effects of geologic, oceanographic, and atmospheric conditions, which vary spatially and temporally. Additional causes include terrestrial water storage, building of reservoirs, changes in runoff, seepage into aquifers, vertical land movements including delta subsidence, tectonic displacements, and glacial isostatic adjustment (Williams 2013). Graphic by Jane Hawkey and Jane Thomas (Integration and Application Network, University of Maryland Center for Environmental Science) available online: http://ian.umces.edu/imagelibrary/ (accessed 27 April 2015).

Table 5. Rates of relative sea-level rise in northeastern North Carolina for the last 18,000 years, based on studies of salt-marsh peat on Roanoke Island, North Carolina (as compiled by Riggs et al. 2011).

Time Period	Rate of Sea-Level Rise	Coastal Events
18,000–11,000 years ago	1.3 m (53 in)/100 years	Shore zone migrates onto and across much of continental shelf.
11,000–8,000 years ago	0.53 m (21 in)/100 years	Initial flooding of the drowned-river estuarine system.
8,000–3,500 years ago	0.25 m (10 in)/100 years	Formation of modern drowned-river estuarine system. Initial formation of barrier islands proximal to their modern location.
3,500–100 years ago	0.13 m (5 in)/100 years	Development of modern barrier island system.
100 years ago–present	0.32 m (12.6 in)/100 years	Increased rate of upslope migration and increased coastal engineering efforts.
late 20th century (1980–2000) (Duck, NC, tide gauge)	0.46 m (18 in)/100 years	Continued increase in sea-level rise rate.

data from 1953–2006 (Zervas 2009). Data from NOAA (2013b) and summarized by Caffrey (2013) show that sea level has risen around Beaufort North Carolina at the rate of 2.8 mm (0.11 in) per year from 1953 to 2012.

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. 23) (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

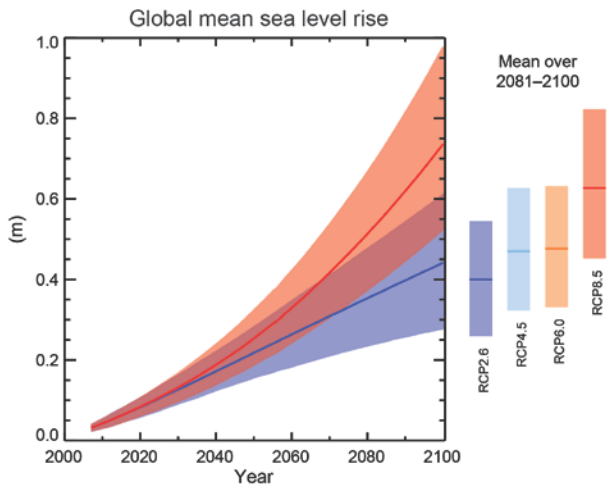

Figure 23. Projected sea-level rise by 2100 (in meters). Over the next century, global sea level will rise, although the magnitude of projections under various modeling scenarios varies. Figure 9 from Church et al. (2013).

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). 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), with variable regional and temporal influences on local rates of sea-level rise depending on geophysical and oceanographic factors (Williams 2013).

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). A 1-m (3.3-ft) rise is considered a good estimate for planning purposes because 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), and because it is not located at the upper or lower extreme of valid projections (NCCRC 2010).

Coastal Impacts of Sea-Level Rise

As sea level rises, various processes modify coastal landforms, causing cumulative impacts at a range of spatial and temporal scales (Williams 2013). Coastal evolution in response to sea-level rise and storms is influenced by several conditions, including geologic framework (underlying geology) and nearshore bathymetry (Honeycutt and Krantz 2003; Browder and McNinch 2006; Miselis and McNinch 2006; Schupp et al. 2006; Wikel 2008), characteristics of coastal landforms, coastal and nearshore oceanographic processes (i.e., waves, currents, circulation), sediment supply and transport, and human actions that alter sediment movement (e.g., jetties) (Williams 2013).

Different rates of sea-level rise are tied to the formation of particular types of landform. For example, global deltas formed approximately 8,000 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).

The northeastern North Carolina coastal plain is highly vulnerable to rising seas due to the low and narrow character of the barrier islands, the flat coastal plain surface extending many kilometers landward from the coast, and the accelerated rate of local sea-level rise relative to global rates (Williams 2013). All barrier islands of Cape Hatteras National Seashore are already within the 100-year flood zone (Pendleton et al. 2004).

Pendleton et al. (2004) evaluated the coastal vulnerability of Cape Hatteras National Seashore to sea-level rise based on six variables: (1) geomorphological type of shoreline, which dictates relative resistance to erosion; (2) historical shoreline change rate (erosion/accretion); (3) regional coastal slope, which indicates relative susceptibility to flooding; and three physical process variables that contribute to the inundation hazards of a coastline: (4) relative sea-level change, (5) mean significant wave height, and (6) 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, personal communication, 12 December 2013). Pendleton et al. (2004) found that the geomorphology of the Cape Hatteras region varies from highly vulnerable barrier islands with dunes to very highly vulnerable washover- and inlet-dominated barrier islands. Of the six equally ranked variables, values for shoreline change, geomorphology, regional coastal slope, and significant wave height had the largest alongshore ranges, and therefore the strongest influence on the overall vulnerability score for each section of the island. Of the 195 km (120 mi) of ocean and inlet shoreline mapped, 54% was classified as having high or very high vulnerability, and 16% as having low vulnerability (fig. 24).

Barrier islands likely have thresholds or tipping points of geomorphic stability, such that when limits of sea-level rise and storm activity are exceeded, or sediment supply rates decrease to an unstable level, they become unstable and prone to irreversible changes in form and position (Riggs and Ames 2003; Gutierrez et al. 2009; Moore et al. 2010, 2011). These changes may result in increased landward migration, geomorphic change such as reduction in size or segmentation, or, in extreme cases, transformation of a barrier island into a subaqueous sand shoal (i.e., submergence of the barrier island) (Williams 2013). Gutierrez et al. (2007) discussed the following indicators of 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

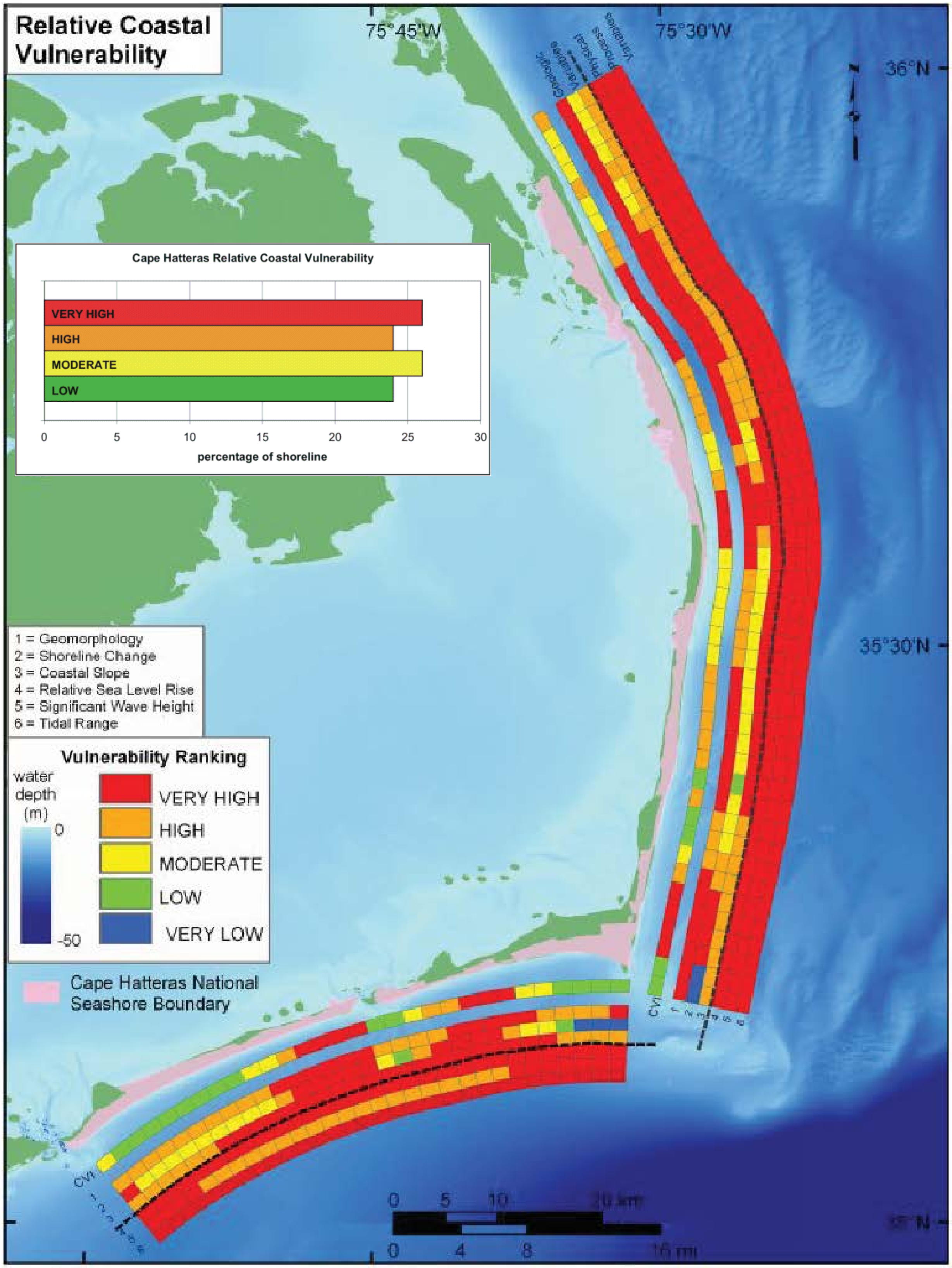

Figure 24. Map of coastal vulnerability of the northeastern portion of the North Carolina barrier islands, including Cape Hatteras National Seashore, to sea-level rise. Vulnerability differs by location, depending on six main variables: geomorphology, shoreline change, coastal slope, relative sea-level rise, significant wave height, and tidal range. Figures 13 and 14 from Pendleton et al. (2004).

- Increased frequency of barrier island breaching and inlet formation and widening
- Barrier island segmentation

In the past, portions of the Outer Banks were segmented for periods of a few hundred years, and later reformed (Mallinson et al. 2005; Culver et al. 2008a). Given the potential for future increases in sea level and/or 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). 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 morphological changes through erosion, overwash, and inlet formation, as they have over the last several centuries (fig. 25, table 6). Model results reported by Moore et al. (2007) 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 (32 ft)/year, about 2.5 times more rapidly than at present but within the range of rates observed for rapidly migrating barrier islands elsewhere (e.g., in Louisiana). When sea level rises more quickly than the rate at which the shoreface can erode to provide sediment to the island, the island begins to disintegrate and a state change (threshold crossing) occurs (Moore et al. 2010). Human mitigation efforts, such as beach nourishment, result in little reduction in barrier island migration rates and barrier island vulnerability to collapse (Moore et al. 2007).

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, although tidal wetlands with sufficient sediment input may prevail (Williams 2013). In North Carolina, vertical accretion rates of marshes have largely matched the rate of sea-level rise, but 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 6). With a rise of 10 mm (0.4 in)/year, fringe wetlands of North Carolina's lower coastal plain would drown, and peat-based wetlands would be unlikely to maintain elevation relative to sea level as the peat, root map, and vegetation would first be killed by brackish water. Creation of additional inlets due to sea-level rise would change the estuarine system from what is now a predominantly wind-driven tide to an astronomical tide–driven regime, increasing tide range, salinity, and wave activity, which would impact wetlands (Feldman et al. 2009).

Impacts of Sea-level Rise on Facilities

In addition to impacts on environmental features and processes, park facilities will also be impacted by rising sea level. The NPS developed a report entitled "Adapting To Climate Change in Coastal Parks: Estimating the Exposure of FMSS-Listed Park Assets to 1 m of Sea-Level Rise" (Peek et al. in press). This report includes the

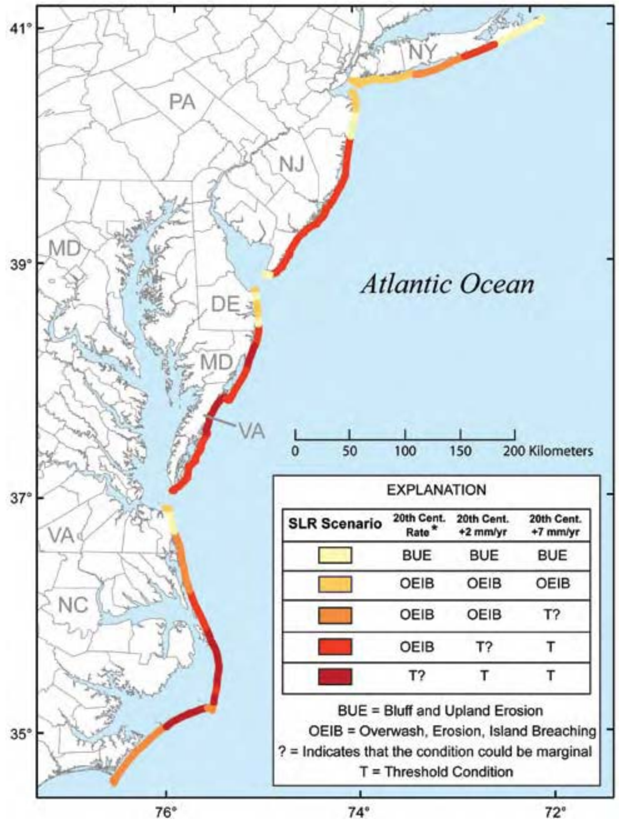

Figure 25. Map showing potential coastal responses to three sea-level rise scenarios. If mid-Atlantic sea-level rise continues at the present rate, the majority of wave-dominated barrier islands along the mid-Atlantic coast will almost certainly continue to undergo morphological changes through erosion, overwash, and inlet formation. Additional changes will occur under higher rates of sea-level rise. Figure 4 from Gutierrez et al. (2009).

geospatial location and approximate elevation of over 10,000 assets in 40 coastal parks, based on information within the NPS Facilities Management Software System (FMSS) and supplemented with other datasets, collaboration with park staff, and field visits to locate assets. Assets were characterized based on their overall exposure to long-term (1 m) sea-level rise and associated storm vulnerability, and were categorized as having either high exposure or limited exposure to sea-level rise impacts. According to Peek et al. (in press), more than 550 coastal assets are mapped within Cape Hatteras National Seashore and all of them are considered "high exposure" to 1 m of sea-level rise. Assets within Wright Brothers National Memorial and Fort Raleigh National Historic Site are included in the Cape Hatteras list.

Coastal Resource Management and Planning

The NPS Coastal Adaptation Handbook (RM 39-3; Beavers et al. in review, expected spring 2015) will provide climate change adaptation guidance to coastal park managers in Cape Hatteras National Seashore, Fort Raleigh National Historic Site, Wright Brothers National Memorial and the 115 other parks that have been identified by their regional offices as potentially vulnerable to sea-level change. Focus topics will include NPS policies relevant to climate change, guidance on

Table 6. The rate of sea-level rise will determine the responses of coastal wetlands and their driving processes. Table 4.3 from Cahoon et al. (2009).

Scenario	Vertical Accretion of Wetland Surface	Shoreline 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

evaluating appropriate adaptation actions, and adaptation opportunities for planning, incident response, cultural resources, natural resources, facilities and assets, and infrastructure. The handbook will also provide guidance on developing communication and education materials about climate change impacts, and it will detail 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 is also developing a cultural resources climate change response strategy that connects climate science with historic preservation planning. The summary report from the Preserving Coastal Heritage workshop in 2014 identified and described six climate change adaptation options for cultural resources and cultural landscapes (no active intervention; offset stressors; improve resilience; manage change; relocate or facilitiate movement; document and release). Additional information about the workshop, and associated presentations and reports, are available at https://sites.google.com/site/democlimcult/ (National Park Service 2014; accessed 21 April 2015).

Hurricane Impacts and Human Responses

Hurricanes and other major storms are important drivers of geomorphological change along the Outer Banks, as the winds, waves, and storm surge move sand across and off of the islands. Riggs and Ames (2006) asserted that migration of the barrier islands upward and landward in a back-stepping motion would be driven by a single large storm or a series of smaller storm events with storm surges of 4 to 10 m (13 to 33 ft; category 3 or higher hurricanes on the Saffir-Simpson scale describing hurricane impacts; table 7). According to data compiled by Caffrey (2013) for Cape Hatteras visitor center and Cape Hatteras Lighthouse (Buxton), storm surges are projected to range from 2.4 m (7.9 ft) above current sea level (storm surge heights will change over time as sea level rises) for a category 2 at mean tide to 3.7 m (12.3 ft) for a category 5 at high tide. Caffrey's (2013) compilation also indicates storm surges at Fort Raleigh National Historic Site from 1.9 m (6.1 ft) for a category 2 at mean tide to 3.6 m (11.7 ft) for a category 5 at high tide. Data for Wright Brothers National Memorial (see Caffrey 2013) suggest the park would be "dry" during a category 2 at mean tide with a storm surge of 4.5 m (14.9 ft) during a category 5 at high tide.

The chance that a hurricane will make landfall somewhere on the Outer Banks in a given year is 12% (8.6-year expected return period), and the likelihood that hurricane-speed winds will affect the Outer Banks in a given year is even higher (18%, equal to a 5.5-year expected return period) (Smith et al. 2006). Although higher-category storms are rare—only one category 4 storm (Hurricane Hazel in 1954) struck the North Carolina coast between 1851 and 2012 (NOAA 2013a)—lower-category storms regularly cause significant erosion and infrastructure damage, as evidenced by Hurricane Isabel in 2013 (category 2) and Hurricane Sandy in 2012 (category 1).

Ecological Impacts of Hurricanes on Estuaries

Perturbations caused by hurricanes affect Pamlico Sound's phytoplankton communities, which account for

Table 7. The Saffir-Simpson Hurricane Wind Scale is a 1 to 5 rating based on a hurricane's sustained wind speed. 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.

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.

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

at least 80% of primary production sustaining the food webs of the Pamlico Sound and its tributaries, according to a study by Paerl et al. (2006). This study found that an increase in the number of hurricanes with high rainfall and high flood production would lead to increased nutrient loading and greater frequency, intensity, and spatial coverage of phytoplankton blooms, as well as expansion of 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).

Impacts of Hurricanes on Infrastructure

Hurricanes, tropical storms, and nor'easters impact infrastructure along the Outer Banks and in Cape Hatteras National Seashore through erosion of protective dunes, damage to Highway 12, and destruction of coastal buildings. Storms buckle asphalt roads and deposit thick beds of overwash sand, as occurred during Hurricane Sandy and nor'easters between October 2012 and March 2013. Storms also open new inlets through the barrier islands, as occurred during Hurricane Isabel in 2003 and Hurricane Irene in 2011. Immediately following each storm, roads are repaired, inlets and breaches are filled, and overwash sand is pushed back toward the beach to create protective dunes (Riggs et al. 2008b, 2011; Saunders et al. 2012). These practices stop natural landward migration by elevating and widening the barrier island, preventing sand from remaining on and moving across the island and through the inlets to the island's estuarine shoreline. Ocean shoreline erosion continues, but the natural overwash processes that elevate and widen islands are prevented. For additional examples of human responses to hurricane impacts, see the "Inlet Modifications" and "Highway 12 Transportation Corridor" sections of this chapter.

Impact of Climate Change on Hurricanes

Climate change is expected to increase hurricane intensity in the North Atlantic Basin, according to the 2013 IPCC report (Kirtman et al. 2013). Saunders et al. (2012) stated that hurricanes have become stronger in the last 30 years, coinciding with an increase of 1.1°C (2°F) in sea-surface temperature where hurricanes form. Temperatures at Cape Hatteras National Seashore were 0.67°C (1.2°F) warmer in 2000–2011 than during 1961–2000, and a medium–high future emissions scenario projects that they will rise an average of 1.67°C (3°F;

average daily summer temperatures up to 30.1°C [86.2°F]) by 2051–2060 (Saunders et al. 2012). Saunders et al. (2012) believe that hurricanes have also increased average summer wave heights along the Atlantic coastline since 1975.

The strength of Atlantic hurricanes is likely to increase in this century, with higher peak winds, rainfall intensity, and storm-surge height and strength (Saunders et al. 2012). An increase in storm activity will increase the rate and extent of ocean and estuarine shoreline erosion and associated land loss throughout the coastal system of North Carolina (Culver et al. 2008a). Additionally, increased storm activity will open new inlets, which will in turn affect estuarine physical and chemical dynamics, including increases in astronomical tidal range, salinity content, and water column mixing, and associated changes in nutrient dynamics and turbidity. These changes 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).

Inlet Modifications

Inlet dynamics are a critical component of natural barrier island processes and sediment transport at Cape Hatteras National Seashore (see the "Geologic and Environmental Features and Processes" chapter for additional information). Inlet size and location shift in response to each storm, and a stable, deep channel is rarely maintained naturally (Riggs et al. 2009). Anthropogenic modifications of an inlet, such as dredging andcoastal engineering, disrupt the inlet's ability to respond to storms, to bypass sediment between islands, to exchange sediment between flood and ebb tidal deltas, to migrate, and to provide sediment to downdrift shorelines (Riggs et al. 2009). Inlet stabilization is one of many examples of human efforts to protect coastal development from waves and flooding, to mitigate erosion, and to maintain navigation channels, which have often altered the behavior of coasts considerably (Williams 2013).

The navigability of some modern inlets through the Outer Banks is actively maintained through dredging. Newly opened inlets are often closed artificially to maintain the highway infrastructure. Only one inlet, Oregon Inlet, has been modified with a terminal groin and revetment in an effort to stabilize it. Several effects of these management actions are described below.

Buxton Inlet: Filling and Dredging Increase Vulnerability

The Ash Wednesday nor'easter of March 1962 opened Buxton Inlet (fig. 26) through a narrow portion of Hatteras Island between the towns of Buxton and Avon. This inlet was 503 m (1,650 ft) wide and had a maximum depth of 3.7 m (12 ft) below National Geodetic Vertical Datum (NGVD) 29 (Wamsley et al. 2009). A bridge built over this inlet was destroyed in another nor'easter in December 1962. The US Army Corps of Engineers then filled the inlet in January and February 1963 by dredging sand from its flood tidal delta and the adjacent estuary. This flood tidal delta was mined again in the 1960s for a series of beach nourishment projects, which created a series of deep channels and holes (e.g., Canadian Hole) along the back of the barrier; such features persist in the area known as the Haulover (Mallinson et al. 2008b). These human modifications to the inlet and flood tidal delta, combined with impacts of storms to the sound side of the island, increased the rate of estuarine shoreline erosion and exacerbated island narrowing (Riggs and Ames 2006). Shoreline erosion between 1852 and 1998 removed approximately 760 m (2,500 ft; 76%) of island width (Riggs et al. 2008). As a result, this location is vulnerable to future breaching (Mallinson et al. 2008b).

Isabel Inlet: Costly Infilling Does Not Reduce Vulnerability

In September 2003, Hurricane Isabel approached the North Carolina coast as a category 5 hurricane on the Saffir-Simpson scale (table 7); it had weakened to a category 2 storm by the time it made landfall (Smith et al. 2006). At the point of landfall, maximum wind speeds were approximately 161 km/h (100 mph) and storm surges were 2 to 2.4 m (6.5 to 8 ft) above normal tide level (Wamsley et al. 2009).

The storm breached Hatteras Island about 10 km (6 mi) northeast of Hatteras Inlet between the villages of Hatteras and Frisco, where a previous inlet had been opened in 1933 (fig. 27). This area, a known erosion hotspot, is one of the narrowest and least elevated sections of Hatteras Island (Sallenger 2003), with a long-term shoreline recession rate of about 0.9 to 1.2 m (3 to 4 ft)/year (Overton and Fisher 2004). The breach was caused by elevated water levels and wave attack from the ocean side (Wamsley et al. 2009).

The 600-m- (1,970-ft-) wide inlet had three channels that formed through underlying, sand-filled tidal channels dissecting the platform marsh and peat deposits, which are more resistant to erosion (fig. 28) (Riggs and Ames 2006). According to Wamsley et al. (2009), peat outcroppings on the ocean sides of the small mid-inlet islands separating the three channels acted as an erosion-resistant barrier. The easternmost channel had the highest flow volume. It was 99 to 107 m (325 to 350 ft) wide with scour depths of 6 m (20 ft) relative to North American Vertical Datum (NAVD) 88 and an ebb shoal that extended up to 381 m (1,250 ft) offshore in water depths of 1.2 to 1.8 m (4 to 6 ft) NAVD88. The middle channel had a peat terrace that resisted scouring and restricted flow to periods of higher tide elevations. The west channel was about 107 m (350 ft) wide with depths of 2.1 to 3 m (7 to 10 ft) NAVD88 and a rapidly changing morphology (fig. 29) (Wamsley et al. 2009).

The US Army Corps of Engineers sealed the Isabel Inlet breach 44 days after it had opened with sand dredged from the federally maintained ferry channel between

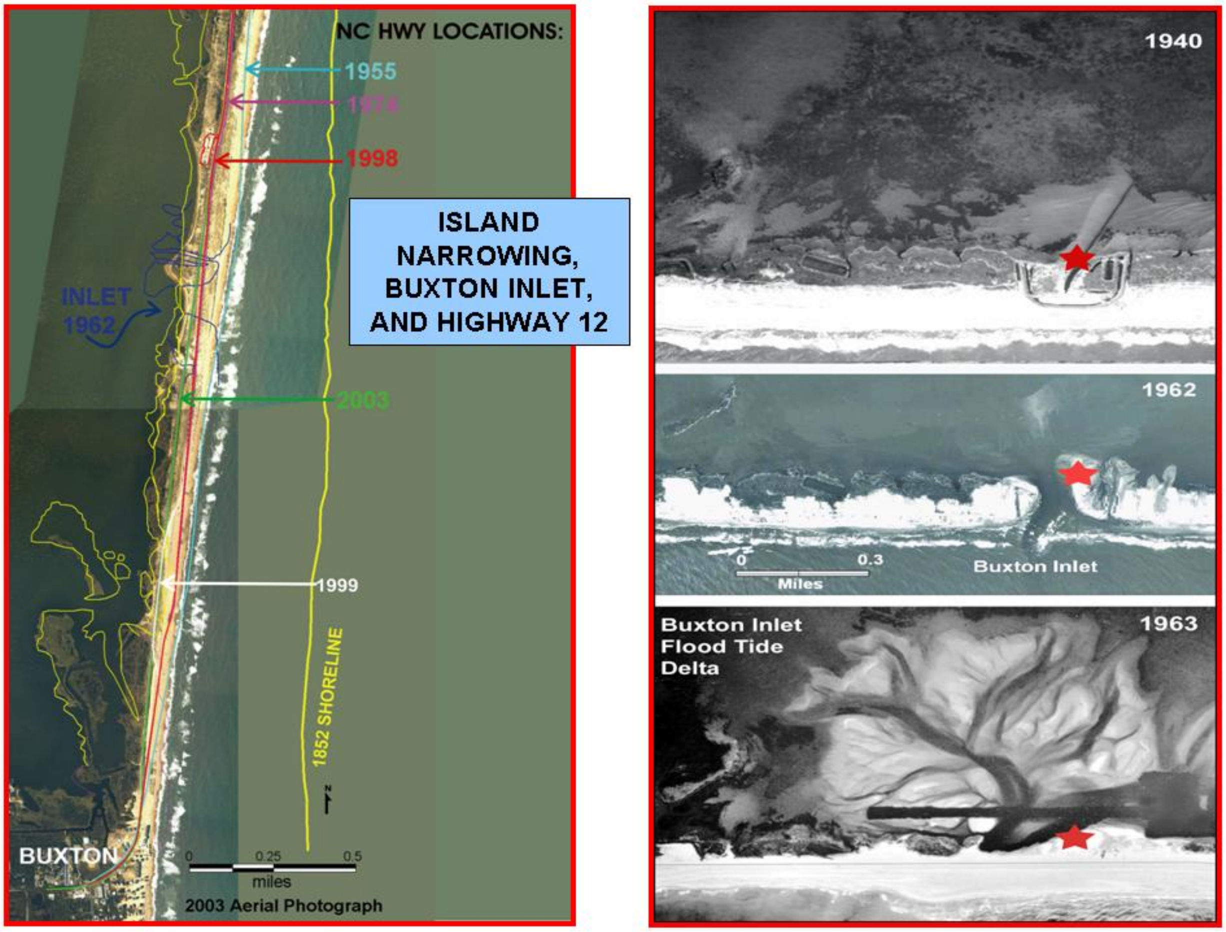

Figure 26. Buxton Inlet. Buxton Inlet formed during a 1962 nor'easter called the Ash Wednesday Storm. The yellow line in the left panel indicates the shoreline position in 1852. The blue, purple, red, white, and green lines and dates are the locations and times of westward relocation of North Carolina Highway 12. Red stars indicate the same geographic location in all three aerial photographs. Notice the engineered channel and dike in the 1953 photograph, the very well-developed flood tidal delta in the 1963 photograph, and the dredge holes produced to close Buxton Inlet visible in the 1963 photograph. Figure 8 from Riggs and Ames (2006).

Figure 27. Inlet formation during Hurricane Isabel. Hurricane Isabel breached Hatteras Island in September 2003. The three-channel inlet was filled using dredged sand, and Highway 12 was rebuilt. The red arrows point to the same geographic locations on both oblique aerial photographs. This location remains vulnerable to future breaching. Figure 11 from Pendleton et al. (2004), created using US Geological Survey aerial photographs.

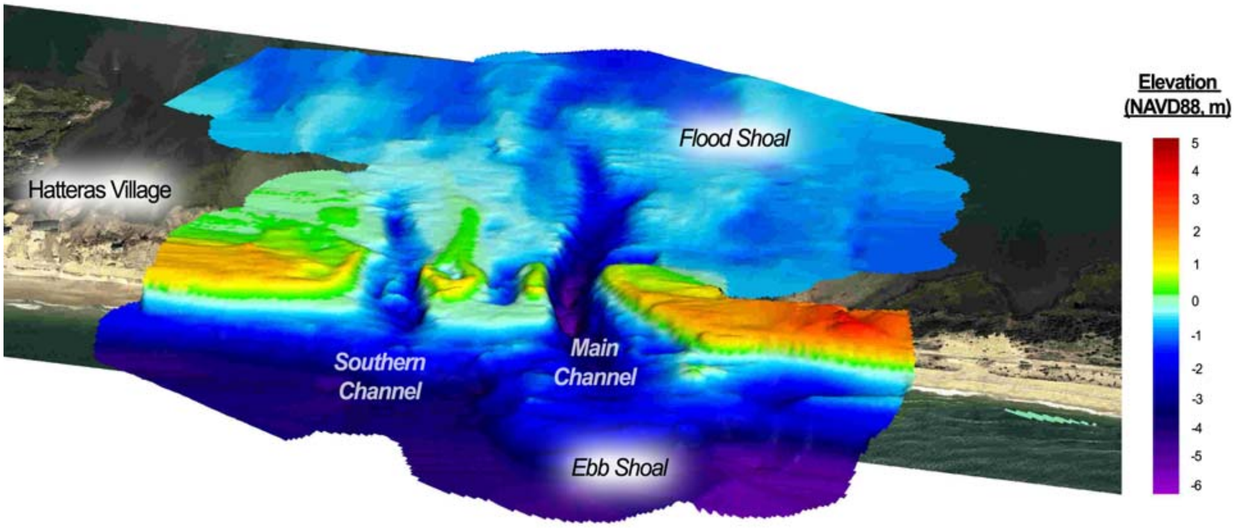

Figure 28. Elevation and bathymetry of Isabel Inlet. This map shows the land elevation (green to red colors) and water bathymetry (blue to purple colors) of Isabel Inlet, which was formed by Hurricane Isabel in 2003. The inlet had three channels, with depths of up to 6 m (20 ft), that were separated by erosion-resistant peat. Figure 7 from Freeman et al. (2004).

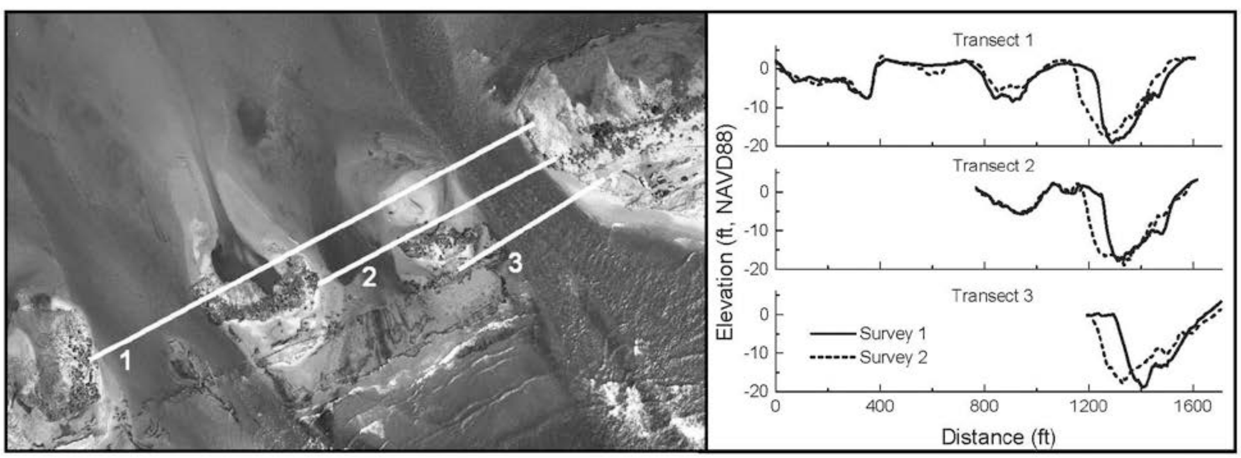

Figure 29. Isabel Inlet transects. Bathymetry and island topography of Isabel Inlet were surveyed along three transects from 3 to 5 October 2003 and again from 13 to 16 October 2003 to evaluate changes in inlet morphology over time. Morphology changed rapidly. Figure 7 from Wamsley et al. (2009), created using photographs from North Carolina Department of Transportation.

Hatteras and Ocracoke islands, at an estimated cost of $6.5 million, excluding road and utility reconstruction (Smith et al. 2006). North Carolina Highway 12 was rebuilt in place. Because the inlet was filled before a flood tidal delta had been deposited, this area of the island remains just as vulnerable to future inlet formation as it was prior to Hurricane Isabel (Riggs and Ames 2006).

Oregon Inlet: Infrastructure Threatened by Migration

Oregon Inlet (fig. 30) opened during a hurricane on 7 September 1846 near the current location of the Bodie Island lighthouse. It is the only inlet in the northern Outer Banks between Cape Hatteras and Cape Henry, Virginia, and it provides a transportation corridor between the Pamlico, Currituck, and Albemarle sounds and the Atlantic Ocean. The Herbert C. Bonner Bridge, completed in 1963, spans Oregon Inlet and connects with Highway 12 on Bodie Island to the north and Pea Island to the south. Since it was opened, the inlet has migrated approximately 4 km (2.5 mi) southward because of accretion on its north bank (Bodie Island) and erosion on its south bank (Pea Island). The rate of this migration has ranged from 23 to 165 m (75 to 541 ft) per year (Riggs et al. 2009).

The maintenance of a navigation channel through the inlet is challenging due to inlet dynamics and the amount of dredging required to hold the channel in place (Riggs

Figure 30. Oregon Inlet. The inlet was stabilized by a terminal groin and revetment to stop southward migration, which undermined the Pea Island Bridge onramp for Highway 12. Bonner Bridge is visible near the center of the photograph. National Park Service photograph taken February 2015, available online: https://www.flickr.com/photos/capehatterasnps/16217489383/ (accessed 27 April 2015).

et al. 2011). A controversial proposal to stabilize the inlet's location has been discussed and involves a pair of 3.2-km- (2-mi-) long jetties (Riggs et al. 2009). Such jetties could have serious environmental consequences and have not yet been built. Jetties are built perpendicular or oblique to a shoreline to trap and hold sand being transported along the shoreline by longshore drift; they protect the attached shoreline from erosion but starve downdrift beaches of sand. In 1989–1991, a 938-m- (3,077-ft-) long terminal groin and rock revetment were built on the southern side of the inlet to prevent disconnection of the southern approach to Bonner Bridge from Pea Island (Riggs et al. 2009). This structure stopped the inlet's southward migration, but a new downdrift beach equilibrium configuration developed (fig. 31) (Joyner et al. 1998). Geomorphic changes included the soundward accretion of the Bodie Island spit to the area of the navigation span of Bonner Bridge, which decreased the width of the inlet, in turn causing the channel to deepen and migrate southward toward the rock structures (Joyner et al. 1998).

From 1960 to 1983, an unknown volume of sand was dredged to maintain the navigability of Oregon Inlet and was deposited offshore in deep water (Riggs et al. 2009). Between 1983 and 2009, 9.2 million m^3 (12 million yd^3) of sediment was dredged from Oregon Inlet and artificially bypassed to Pea Island beaches between mileposts 1 and 3 (Riggs and Ames 2011). As a result of inlet stabilization, and despite beach nourishment efforts, Pea Island's ocean shoreline continues to erode at rates of up to 4 m (13 ft)/year, among the highest rates in North Carolina (Riggs et al. 2011).

The aging Bonner Bridge is decades past its planned date of decommissioning (1993). Adjacent sections of Highway 12 on Pea Island continue to be undermined by storm erosion and overwash. As of September 2014, work on replacing the bridge was suspended by court

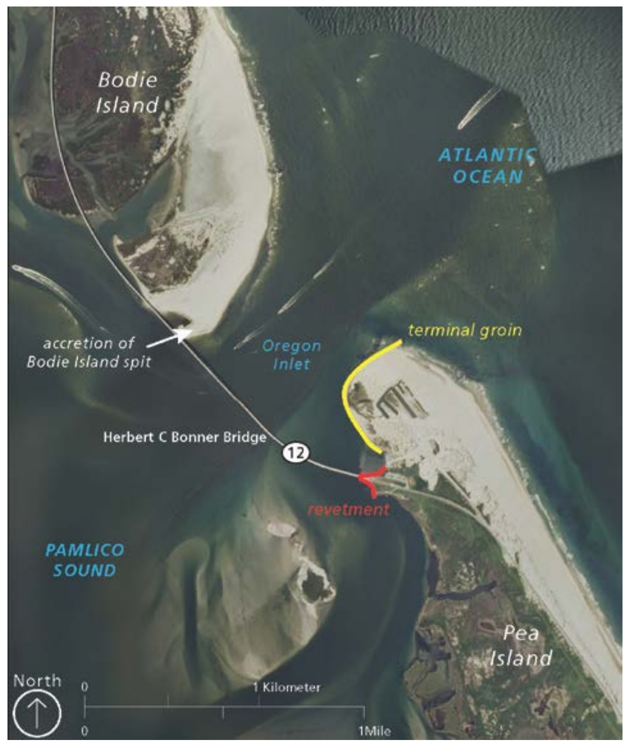

Figure 31. Aerial image of Oregon Inlet, stabilizing terminal groin and revetment, and erosion and accretion resulting from the hard stabilization. Aerial imagery from ESRI World Imagery base layer (accessed 23 July 2013), annotation by Jason Kenworthy (NPS Geologic Resources Division).

ruling while NCDOT and the Southern Environmental Law Center (SELC) discuss a long-term solution that considers whether the 4 km (2.5 mi) bridge should be rebuilt in place or instead replaced by a 27 km (17 mi) bridge that bypasses areas particularly vulnerable to breaching (SELC 2014). More information on these issues is provided in the "Highway 12 Transportation Corridor" section of this chapter.

Recreational and Watershed Land Use

Disturbed Lands

Humans have disturbed the natural landscape and coastal processes at Cape Hatteras National Seashore in several ways: (1) coastal settlement and development; (2) extraction of oak maritime forests for shipbuilding; (3) early mosquito control and waterfowl management efforts, which involved excavation of drainage ditches and construction of water control structures; (4) construction and vegetative stabilization of primary dunes along the length of the seashore; and (5) excavation of borrow ponds for roadbed material during road construction (NPS 2012). Current practices continue to disturb the ecosystem, including off-road vehicle (ORV) use and nutrient inputs at the local and watershed levels.

An increase in the area of impervious surfaces adjacent to the park has led to increased runoff of pollutant-containing stormwater into Cape Hatteras National Seashore (Mallin et al. 2006). Increased impervious surface coverage in coastal areas is strongly correlated with increases in freshwater discharge, fecal coliform bacterial loading, shellfish area closures, and degradation of benthic biological communities (Mallin et al. 2001; Holland et al. 2004).

Increased development of lands adjacent to Wright Brothers National Memorial, along with increased population and demographic transformation of adjacent communities, have changed the uses of and use impacts on the park. Due to limited availability of non-federal lands, park staff is often pressured to permit land uses that are incompatible with park values (NPS 2005).

Water Quality

Cape Hatteras National Seashore faces several threats related to water quality (table 8) (Mallin et al. 2006). The long residence time (approximately 1.7 years) of Pamlico Sound waters fosters the sound's high productivity, but also makes this nitrogen-limited estuary sensitive to excessive nutrient input and eutrophication (Paerl et al. 2006). Fortunately, the distances between Outer Banks islands and the mainland likely protect the park from mainland sources of nutrients and pollutants to some degree (Mallin et al. 2006).

Nutrients and contaminants enter the estuary from several sources. Since the late 1950s, nutrient loading to the tributary rivers has increased by 50% in association with increased agriculture, silviculture, urbanization, and industrialization. Increases in impervious surface area have increased stormwater runoff, with associated contaminants potentially degrading offshore water quality (Wright et al. 2012). Manmade drainage ditches affect water distribution and quality on Bodie and Hatteras islands; traffic crossing these ditches may contribute polycyclic aromatic hydrocarbons (fig. 32A) (Mallin et al. 2006). Estuarine waters at the southern end of Ocracoke Island receive effluent from the reverse-osmosis drinking water plant, which discharges 122 m (400 ft) offshore; nitrogen concentrations exceed 5 mg/L and have the potential to cause localized algal blooms in nutrient-limited Pamlico Sound (Mallin et al. 2006). Three other reverse-osmosis water plants operate elsewhere in Dare County at Kill Devil Hills, Stumpy Point, and Rodanthe. The Rodanthe/Waves/Salvo water treatment plant discharges into Blackmar Gut, approximately 0.8 km (0.5 mi) north of the southern boundary of Pea Island National Wildlife Refuge. Effluent from the water treatment plant had lower salinity but higher alkalinity and phosphorous concentrations compared with the average conditions of the receiving water (US Fish and Wildlife Service 2008). Due to the limited exchange between Blackmar Gut and Pamlico Sound, the potential that the effluent will impact sensitive resources in Pamlico Sound or Pea Island National Wildlife Refuge is low (US Fish and Wildlife Service 2008).

Septic leachate is a significant source of contamination. Human population has increased along the northern Outer Banks over the past 30 years, with summer tourists tripling the population and increasing nutrient and bacterial loads on septic systems (Mallin et al. 2006). Portions of the park on South Bodie Island receive nutrients and microbial pathogens via septic leachate from the town of Nags Head and from the movement of groundwater through the sandy saturated soils into drainage ditches within the park (fig. 32B) (Mallin et al. 2006). Studies conducted in 1988 and 1995 showed that septic leachate has a considerable impact on drainage ditches on NPS land, and a lesser impact on marshes (Mallin et al. 2006). Septic leachate may sometimes enter the groundwater table; because much of the area has a seasonal water table of less than 0.76 m (2.5 ft), the amount of unsaturated soil may be insufficient to provide proper aerobic treatment to wastewater entering the subsurface (Evans and Houston 2000, as cited in Mallin et al. 2006).

Estuarine water-quality sampling at 17 sites in Cape Hatteras National Seashore in 2010 yielded mostly good and fair water-quality ratings, with water from some areas containing elevated nitrogen and phosphorus concentrations (Gregory and Smith 2011). However, many areas along the park's estuarine shoreline have water bodies that were 303(d) listed as impaired between 2006 and 2010 (fig. 33) (North Carolina Department of Environment and Natural Resources Division of Water Quality 2012), meaning that the existing controls on pollution are insufficient to attain or maintain applicable water quality standards. Some areas have been closed to shellfishing due to pathogens. Commercial fisheries landings in Pamlico Sound have been declining rapidly since 1980 and indicate major changes in the sound's trophic dynamic structure, likely related to eutrophication, algal blooms, and hypoxia, and accelerated by overfishing and habitat destruction (Paerl et al. 2006).

Toxic blooms of *Pfiesteria* spp. in the waters of Cape Hatteras National Seashore are unlikely because this species prefers nutrient-enriched waters and more

Table 8. Existing and potential stressors that are affecting or may affect Cape Hatteras National Seashore habitats. Redrafted after Mallin et al. (2006).

Ocracoke Island

Stressor	Ocean beach	Sound shore	Tidal creeks	GW	Marsh	FW ponds
Algal blooms	L	P	P	L	E	L
Toxic algae	L	P	P	L	P	X
Nutrient loading	L	E	P	L	P	L
Excessive nitrate	L	L	L	X	L	L
Fecal bacteria	L	E[1]	P	X	X	L
Metals contamination	E; Hg[2]	E; Hg[2]	P; Hg[2]	X	X	X
Toxic compounds	X	L	P; PAHs	X	X	X
Invasive species	lionfish	X	X	L	E[3]	X
Habitat disruption	E; ORVs	L	L	L	L	P; ORVs

Hatteras Island

Stressor	Ocean beach	Sound shore	Tidal creeks	GW	Ditches	Sedges/ swales
Algal blooms	L	P	P	L	E	L
Toxic algae	L	P	P	L	P	L
Nutrient loading	L	P	P	E	E	E
Excessive nitrate	L	L	L	E	E	L
Fecal bacteria	E; drainage	P	P	E	E	E
Metals contamination	E; Hg[2]	E; Hg[2]	P; Hg[2]	X	X	X
Toxic compounds	X	E	X	X	X E	X
Invasive species	P; lionfish	X	X	L	E[3]	X
Habitat disruption	E; ORVs	E; ORVs	L	E	E	P; drainage

Bodie Island

Stressor	Ocean beach	Sound shore	Tidal creeks	GW	Ditches	Sedges/ swales
Algal blooms	L P	P	P	L	E	E
Toxic algae	L	P	P	L	P	X
Nutrient loading	L P	P	E	E	E	E
Excessive nitrate	L	L	L	E	E	E
Fecal bacteria	E	P	L	E	E	E
Metals contamination	E; Hg[2]	E; Hg[2]	P; Hg[2]	X	X	X
Toxic compounds	X	E	X	X	P; PAHs	X
Invasive species	P; lionfish	E	P	L	E[3]	X
Habitat disruption	E; ORVs	L	L	L	L	X

Legend

X	**no data to make judgment**	P	**potential problem**
L	**low or no problem**	E	**existing problem**

Notes: 1 = based on closed shellfishing area around developed canal community soundside; 2 = fish tissue consumption advisory by North Carolina Division of Water Quality; 3 = Phragmites *is abundant in areas of the oligohaline marsh. GW = groundwater; FW = freshwater; Hg = mercury; PAH = polycyclic aromatic hydrocarbon; ORV = off-road vehicle.*

Figure 32. Drainage ditches near Cape Hatteras. A) Human -constructed drainage ditches affect water distribution and quality on Hatteras Island, and traffic crossing these ditches may contribute polycyclic aromatic hydrocarbons. ESRI World Imagery base layer (accessed 27 March 2014); annotation by Trista Thornberry-Ehrlich (Colorado State University). NPS boundary (2012; green line) courtesy Laura Pickens (Cape Hatteras National Seashore). B) Photograph of a ditch draining groundwater from Nags Head Village toward Pamlico Sound. Portions of Cape Hatteras National Seashore on South Bodie Island receive nutrients and microbial pathogens via septic leachate from the town of Nags Head and from the movement of groundwater through the sandy saturated soils into drainage ditches within the park. Photograph by Michael Mallin (University of North Carolina Wilmington) extracted from Mallin et al. (2006), plate 3.

estuarine conditions, but blooms are possible given the leaching of nutrients from septic systems adjacent to park waters (Mallin et al. 2006). Toxic blue-green algal blooms or nuisance algal blooms may occur in freshwater areas of the park, such as the nutrient-enriched drainage ditches on Bodie Island, Hatteras Island swales that are impacted by runoff or septic system leachate, and tidal creeks, marshes, and ponds on Ocracoke Island. Swales may also be impacted by groundwater withdrawals in wellfield areas, which can disrupt habitat by limiting plant species richness and diversity in nearby swales, according to a study conducted on Hatteras Island (Mallin et al. 2006). Fortunately, however, Buxton Woods swales that are well within the park are insulated from anthropogenic impacts (Mallin et al. 2006).

Contact the NPS Water Resources Division (http://nature.nps.gov/water/) for assistance with water quality issues.

Off-Road Vehicles

Cape Hatteras National Seashore permits ORVs to drive and park on the beach seaward of the primary dune line via several access ramps. A 10-m (33-ft) backshore area seaward of the primary dune line is protected seasonally to allow for turtle and shorebird nesting, and additional protection buffers may be established when wildlife or nests are observed. Historically, beach driving at the seashore was for the purpose of transportation, not recreation. Improved access to the island, increased population, and popularity of sport utility vehicles have resulted in a dramatic increase in recreational vehicle use

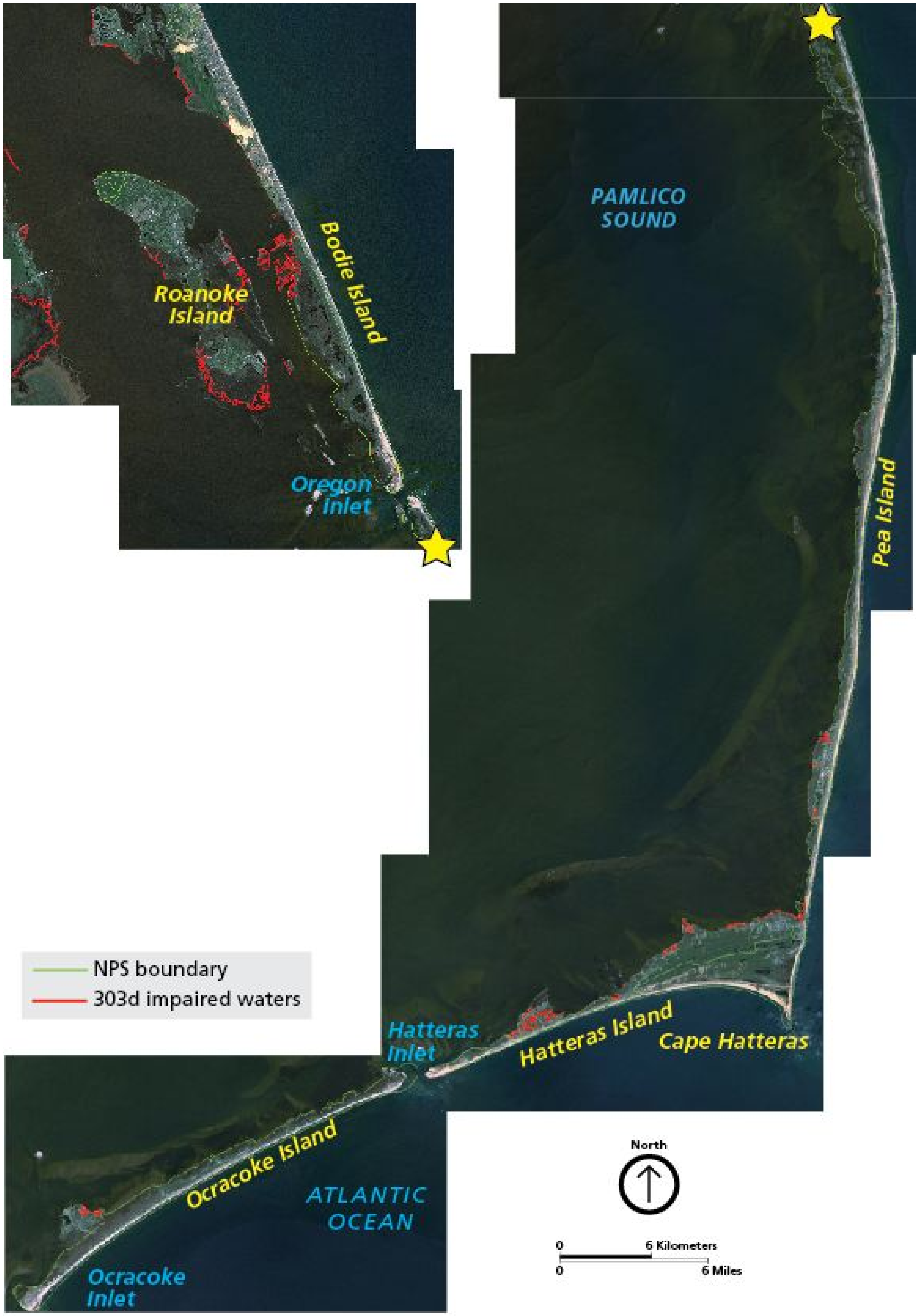

Figure 33. Map of polluted ("303(d)") waterways. Multiple water bodies along the Cape Hatteras National Seashore estuarine shoreline were 303d listed as polluted in the state's 2010 report. Stars indicate where images join. Figure created by Trista Thornberry-Ehrlich (Colorado State University) using information from the US Environmental Protection Agency "How's My Watershed?" tool, available online: http://watersgeo.epa.gov/mywaterway/#/mywaterway/map.htm (accessed 27 March 2014). Imagery from ESRI World Imagery base layer (accessed 27 March 2014).

on Cape Hatteras National Seashore beaches. Efforts to establish a balance among recreational access, various user groups, and habitat preservation has been controversial. New ORV policies were established through an Environmental Impact Statement in November 2010 and became active in February 2012 (NPS 2010).

Studies conducted along beaches similar to those at Cape Hatteras 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; see GRI report by Schupp 2013), 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 post-storm dune recovery. In comparison with those in adjacent no-driving 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 destabilize coastal dunes through direct damage to vegetation on 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 astronomical and storm 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 impacted.

Off-road driving also has numerous biological impacts on habitats, organisms, and ecosystems. On the unvegetated beach, off-road driving limits the survival, abundance, and diversity of shorebirds, sea turtles (Leatherman and Godfrey 1979; Godfrey and Godfrey 1980; Hosier et al. 1981; Wolcott and Wolcott 1984; Watson et al. 1996; Williams et al. 2004; Schlacher et al. 2007) and invertebrates (Moss and McPhee 2006; Schlacher et al. 2008), including ghost crabs, which can be crushed even in burrows located 30 cm (12 in) below the surface (Schlacher et al. 2007). Studies conducted at Assateague Island National Seashore have shown that ORV use limits the abundance of the tiger beetle (*Cicindela dorsalis media*), listed by the State of Maryland as rare (Knisley and Hill 1990); it also reduces migratory seabird species richness, abundance, size, number of roosts, and time spent foraging (Forgues 2010).

Dune Stabilization

On natural barrier island systems, broad beaches and beach berms absorb most storm wave energy, and remaining wave energy rapidly weakens as water flows between dunes and across islands (Dolan and Godfrey 1972). Along the Outer Banks, however, a line of constructed dune ridges is maintained to protect roads and other infrastructure. This perception of the protective role of the dune ridges contributes directly to increased pressure to protect, maintain, and rebuild the artificial dunes.

The dunes were first built between 1936 and 1940 under the direction of the NPS, Civilian Conservation Corps, and Works Progress Administration. Workers constructed 1,258 km (782 mi) of dunes and erected nearly 914 km (568 mi) of sand fencing to create a continuous barrier dune ridge along the entire length of the Outer Banks, from the Virginia state line to Ocracoke (Dolan and Godfrey 1972; Riggs et al. 2009). The resulting dune ridge was up to 6 m (20 ft) high and in many places was backed by multiple rows of dune ridges. Other modifications followed, including the construction of 120 km (75 mi) of dikes and jetties, and planting of 2,650 ha (6,548 ac) grass and 3.4 million seedlings, trees, and shrubs until a nearly continuous band of vegetation blanketed the area (Riggs et al. 2009). Some stretches were not maintained and now contain only partial or terminated ridges (Ames and Riggs 2006j). In areas with adequate sediment supply, some constructed dune ridges have become incorporated into natural dune fields (Ames and Riggs 2006j).

Geomorphologists find determination of the point at which a man-made dune has become “natural” on the barrier islands difficult (Hoffman et al. 2007g). For example, prior to 1962, Ocracoke Village was growing southeastward as ringed dune-beach ridges formed naturally. Following the 1962 Ash Wednesday storm, a set of dune ridges was constructed using sand fences and, along with the adjacent overwash plain, was stabilized with vegetation. These features are currently heavily vegetated with dune grasses and scrub-shrub communities, and the previous overwash plain now supports marsh vegetation. Natural dune growth has ceased on the southeastern side of the village, and the northern side of the village is eroding at an approximate rate of 1.2 m (4 ft)/year in response to storm wind and waves from Pamlico Sound (Riggs and Ames 2006).

Artificial dune stabilization has greatly altered the ecosystem and geologic structure of Cape Hatteras National Seashore. Stabilized dunes have minimized natural overwash and inlet-formation processes, modified vegetation communities, and altered back-barrier estuarine processes. These effects have resulted in narrower beaches, a steeper shoreface, and deeper inshore water depths (Dolan and Lins 1986), as well as increased wave energy dissipating on the shoreface, a steeper beach profile, increased turbulence, and accelerated mechanical weathering of sand into finer particles. As the buffering beaches erode away, wave energy and storm surges attack the dunes, causing rapid scarp formation while the system is out of equilibrium (Ames and Riggs 2006j). For example, 30 years after initial stabilization, several beaches on Hatteras Island had all but disappeared (Dolan and Godfrey 1972). Additionally, along the barrier segment between Avon and Buxton, maintained dunes have prevented inlet formation and minimized overwash, resulting in substantial island narrowing and the relocation of Highway 12 at least four times (fig. 26) (Riggs and Ames 2006). Natural maintenance of this barrier island segment over the short term (months to years) and evolution over the long term (decades to centuries) in response to ongoing sea-level rise would require inlet formation followed by extensive overwash (Riggs and Ames 2006).

Back-barrier areas are also impacted by the dunes, which cut off the overwash source of sediments, causing scarp development in landward marshes and decreasing the biological productivity of sound ecosystems. Dune stabilization also causes flooding behind the barrier dunes from the direction of the Pamlico Sound when strong northwest winds push water up against the western coasts of the barrier islands. This influx of water formerly flowed relatively freely between the dunes eastward and out to sea (Dolan and Lins 1986).

Coastal Engineering and Shoreline Armoring

NPS management policies (NPS 2006; see also "Appendix B") require that natural shoreline 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. The 1984 General Management Plan for Cape Hatteras National Seashore allows for natural processes to continue with three exceptions for infrastructure and cultural resources: Highway 12, Ocracoke Village, and the Cape Hatteras lighthouse (Riggs et al. 2009).

Dallas et al. (2013) completed an inventory of 72 coastal engineering projects in or immediately adjacent to Cape Hatteras National Seashore. Forty-eight of these projects are coastal structures (extending a total of 5,723 m [18,360 ft]), 17 are beach nourishment projects, five are dredging projects, and two are dune construction projects. That report also discusses impacts due to coastal engineering projects, as well as recommendations for further study and management.

Since 1985, state regulations disallowed the installation of hardened structures (e.g., jetties, groins, bulkheads, seawalls, and revetments) to prevent ocean shoreline erosion, 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 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 control methods (e.g., relocation) were impractical. Additional exceptions can be made to stabilize commercial navigation channels (including Oregon Inlet) and erosion-threatened bridges, and to protect historic sites (Riggs et al. 2008b). Many forms of estuarine shoreline armoring are permitted (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).

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 renourishment, 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. Unfortunately, bulkheads composed of sandbags act in a similar manner to those composed of rock or steel (fig. 34). 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

Figure 34. Stabilization and relocation. Hard stabilization is not permitted in North Carolina except in special circumstances (e.g., Oregon Inlet). Short-term solutions include sandbags (top, along Highway 12 in Rodanthe; North Carolina Department of Transportation photograh). Relocation provides a longer-term solution, as in the case of moving the Cape Hatteras lighthouse to an inland location (bottom; NPS photograph by Mike Booher, February 1999, with move path cleared).

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). Between 1962 and 2011, over 7.8 million m^3 (10.2 million yd^3) of sediment were emplaced on Cape Hatteras National Seashore beaches (Dallas et al. 2013).

Another feasible solution to protect infrastructure from shoreline erosion is to build or relocate structures farther away from the shoreline. One successful example is the relocation of the Cape Hatteras lighthouse, an iconic structure built in 1870 approximately 500 to 750 m (1,640 to 2,460 ft) from the shoreline (fig. 34). By 1935, shoreline erosion threatened the structure, and coastal engineering projects to protect the lighthouse began in earnest. Early efforts included sand fencing and planting to foster dune growth. Beginning in 1966, successive engineering efforts included the construction and rebuilding of three groins; several beach nourishment projects; the use of rock revetments, nylon sandbags, and artificial seaweed; and the dumping of asphalt rubble onto the beach (Mallinson et al. 2009). In 1999, a new management approach was employed; the lighthouse and light station components were moved away from the eroding shoreline and rising sea level to a new location 880 m (2,900 ft) inland, where they are available for public visitation (Mallinson et al. 2009).

Highway 12 Transportation Corridor

Highway 12 is the only road providing access to Cape Hatteras National Seashore and the only evacuation route for the 5,000 Outer Banks residents and additional tourists during hurricanes (plate 1). However, this road is very vulnerable to shoreline erosion and storm overwash, and has been repeatedly damaged in numerous places in the last few decades. Highway 12 has been destroyed repeatedly at two locations on Pea Island in recent years, during Hurricane Irene in 2011, Hurricane Sandy in 2012, and a series of nor'easters in 2012–2013.

The northeastern half of Ocracoke Island, as well as the barrier segments from Frisco to Hatteras Village and from Buxton to Avon, have histories of inlet formation and continue to be vulnerable to these changes. In addition, the entire length of Pea Island (a U.S. National Wildlife Refuge) is vulnerable to inlet formation. Three locations were predicted to have a particularly high likelihood of becoming inlets during a major storm or series of storms (Riggs et al. 2009), and in fact the northernmost two of them did breach during Hurricane Irene in 2011:

- The historic location of New Inlet and associated flood tidal delta, approximately 11 km south of the inlet;
- A narrow island segment underlain by molar-tooth platform marsh with sand-filled overwash tidal channels, approximately 17 km south of Oregon Inlet; and
- The historic location of Chickinacommock Inlet, which is filled with sand and underlies the island, approximately 19 km south of the inlet.

Highway 12 is particularly vulnerable to overwash and storm damage at these three erosional hotspots, which extend a total of almost 10 km (6 mi), half the length of Pea Island (Riggs et al. 2011).

Even with continued beach nourishment and dune ridge construction, the long-term viability of the Pea Island portion of Highway 12 is expected to be severely threatened by the narrowness of the island. Major changes in road location, by relocation to a back-barrier causeway or elevation as a causeway above the island within the lifespan of a new Oregon Inlet bridge, are required in the immediate future (Riggs et al. 2011).

As of September 2014, the long-term plan to replace the aging Bonner Bridge over Oregon Inlet (figs. 30 and 31) and adjoining sections of Highway 12 continues to be mired in controversy. Court appeals had been filed to rescind permits issued for rebuilding of the adjoining Pea Island highway in its present location, with the possibility of building a permanent 4 km- (2.5 mi) bridge where a temporary bridge was constructed following Hurricane Irene in 2011. The Southern Environmental Law Center (2012) has argued that current plans to rebuild Bonner Bridge and other portions of Highway 12 on Pea Island would impact wildlife, habitat, and pristine beaches; would require expensive ongoing repairs in response to continued overwash and storm events; and involve permitting in an inappropriately piecemeal fashion, rather than as an entire project with cumulative impacts. An August 2014 court ruling suspended work on the bridge so that SELC and NCDOT could develop a long-term solution (SELC 2014).

The long-term future of maintaining a highway along a highly mobile barrier system is controversial and pits short-term economic development against long-term natural island dynamics (Riggs et al. 2009). Alternatives that consider the infrastructure's long-term reliability include the implementation of a system of ferries and water taxis (Riggs et al. 2008b), and construction of a long bridge that bypasses vulnerable island areas and the Pea Island National Wildlife Refuge by running over Pamlico Sound with ramp access to Pea Island (Riggs et al. 2008b; SELC 2012). This bridge would be 27 km (17 mi) long, with the Oregon Inlet portion built over the flood tidal delta and the deeper water of Pamlico Sound; the southern end of the bridge would come ashore at the village of Rodanthe (Riggs et al. 2011).

Geomorphic Mapping

An understanding of geomorphic processes and landform evolution along the Outer Banks is critical to park managers' ability to prepare for the island's response to coastal processes and its evolution throughout the coming decades. To describe the geomorphology of Cape Hatteras National Seashore, geologists produced maps of landforms and sedimentary facies. These maps, which are described in detail in the "Geologic and Environmental Features and Processes" chapter and included in the map pocket, provide a snapshot of the landscape at a particular instant in geologic time. Examples of mapped features include beaches, dunes, overwash fans, relict inlets, and anthropogenic modifications.

The US Geological Survey, North Carolina Geological Survey, East Carolina University, and Virginia Institute of Marine Science participated in a North Carolina Geology Coastal Cooperative Research Program that includes the barrier islands of the Outer Banks of North Carolina. The goals of the cooperative research program were to develop a thorough understanding of (1) the Quaternary geologic framework of the northeastern North Carolina coastal system, (2) the processes that formed the coastal geologic system over the past 10,000 years, and (3) the climatic and sea-level history that produced the modern coastal system of the Outer Banks (Ames and Riggs 2006j). Program techniques and products include seafloor mapping of the inner shelf (e.g., Capone et al. 2002a, 2002b) and nearshore (e.g., McNinch 2004; Miselis and McNinch 2006; Schupp et al. 2006), shoreline surveys to determine storm event responses and erosional hotspot behavior (e.g., List et al. 2006), core drilling to determine paleoenvironment characteristics (e.g., Culver et al. 2008b; Mallinson et al. 2010a), seismic and ground-penetrating radar surveys to map shallow stratigraphy beneath the estuary and islands (e.g., Mallinson et al. 2010a, 2011), airborne topographic mapping using LiDAR to detect elevation and beach and dune changes after storms (e.g., Hoffman et al. 2007g), and detailed field surveys to supplement the remotely sensed data (e.g., Ames and Riggs 2006j). These products address many of the needs expressed by park resource managers at Cape Hatteras National Seashore during the initial GRI scoping meeting (NPS 2000), and their findings are described in this report.

An understanding of the detailed processes and responses that led to development of the North Carolina Outer Banks and their associated geomorphic and ecologic systems provides a foundation for the development of long-term resource management strategies (Ames and Riggs 2006j).

Continued topographic surveys (e.g., LiDAR) are recommended to evaluate barrier island vulnerability, storm response, and potential changes in habitats. Post-processed LiDAR data provide a reliable and cost-effective representation of coastal dunes at Cape Hatteras National Seashore for volumetric change measurements (Woolard and Colby 2002). Although the nearshore seafloor is not contained within the boundaries of Cape Hatteras National Seashore, its habitats support organisms in the park (e.g., shorebird foraging, nesting sea turtles) and the benthos can be used as indicators of environmental health or change. For these reasons, park managers may want to consider the development of benthic habitat maps for the estuary and nearshore areas, to complement and enhance existing seafloor data.

Paleontological Resource Inventory, Monitoring, and Protection

Fossils within Cape Hatteras National Seashore are summarized by Tweet et al. (2009) and the "Paleontological Resources" section of this report. 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 April 2015, Department of the Interior regulations associated with the Act were being developed.

Beachcombers are allowed to collect unoccupied shells at Cape Hatteras National Seashore, but NPS (2006) policy states that fossils cannot be collected from NPS lands. The NPS defines a "fossil" as any remains of life preserved in a geologic context; although this definition does not include an arbitrary date separating older (fossil) from younger specimens, the term "geologic context” implies some degree of antiquity (Tweet et al. 2009). Cape Hatteras National Seashore staff may need to consider refinement of the definition of a fossil, or of what beachcombers are allowed to collect, in concert with an outreach effort to educate visitors about paleontological resources and collection. Differentiation between true fossil material and the remains of coastal organisms that died recently can include documentation of the presence or absence of staining, boring by other invertebrates, and abrasion, and the measurement of trace element compositions. In general, older age is associated with more wear, staining, damage, and boring on a shell specimen (Tweet et al. 2009). Specimens collected at Cape Hatteras National Seashore are Pleistocene to Holocene in age (Tweet et al. 2009).

A field-based paleontological resource survey can provide detailed, site-specific descriptions and resource management recommendations that are beyond the scope of this report. Potential sources for paleontological expertise include Geologic Resources Division refresher-training courses for NPS rangers, baseline paleontological inventories, and paleontological surveys. The 2009 paleontological summary for Cape Hatteras National Seashore includes a literature review, recognition of type specimens, species lists, and guidance for developing resource management plans (Tweet et al. 2009). Brunner et al. (2009) presents a summary of paleontological resource management challenges associated with coastal parks and suggests policy-based resource management considerations. An additional resource, Santucci et al. (2009), 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.

Additional Information Needs

Cape Hatteras National Seashore staff could benefit from additional research or information related to the following issues:

- Benthic habitat maps of the estuary and nearshore (NPS 2000)
- Survey of septic systems to define present pollutant loading to ditches and marshes within the park (Mallin et al. 2006)
- Survey of benthic macroinvertebrates in park estuarine waters and tidal creeks to assess current benthic community health (Mallin et al. 2006)
- The Cape Hatteras National Seashore Foundation Statement (NPS 2011) identified a resource stewardship strategy as a future management need.

Geologic History

This chapter describes the surficial geomorphologic units, environments of formation, and evolutionary history of the modern barrier islands and estuaries in Cape Hatteras National Seashore.

The North Carolina barrier islands are very young in terms of geologic time. The geologic history occurred within the Cenozoic Era (the past 66 million years). The geologic story at Cape Hatteras National Seashore is one of cyclic rise and fall of relative sea level. The geologic framework controls the sediments available to the modern barrier island, and the ways in which the island responds to natural and anthropogenic processes. The oldest known parts of the Outer Banks, including the portion currently blocking the mouth of Albemarle Sound where Wright Brothers National Memorial is located, were formed less than 3,000 years ago (Culver et al. 2008b).

Modern-day 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 Outer Banks.

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, a regional depositional basin. Such conditions would have existed in a shelf basin protected from shelf currents by the Cape Lookout High to the south (Popenoe 1985). Upper units of early Miocene and early Pliocene age are sandy to silty clay beds that were deposited in inner to middle neritic depths (Zarra 1989) of approximately 50 m (164 ft) 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, seas lapped over the eastern portion of the coastal plain in the region of present-day North Carolina (Richards 1968). This transgression deposited widespread marine sediments along the east coast, which 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 pre-Holocene sedimentary sequence below Pamlico Sound (Wells and Kim 1989). The upper surface of the Yorktown Formation was eroded during the Pliocene–Pleistocene interval, when stream channels cut irregular depressions. The topography that it formed may be responsible for many of the modern bathymetric features in the lagoon, and may control the position of features such as Ocracoke Island and Ocracoke Inlet.

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. Early Pleistocene deposits mimic the orientation of the underlying Pliocene surface (Mallinson et al. 2010a).

The Albemarle Embayment, a regional depositional basin, is filled with sediments that were deposited during many sea-level fluctuations that occurred during the multiple glaciations and interglacial periods of the Quaternary (Riggs et al. 1995; Riggs and Ames 2006). Quaternary sediments in the Albemarle Embayment are up to 90 m (295 ft) thick (Culver et al. 2008b). They 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 paleovalleys such as the paleo–Roanoke River drainage system (Culver et al. 2008b).

The Quaternary evolution of the continental shelf system has been influenced in part by the erosional topography inherited from the Pliocene surface (Mallinson et al. 2010a). During multiple glacial episodes in the Pleistocene, fluvial channels cut into existing strata. These channels were then backfilled when sea level rose. On top of Pleistocene sediments located close to the surface, Holocene sea-level rise has deposited modern barrier island and estuarine sediments consisting of compact peat and mud and unconsolidated sands, gravels, and shell beds (Mallinson et al. 2010a).

Recent studies interpreted past climate conditions and depositional environments, and reconstructed environmental changes, by combining seismic stratigraphic data with micropaleontological (foraminifera, diatoms, and pollen) data from drill cores in the Cape Hatteras region of the northern Albemarle Embayment and Outer Banks (Culver et al. 2007, 2008b). Because the paleoenvironments preserved in the Quaternary section are generally the result of highstand warm climate and sea-level conditions, they may inform us about potential future environmental shifts that could occur if ongoing relative climate and sea-level changes continue (Culver et al. 2008b).

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) with cooler climate conditions (Culver et al. 2008b).

The early Pleistocene Epoch was characterized by climate and sea-level changes 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 fluvial channels dissected coastal systems along the continental margin. When the ice melted during interglacial periods, the flooding that resulted from meltwater flow back into the oceans caused the backfilling of incised valleys with fluvial and estuarine sediments. The advancing shoreline and shoreface produced an erosional shoreface 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 lowstand terrace with shelf-sand ridge deposits occurs at a deeper level, about 45 to 70 m (148 to 230 ft), beneath the modern barrier system and northern Pamlico Sound (Mallinson et al. 2010a).

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

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) and the shoreline was tens of miles west of its present location (Riggs et al. 2008b).

During the Last Glacial Maximum (approximately 21,000 years before present), when much of North America and northern Europe was covered with ice sheets, sea level was 120 to 130 m (394 to 425 ft) lower than present and the coastal system occurred as far out as the present-day continental shelf (Williams 2013), which extended from 15 km (10 mi) off modern Cape Hatteras to 100 km (62 mi) seaward of the barrier islands at the present-day North Carolina/Virginia state line (Riggs et al. 2011). 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.

These drainage channels and the deposits that filled them have played a significant role in the evolution of the modern coastal system (Mallinson et al. 2010a). Paleodrainage systems may have a role in controlling the locations and similarities of the Carolina capes (Hatteras, Lookout, Fear, and Romain) (Swift et al. 1972; Moslow and Heron 1981).

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 (Horton et al. 2009; Williams 2013).

Near the end of the Pleistocene, approximately 12,000 years ago, the landscape of the northern Albemarle Embayment was largely subaerial, and the paleo–Roanoke River was still entrenched in a broad valley that cut 35 to 40 m (115 to 131 ft) into older Pleistocene deposits (fig. 35A) (Mallinson et al. 2005; Culver et al. 2008b) and extended about 20 km (12 mi) offshore from Albemarle Sound (Culver et al. 2008b). This paleovalley was being refilled with Late Pleistocene to Holocene fluvial/estuarine sediments (Boss and Hoffman 2001, as cited in Culver et al. 2008b; Boss et al. 2002, as cited in Culver et al. 2008b; Mallinson et al. 2005).

The current barrier islands are perched upon the Hatteras Flats Interstream Divide, a Pleistocene feature that separated the southwest-flowing Pamlico Creek from another creek to the east (Riggs and Ames 2006; Culver et al. 2007). By 11,000 years ago, the shoreline was about 30.5 m (100 ft) below present sea level (Riggs et al. 2011).

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

Between 11,000 and 8,000 years ago, sea level rose at a rate of 5.3 mm (0.21 in)/year, causing initial flooding of what is now the Albemarle Sound area, west of the modern barrier islands (fig. 35A) (Riggs et al. 2011). Marine waters flooded the paleo–Roanoke River, the Pamlico Creek drainage, and the Tar and Neuse river valleys west of the present barrier islands approximately 9,000 to 7,000 years before present (Mallinson et al. 2005; Culver et al. 2007, 2008b). Around 7,000 years ago, sea-level rise continued and increased flooding up the drowned-river valleys formed Pamlico Sound (fig. 36A) (Culver et al. 2007; Mallinson et al. 2010b).

From 6,000 to 3,000 years ago, global sea level continued to rise at a slower rate of about 0.5 mm (0.02 in)/year (Williams 2013). By 5,000 years ago, the paleo–Roanoke River Valley had become an open embayment (Albemarle Bay) and had tidal exchange with the open Atlantic Ocean and estuarine environments to the west. Colington Shoals had developed at the mouth of the bay (fig. 35B) (Mallinson et al. 2005; Culver et al. 2008b). Other fluvial valleys along the coast were also flooded by rising seas, and shoals and shoreparallel spits and

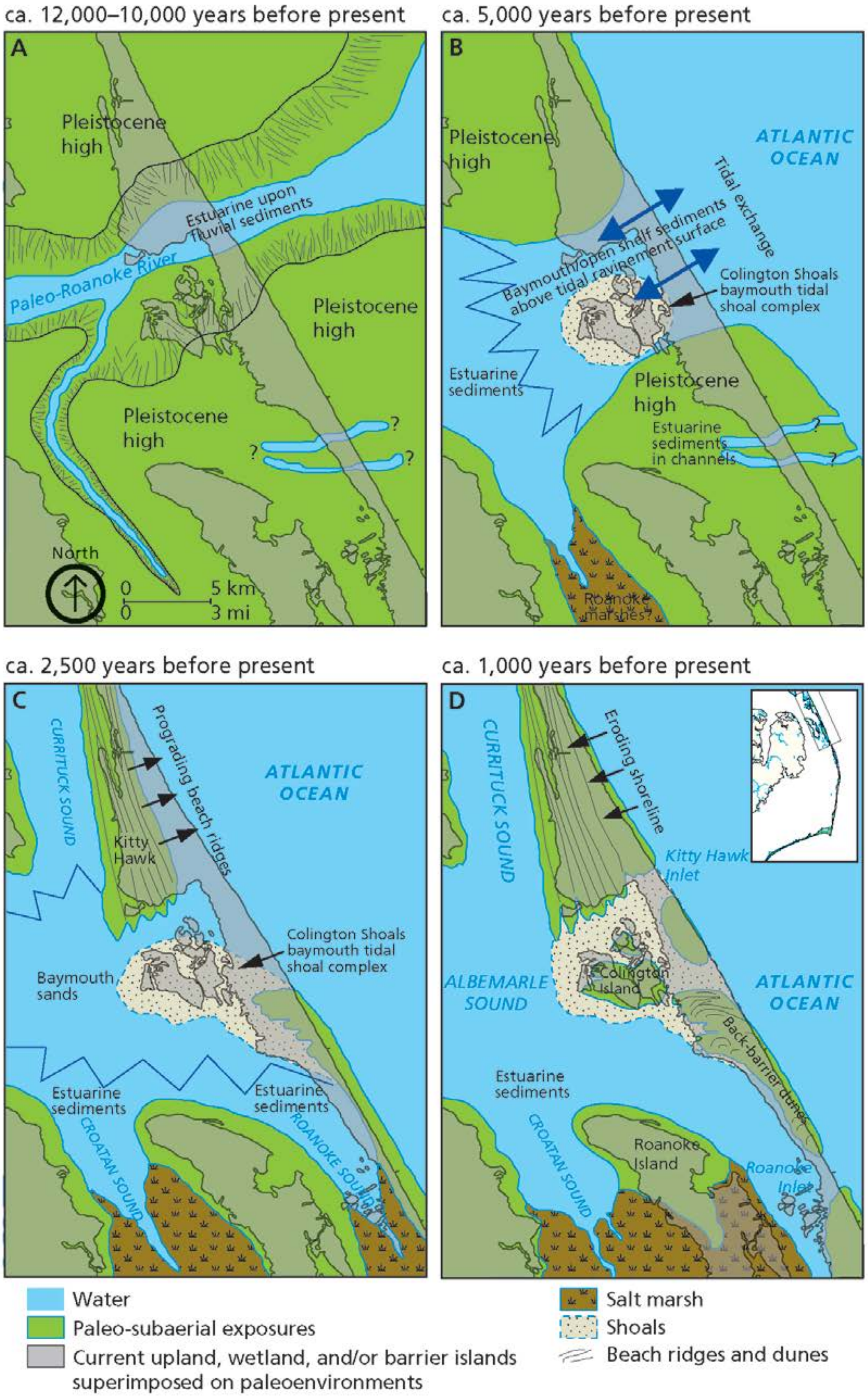

Figure 35. Paleogeographic reconstructions for the northern Albemarle Embayment during the Late Pleistocene and Holocene. Inset on panel D shows the location of the reconstruction maps. Gray areas and modern shorelines are shown as guides to changes occurring over time. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 14 in Culver et al. (2008b).

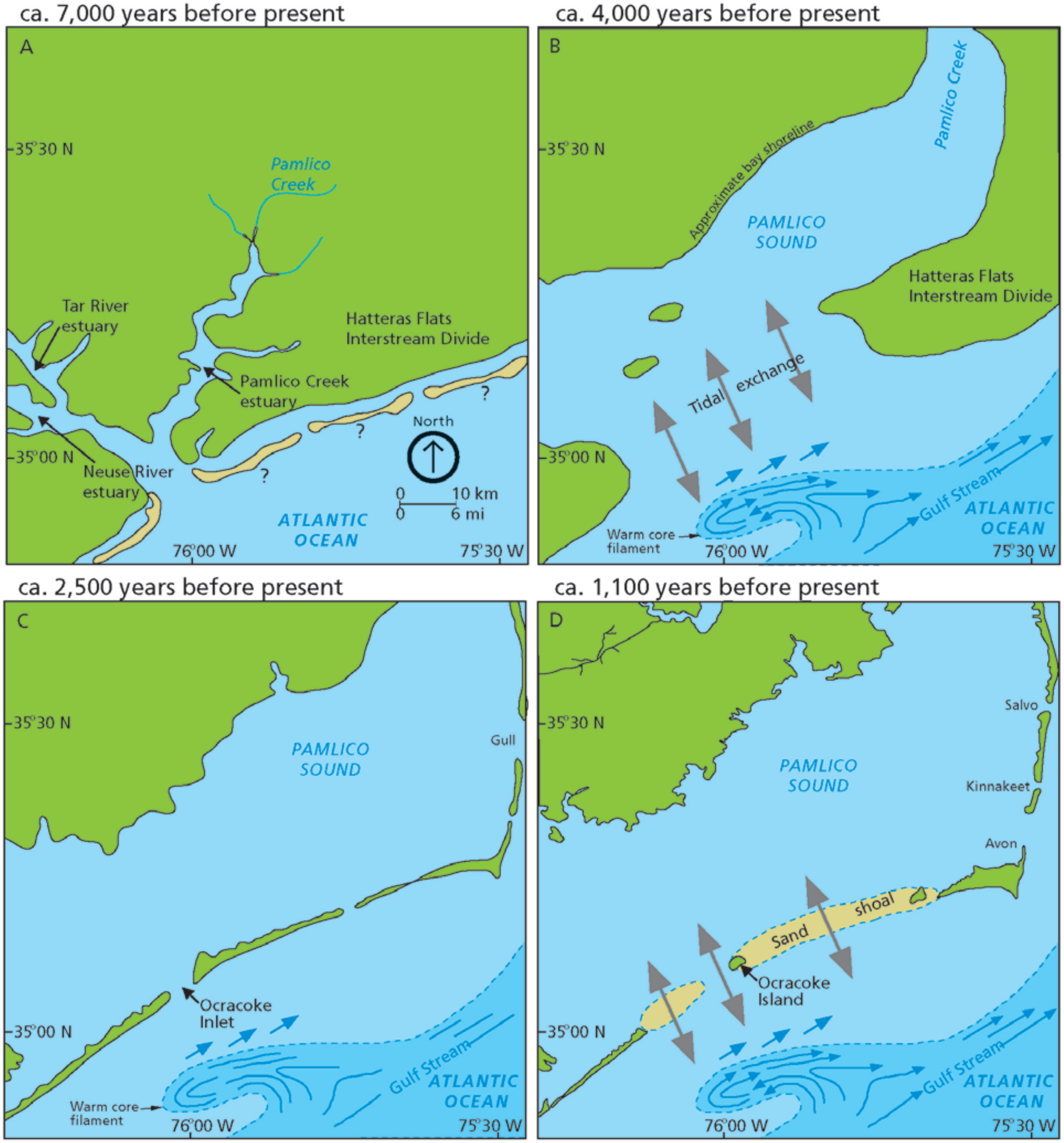

Figure 36. Paleogeographic reconstructions for the southern Pamlico Basin during the Holocene. Graphic redrafted by Trista Thornberry-Ehrlich (Colorado State University) after figure 3 in Culver et al. (2007) and figure 7 in Mallinson et al. (2009).

barriers cut off open-marine access to local river channels, forming sounds (Culver et al. 2007, 2008b). Upward-fining, muddy units in Pamlico Sound, deposited approximately 4,070 to 4,340 years ago, indicate that conditions were highly brackish and estuarine at that time as rising seas overtopped the Hatteras Flats Interstream Divide (fig. 36B) (Culver et al. 2007).

Thieler and Ashton (2011) suggested that a cuspate foreland existed between Cape Hatteras and Cape Lookout in the Early Holocene, from about 9,000 to 4,000 years ago. This cape was likely captured by the present-day capes.

Around 3,600 years ago, the shoreline was about 4.2 m (13.8 ft) below present sea level (Horton et al. 2009). By 3,000 years ago, the initial configuration of barrier islands had formed slightly seaward of their modern location (fig. 36C) (Riggs et al. 2011), effectively blocking the drowned river drainages to form semi-enclosed estuaries, including Pamlico Bay (Culver et al. 2007). Beach ridges began to develop north of the flooded paleo–Roanoke River Valley and formed Currituck Sound (Mallinson et al. 2005).

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

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). According to Kemp et al. (2011), sea level in the region of present-day North Carolina was stable 1,060 to 2,100 years ago (from 100 BCE to 950 CE). Sea level rose over the subsequent 450 years (950 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 due to cooler temperatures. As sea level rose, the ocean shorelines of simple barrier islands receded westward.

Between 2,500 and 1,500 years ago, several sets of beach ridges prograded to the east (fig. 35C), and barrier islands to the south of the paleo–Roanoke River Valley developed on top of flooded Late Pleistocene highs in the area between Oregon Inlet and Ocracoke Inlet (fig. 36C) (Culver et al. 2008b).

According to core studies performed north of Cape Hatteras, islands partially collapsed into a submarine shoal system during intervals between 3,000 and 500 years before present (Culver et al. 2007). Large portions of the southern Outer Banks were segmented, likely due to increased hurricane activity, during the Medieval Warm Period approximately 1,100 years before present (fig. 36D) (Mallinson et al. 2011). Major disruptions in barrier island continuity occurred between Ocracoke Inlet and Rodanthe (a 90-km [56-mi] section), including barrier segmentation on Ocracoke Island, between Hatteras Village and Frisco, between Buxton and Avon, in the Kinnakeet region, and on Pea Island (Mallinson et al. 2011). These processes allowed open marine environments to inundate the sound for varying periods of time before the barrier island system recovered. Vast amounts of sediment moved into Pamlico Sound, forming the shallows of Hatteras Flats, a vast submarine shoal west of the Cape Hatteras National Seashore barrier islands (fig. 36D) (Culver et al. 2007). As a result of these events, the sediments beneath the Outer Banks and Hatteras Flats are largely marine, with an extensive erosional surface at an average depth of approximately 9 m (30 ft) below present sea level (Mallinson et al. 2010a). The widest portions of the Outer Banks at Rodanthe, Salvo, Kinnakeet, and Avon are underlain by migrating inlet sediments and associated spit and beach ridge deposits (Mallinson et al. 2010b).

Farther north, approximately 1,000 years ago, the beach ridges at Kitty Hawk ceased accumulating and prograding to the east (Mallinson et al. 2008a). Erosion started to move the shoreline westward, truncating the previously deposited beach ridges. Shoals that developed at the mouth of the embayment became subaerially exposed and are now known as Colington Island. Large back-barrier dunes formed on the western sides of local barrier islands (fig. 35D) (Havholm et al. 2004; Culver et al. 2008b). Inlets such as Kitty Hawk and Roanoke inlets began to form and migrate (Culver et al. 2008b). Roanoke Island remained connected to the mainland by a series of extensive salt marshes (Culver et al. 2008b).

The Little Ice Age occurred from approximately 1400 to 1900 CE, with peak cooling occurring between approximately 1570 and 1650 CE (Mallinson et al. 2011). During this peak, as many as 20 inlets may have been open along the Outer Banks in an area that today has only four inlets (fig. 13) (Mallinson et al. 2011). The formation and maintenance of numerous paleo-inlets during the Little Ice Age are likely due to the increased frequency of nor’easter storms (Mallinson et al. 2011).

In theory, existing inlets are in equilibrium with the modern tidal prism. Newly opened inlets that are not in equilibrium will not be stable and will shoal quickly (Mallinson et al. 2011). Four possible explanations have been offered for the occurrence of so many inlets through the Outer Banks in the past:

1) Frequent and severe storms maintained an overall elevated wind-driven tidal prism (storm surge) that kept the inlets open.
2) Increased runoff from rivers due to storm patterns required more outlets through the barriers.
3) A threshold was crossed during the Medieval Warm Period and perhaps again during the Little Ice Age, causing island segmentation that allowed for a modified tidal regime and an increase in tidal prism to maintain the newly formed inlets.
4) Some combination of these conditions occurred (Mallinson et al. 2011).

Most Outer Banks inlets have closed naturally over the last 300 years, likely due to more stable climate conditions, fewer storm impacts (hurricanes and nor’easters), and decreases in the average wind intensity and wave energy field in the mid-latitudes of the North Atlantic (Mallinson et al. 2011). The renewed development of the simple barrier islands returned Pamlico Sound to an estuarine state, with lower energy and deposition of organic-rich mud (Riggs et al. 2009). Thus, most back-barrier marshes and surficial geomorphic features on the simple barrier islands (from Pea Island to Portsmouth Island) formed within the last 500 years (Riggs et al. 2009), after Columbus arrived in North America.

Modern Barrier System

Global sea level has risen at an average rate of 1.8 mm (0.07 in)/year over the past century (Douglas 1997), and at a rate of 0.6 to 1.0 mm (0.02 to 0.04 in)/year since about 1990 (Sallenger et al. 2012).

Recent local sea-level rise in the Outer Banks (table 5) has been higher than global sea-level rise. As detailed in the “Coastal Vulnerability and Sea-Level Rise” section, the rate of local sea-level rise in the Outer Banks increased to about 1.5 mm (0.06 ft)/year) in the beginning of the 19th century, with a resulting increase in the rate of upslope migration of the barrier islands (Riggs et al. 2009). Beginning around 1880 to 1920, sea-level rose along the North Carolina coast at a mean rate of 2.1 mm

(0.08 in)/year (Kemp et al. 2011). Along the northern Outer Banks, sea level has been rising at rates between 2.82 mm (0.11 in)/year), as measured at the Oregon Inlet Marina (1977–2006; Zervas 2009), and 4.5 mm (0.18 in)/year) at Duck, North Carolina (1980–2000; Zervas 2004, as cited in Riggs et al. 2008b).

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.

Geomorphological processes continue to shape the dynamic barrier island system under the control of the underlying geologic framework, in concert with ongoing storm dynamics and sea-level rise. In addition, anthropogenic activity is one of the largest influences on modern barrier island morphology (see the "Geologic Resource Management Issues" chapter for additional information.) Stabilization of shorelines and dunes (with sandbags and constructed and interior dune ridges), beach renourishment, urban development, excavations, dredging, and road and bridge construction all influence natural geomorphic processes (Ames and Riggs 2006j), and in turn the dependent natural habitats within Cape Hatteras National Seashore.

Geologic Map Data

This chapter summarizes the geologic map data available for Cape Hatteras National Seashore. Posters (in pocket) display the map data draped over imagery of the park and surrounding area. The Map Unit Properties Tables (in pocket) summarize this report's content for each geologic map unit. Complete GIS data are included on the accompanying DVD and are also 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. Geologic maps can be divided into two primary types: surficial and bedrock. 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. These maps may also be referred to as "geomorphic." Bedrock geologic maps encompass older, typically more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type. Surficial (geomorphic) map data are provided for Cape Hatteras National Seashore that also cover Wright Brothers National Memorial and Fort Raleigh National Historic Site.

Geologic maps often depict geomorphic features, structural interpretations (such as faults or folds), and locations of past geologic hazards that may be susceptible to future activity. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. 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.

This report is supported by two digital maps of Cape Hatteras National Seashore surficial geology, each developed using a distinct methodology and resulting in a unique set of geomorphic units and different area of coverage.

The first map, developed by Riggs and Ames (2006) and produced as Ames and Riggs (2006a–j) 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). This detailed map covers portions, but not all, of the northern Outer Banks and Cape Hatteras National Seashore.

Products of the Riggs and Ames mapping informed the North Carolina Geological Survey's development of a second map, which classifies surficial features using remotely sensed data as described by Hoffman et al. (2007g) and produced as Hoffman et al. (2007a–f). The map includes complete areal coverage of Cape Hatteras National Seashore.

GRI GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available at http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm. 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 Hatteras National Seashore using data model version 1.4. The GRI Geologic Maps website, http://www.nature.nps.gov/geology/inventory/geo_maps.cfm, provides more information about GRI map products.

GRI digital geologic data are included on the attached CD and are available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Reference/Search?SearchType=Q). Enter "GRI" as the search text and select a park from the unit list.

The following components are part of the data set:

- A readme file (caha_gis_readme.pdf) that describes data formats, naming conventions, extraction directions, use constraints, and contact information.
- Data in ESRI geodatabase and shapefile GIS format;
- Layer files with feature symbology (table 9);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (caha_geology.pdf) that contains information captured from source maps such as map unit descriptions; and
- ESRI map documents (cahg_geology.mxd; caha_geology.mxd) that display the digital geologic data.

Table 9. Geology data layers in the Cape Hatteras National Seashore GIS data. The North Carolina Geological Survey data are compiled as caha_geology.mxd and on maps 1–7 (poster, in pocket). The East Carolina University data are compiled as cahg_geology.mxd and on sheets 1–10 (in pocket).

Data Layer	Data Layer Code	On Posters?
Geomorphic Ridge Lines	GLF	Yes
Anthropic Overprint Area (ECU data only)	ANTHRO	Yes
Geomorphic Contacts	GLGA	Yes
Geomorphic Units	GLG	Yes

GRI Map Posters

A poster of the GRI digital geologic data draped over aerial imagery of the park and surrounding area is included with this report. The poster (maps 1–7) displays the North Carolina Geological Survey data for Cape Hatteras National Seashore. The individual sheets (sheets 1–10) display the detailed East Carolina University data. 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.

Map Unit Properties Tables

The Map Unit Properties Tables list the geologic time division, symbol, and a simplified description for each of the geologic map units in the GRI GIS data sets. Following the structure of the report, the table summarizes the geologic features, processes, resource management issues, and history associated with each map unit.

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 GRI 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 (1:24,000 for North Carolina Geological Survey data, 1:10,000 for East Carolina University data) and US National Map Accuracy Standards, geologic features represented in the geologic map data are horizontally within 12 m (40 ft; 1:24,000-scale data) or 5 m (17 ft; 1:10,000-scale data) of their true locations.

Glossary

These brief definitions are for selected geologic terms relevant to this report. Definitions are based on those in the American Geosciences Institute Glossary of Geology *(5th edition; 2005). Additional terms are defined at http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.*

absolute age. The geologic age (in years) of a fossil, rock, feature, or event. The term is now in disfavor as it implies a certainty or exactness that may not be possible by present dating methods. See "isotopic age" and "radiometric age."

accretion (sedimentary). The gradual addition of new land to old by the deposition of sediment, for example, on a beach by the washing up of sand from the sea.

accretion (streams). The filling-up of a stream bed as a result of such factors as silting or wave action.

aeolian. Describes materials formed, eroded, or deposited by or related to the action of wind.

aggradation. The building up of Earth's surface by depositional processes.

amphibole. A group of silicate (silicon + oxygen) minerals composed of hydrous calcium and magnesium with the general formula $(Ca_2Mg_5)Si_8O_{22}(OH)_2$.

amphibolite. A metamorphic rock consisting mostly of the minerals amphibole and plagioclase, with little or no quartz.

anticline. A fold, generally convex upward ("A"-shaped) whose core contains the stratigraphically older rocks. Compare with "syncline."

apatite. A group of phosphate (phosphorus + oxygen) minerals composed of calcium together with fluorine, chlorine, hydroxyl, or carbonate in varying amounts and having the general formula $Ca_5(F,OH,Cl)(PO_4,CO_3)_3$.

aquiclude. A saturated geologic unit that is incapable of transmitting significant quantities of water under ordinary hydraulic gradients. Replaced by the term "confining bed."

aquifer. A rock or sedimentary unit that is sufficiently porous to hold water, sufficiently permeable to allow water to move through it, and saturated to some level.

aragonite. A carbonate (carbon + oxygen) mineral of calcium, $CaCO_3$; it is the second most abundant cave mineral after calcite and differs from calcite in its crystal structure.

astronomical tide. The periodic rise and fall of a body of water resulting from gravitational interactions between the Sun, Moon, and Earth. Synonymous with "tide," but used to emphasize the absence of atmospheric influences.

back-barrier. Refers to areas along the landward (estuarine) side of a barrier island; it is influenced predominantly by estuarine processes such as lagoonal tides and landforms such as mudflats and overwash fans.

bank. A submerged ridge of sand in the sea, a lake, or a river, usually exposed during low tide or low water.

barrier island. A long, low, narrow island consisting of a ridge of sand that parallels the coast.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface, commonly sedimentary. In many regions the basement is of Precambrian age, but it may be much younger. Also, Earth's crust below sedimentary deposits that extends down to the Mohorovicic discontinuity.

basin (sedimentary). Any depression, from continental to local scale, into which sediments are deposited.

bathymetry. The measurement of ocean or lake depths and the charting of the topography of the ocean or lake floor.

beach. A gently sloping shoreline covered with sediment, usually sand or gravel, extending landward from the low-water line to the place where there is a definite change in material, physiographic form, or permanent vegetation.

beach face. The section of the beach normally exposed to the action of wave uprush.

beachrock. A poorly to well-cemented sedimentary rock formed in the intertidal zone, consisting of sand and gravel cemented with calcium carbonate.

bed. The smallest sedimentary stratigraphic unit, commonly ranging in thickness from about 1 cm (0.4 in) to 1 to 2 m (40 to 80 in) and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

bedrock. Solid rock that underlies unconsolidated, superficial material and soil.

benthic. Pertaining to the ocean bottom or organisms living on or in the substrate; also, referring to that environment.

berm. A low, impermanent, nearly horizontal or landward-sloping bench, shelf, or ledge on the backshore (zone above the high-water line) of a beach.

biotite. A dark-colored, shiny silicate mineral (silicon + oxygen) of the mica group composed of magnesium and/or iron, $K(Mg,Fe)Si_3O_{10}(OH)_2$; characterized by perfect cleavage, readily splitting into thin sheets.

bioturbation. The reworking of sediment by organisms.

bivalve. Having a shell composed of two distinct, but equal or nearly equal, movable valves, which open and shut.

brachiopod. Any marine invertebrate belonging to the phylum Brachiopoda, characterized by two bilaterally symmetrical valves that are commonly attached to a substratum but may also be free. Range: Lower Cambrian to Holocene.

breakwater. An offshore, generally shore-parallel structure that breaks the force of the waves.

bryozoan. Any invertebrate belonging to the phylum Bryozoa; characterized by colonial growth and a calcareous skeleton. Range: Ordovician (and possibly Upper Cambrian) to Holocene.

burrow. A tubular or cylindrical hole or opening, made in originally soft or loose sediment by a mud-eating worm, mollusk, or other invertebrate; may be later filled with clay or sand and preserved.

calcareous. Describes a substance that contains calcium carbonate. When applied to a rock name it implies that as much as 50% of the rock is calcium carbonate.

calcite. A carbonate (carbon + oxygen) mineral of calcium, $CaCO_3$; calcium carbonate. It is the most abundant cave mineral.

calcium carbonate. A solid, $CaCO_3$, occurring in nature as primarily calcite and aragonite.

cape. An extensive, somewhat rounded irregularity of land jutting out from the coast into a large body of water, either as a peninsula (e.g., Cape Cod, Massachusetts) or as a projecting point (e.g., Cape Hatteras, North Carolina). Also, the part of the projection extending farthest into the water.

carbonate. A mineral group composed of carbon and oxygen plus an element or elements; for example calcite, $CaCO_3$; and dolomite, $CaMg(CO_3)_2$.

carbonate rock. A rock, for example, limestone, calcite, and dolomite, that consist primarily of carbonate minerals.

cement (sedimentary). Mineral material, usually chemically precipitated, that occurs in the spaces among the individual grains of sedimentary rocks, thus binding the grains together.

cementation. The process by which clastic sediments become lithified or consolidated into hard, compact rocks, usually through deposition or precipitation of minerals in the spaces among the individual grains of the sediment; may occur simultaneously with sedimentation or at a later time.

channel. A relatively narrow sea or stretch of water between two nearby landmasses, connecting two larger bodies of water.

chlorite. A group of silicate (silicon + oxygen) minerals composed of iron, magnesium, and aluminum with the general formula $(Mg,Fe)_6(AlSiO_3)O_{10}(OH)_8$.

chronology. The arrangement of events in their proper sequence in time.

chronostratigraphy. The branch of stratigraphy that deals with the age of strata and their time relations.

clay. Refers to clay minerals and sedimentary fragments that are less than 1/256 mm (0.00015 in) across.

clay mineral. Any mineral occurring in the clay-sized fraction with the understanding that size imposes physical and chemical characteristics.

coarse-grained. Describes a crystalline rock and texture in which the individual minerals are relatively large, specifically an igneous rock whose particles have an average diameter greater than 5 mm (0.2 in). Also, describes sediment or sedimentary rock and texture in which the individual constituents are easily seen with the unaided eye, specifically sediment or rock whose particles have an average diameter greater than 2 mm (0.08 in).

coastal plain. Any lowland area bordering a sea or ocean, extending inland to the nearest elevated land, and sloping very gently seaward; may result from the accumulation of material along a coast.

compaction. The process whereby fine-grained sediment is converted to consolidated rock.

confining bed. A body of relatively impermeable or distinctly less permeable material stratigraphically adjacent to one or more aquifers. Replaced the term "aquiclude."

continental rise. Gently sloping region from the foot of the continental slope to the deep ocean abyssal plain; generally has smooth topography but may have submarine canyons.

continental shelf. The shallowly submerged—covered by water depths of less than 200 m (660 ft)—part of a continental margin that extends from the shoreline to the continental slope.

continental slope. The relatively steep slope from the outer edge of the continental shelf down to the more gently sloping ocean depths of the continental rise or abyssal plain.

core (drill). A cylindrical section of rock or sediment. usually 5–10 cm (2–4 in) across and up to several meters long, taken as a sample of the interval penetrated by a core bit, and brought to the surface for geologic examination and/or laboratory analysis.

cross section. A graphic interpretation of geology, structure, or stratigraphy based on mapped and measured geologic extents and attitudes, depicted in a vertical plane (i.e., a cut or profile view).

delta. The low, nearly flat, alluvial tract of land at or near the mouth of a river, commonly forming a triangular or fan-shaped plain of considerable area; resulting from the accumulation of sediment supplied by the river in such quantities that it is not removed by tides, waves, and currents.

delta fan. A deposit formed by the merging of an alluvial fan with a delta.

delta plain. The level or nearly level surface composing the landward part of a large or compound delta; strictly, an alluvial plain characterized by repeated channel bifurcation and divergence, multiple distributary channels, and interdistributary flood basins.

diatom. A microscopic, single-celled alga that secretes walls of silica, called frustules; lives in freshwater and marine environments.

discharge. The rate of flow of surface water or groundwater at a given moment, expressed as volume per unit of time.

drainage. The manner in which the waters of an area flow off in surface streams or subsurface conduits; also, the processes of surface drainage of water from an area by streamflow and sheet flow, and the removal of excess water from soil by downward flow.

drainage basin. The total area from which a stream system receives or drains precipitation runoff.

dredge (engineering). A floating machine for excavating sedimentary material from the bottom of a body of water, raising it to the surface, and discharging it to the bank through a floating pipeline or conveyor, into a scow for removal, or, in the case of certain mining dredges, into the same body of water after removal of the ore mineral.

dune. A low mound or ridge of sediment, usually sand, deposited by the wind.

dune field. Extensive deposits of sand in an area where the supply is abundant; individual dunes resemble barchans but are highly irregular in shape and crowded.

ebb-tidal delta. A tidal delta formed on the seaward side of a tidal inlet.

electrical resistivity survey. A measure of the difficulty with which electric current flows through unconsolidated sediment and rock.

electromagnetic survey. An electrical exploration method based on the measurement of alternating magnetic fields associated with currents artificially or naturally maintained in the subsurface.

emergence. A change in the levels of water and land such that the land is relatively higher and areas formerly under water are exposed; results from either an uplift of land or fall of water level. Compare to "submergence."

entrainment. The process of picking up and transporting sediment, commonly by wind or water.

ephemeral stream. A stream that flows briefly, only in direct response to precipitation, and whose channel is always above the water table.

erosion. The general process or group of processes that loosen, dissolve, wear away, and simultaneously move from one place to another, the materials of Earth's crust; includes weathering, solution, abrasive actions, and transportation, but usually excludes slope movements.

estuary. The seaward end or tidal mouth of a river where freshwater and seawater mix.

eustatic. Describes a worldwide rise or fall in sea level.

evapotranspiration. Loss of water from a land area through transpiration (passage of water vapor from a living body through a membrane) of plants and evaporation from the soil and surface-water bodies. Also, the volume of water lost through evapotranspiration

facies (sedimentary). The depositional or environmental conditions reflected in the sedimentary structures, textures, mineralogy, fossils, and other components of a sedimentary rock.

fan delta. A gently sloping alluvial deposit produced where a mountain stream flows out onto a lowland.

feldspar. A group of abundant silicate (silicon + oxygen) minerals, comprising more than 60% of Earth's crust and occurring in all types of rocks. Compare to "alkali feldspar" and "plagioclase."

feldspathic. Describes a rock containing feldspar.

felsic. Derived from ***fel***dspar +***si***lica to describe an igneous rock having abundant light-colored minerals such as quartz, feldspars, or muscovite; also, describes those minerals.

fetch. The area of the ocean surface over which a constant and uniform wind generates waves.

fine-grained. Describes a crystalline or glassy rock and texture in which the individual minerals are relatively small, specifically an igneous rock whose particles have an average diameter less than 1 mm (0.04 in). Also, describes sediment or sedimentary rock and texture in which the individual constituents are too small to distinguish with the unaided eye, specifically sediment or rock whose particles have an average diameter less than 1/16 mm (0.002 in), that is, silt-size particles and smaller.

flood-tidal delta. A tidal delta formed on the landward side of a tidal inlet.

floodplain. The surface or strip of relatively smooth land composed of alluvium and adjacent to a river channel, constructed by the present river in its existing regimen and covered with water when the river overflows its banks. A river has one floodplain and may have one or more terraces representing abandoned floodplains.

fluvial channel. A natural passageway or depression produced by the action of a stream or river.

foraminifer. Any protozoan belonging to the subclass Sarcodina, order Foraminiferida, characterized by the presence of a test of one to many chambers composed of secreted calcite (rarely silica or aragonite) or of agglutinated particles; most foraminifers are marine but freshwater forms are known. Range: Cambrian to Holocene.

foreshore. The part of the beach face that lies between the berm crest and the low water line, and that is shaped by waves and tides.

formation. Fundamental rock-stratigraphic unit that is mappable, lithologically distinct from adjoining strata, and has definable upper and lower contacts.

fossil. A remain, trace, or imprint of a plant or animal that has been preserved in the Earth's crust since some past geologic time; loosely, any evidence of past life.

garnet. A hard silicate (silicon + oxygen) mineral with a glassy luster, and commonly well-defined crystal faces; characteristically dark red but occurs in a variety of colors.

gastropod. Any mollusk belonging to the class Gastropoda, characterized by a distinct head with eyes and tentacles and, in most, by a single calcareous shell that is closed at the apex, sometimes spiraled, not chambered, and generally asymmetrical (e.g., a snail). Range: Upper Cambrian to Holocene.

geodetic surveying. Surveying that takes into account the figure and size of Earth, with corrections are made for curvature; used where the areas or distances involved are so great that results of desired accuracy and precision cannot be obtained by plane (ordinary field and topographic) surveying.

geology. The study of Earth, including its origin, history, physical processes, components, and morphology.

geomorphology. The study of the general configuration of surface landforms and their relationships to underlying structures, and of the history of geologic changes as recorded by these surface features.

gradient. A degree of inclination (steepness of slope), or a rate of ascent or descent, of an inclined part of Earth's surface with respect to the horizontal; expressed as a ratio (vertical to horizontal), a fraction (such as m/km or ft/mi), a percentage (of horizontal distance), or an angle (in degrees).

granite. A coarse-grained, intrusive igneous (plutonic) rock in which quartz constitutes 10%–50% percent of the felsic ("light-colored") components and the alkali feldspar/total feldspar ratio is generally restricted to the range of 65% to 90%; perhaps the best known of all igneous rocks.

gravel. An unconsolidated, natural accumulation of typically rounded rock fragments resulting from erosion; consists predominantly of particles larger than sand, greater than 2 mm (1/12 in) across.

groundwater. That part of subsurface water that is in the zone of saturation, including underground streams.

hematite. An oxide mineral composed of oxygen and iron, Fe_2O_3.

heterogeneous. Consisting of dissimilar or diverse ingredients or constituents.

highstand. The interval of time during one or more cycles of relative sea-level change when sea level is above the edge of the continental shelf in a given area. Compare to "lowstand."

hornblende. A silicate (silicon + oxygen) mineral of sodium, potassium, calcium, magnesium, iron, and aluminum; the most common mineral of the amphibole group; commonly black and occurring in distinct crystals or in columnar, fibrous, or granular forms in hand specimens.

hurricane. The term applied in the Northern Hemisphere for an atmospheric low-pressure system with a closed roughly circular wind motion that is counterclockwise; sustained near-surface wind speed equals or exceeds 64 knots (73 mph).

hydrogeology. The science that deals with subsurface waters and related geologic aspects of surface waters, including the movement of groundwater; the mechanical, chemical, and thermal interaction of groundwater with the porous medium; and the transport of energy and chemical constituents by the flow of groundwater. Synonymous with "geohydrology."

hydrology. The study of liquid and solid water properties, circulation, and distribution, on and under the Earth's surface and in the atmosphere.

ilmenite. An oxide mineral composed of oxygen, titanium, and iron $FeTiO_3$; iron titanium oxide. It commonly contains considerable magnesium and manganese. Ilmenite is a common accessory mineral in basic igneous rocks (e.g., gabbro), and is also concentrated in mineral sands.

incision. Downward erosion by a stream, resulting in a deepened channel and commonly a narrow, steep-walled valley.

indurated. Describes a rock or soil hardened or consolidated by pressure, cementation, or heat.

induration. Hardening by heat, pressure, or the introduction of cementing material, especially the process by which relatively consolidated rock is made harder or more compact.

interdune. The relatively flat surface between dunes, commonly a long, troughlike, wind-swept passage between parallel dunes; may be covered with sand or sand free.

interfluve. The area between rivers, especially the relatively undissected upland or ridge between two adjacent valleys containing streams flowing in the same general direction.

intertidal. Pertaining to the benthic ocean environment or depth zone between high water and low water; also, pertaining to the organisms of that environment. Synonymous with "littoral."

isostacy. The condition of equilibrium, comparable to floating, of the units of the lithosphere above the asthenosphere.

isotopic age. An age (in years) calculated from the quantitative determination of radioactive elements and their decay products. Synonymous with "radiometric age."

lag gravel. An accumulation of coarse material remaining on a surface after finer material has been blown or washed away.

lagoon. A narrow body of water that is parallel to the shore and between the mainland and a barrier island; characterized by minimal or no freshwater influx and limited tidal flux, which cause elevated salinities. Also, a shallow body of water enclosed or nearly enclosed within an atoll.

lens. A sedimentary deposit that resembles a convex lens and is characterized by converging surfaces, thick in the middle and thinning out toward the edges.

lenticular. Resembling in shape the cross section of a lens.

light detection and ranging/LiDAR. A method and instrument that measures distance to a reflecting object by emitting timed pulses of light and measuring the time between emission and reception of reflected pulses; the measured interval is converted to distance.

limestone. A carbonate sedimentary rock consisting of more than 95% calcite and less than 5% dolomite.

lithofacies. A lateral, mappable subdivision of a designated stratigraphic unit distinguished from adjacent subdivisions on the basis of lithology.

lithology. The physical description or classification of a rock or rock unit based on characteristics such as color, mineral composition, and grain size.

lithostratigraphy. The branch of stratigraphy that deals with the description and systematic organization of the rocks of Earth's crust into distinctive named units based on the lithologic character of the rocks and their stratigraphic relations.

littoral. Pertaining to the benthic ocean environment or depth zone between high water and low water; also, pertaining to the organisms of that environment. Synonymous with "intertidal."

longitudinal dune. A long, narrow sand dune, usually symmetrical in cross profile, oriented parallel with the direction of the prevailing wind; characteristically wider and steeper on the windward side and tapering to a point on the leeward side; may be a few meters high and as much as 100 km (60 mi) long.

longshore current. A current parallel to a coastline caused by waves approaching the shore at an oblique angle.

lowstand. The interval of time during one or more cycles of relative sea-level change when sea level is below the edge of the continental shelf in a given area. Compare to "highstand."

magnetite. An oxide mineral composed of oxygen and iron, Fe_3O_4; iron oxide. It commonly contains manganese, nickel, chromium, and titanium. It is a very common and widely distributed accessory mineral in rocks of all kinds, and occurs as a "heavy mineral" in sand.

marine terrace. A relatively flat-topped, horizontal or gently inclined, surface of marine origin along a coast, commonly veneered by a marine deposit (typically silt, sand, or fine gravel).

medium-grained. Describes an igneous rock and texture in which the individual crystals have an average diameter in the range of 1 to 5 mm (0.04 to 0.2 in.). Also, describes sediment or sedimentary rock and texture in which the individual particles have an average diameter in the range of 1/16 to 2 mm (0.002 to 0.08 in), that is, sand size.

member. A lithostratigraphic unit with definable contacts; a subdivision of a formation.

mica. A group of abundant silicate (silicon + oxygen) minerals characterized by perfect cleavage, readily splitting into thin sheets. Examples include "biotite" and "muscovite."

micaceous. Consisting of, containing, or pertaining to mica; also, resembling mica, for example, a "micaceous mineral" capable of being easily split into thin sheets.

mid-ocean ridge. The continuous, generally submarine and volcanically active mountain range that marks the divergent tectonic margins in Earth's oceans.

mineral. A naturally occurring inorganic crystalline solid with a definite chemical composition or compositional range.

mud flat. A relatively level area of fine silt along a shore or around an island, alternately covered and uncovered by the tide, or covered by shallow water; a muddy tidal flat barren of vegetation.

mollusk. A solitary invertebrate such as gastropods, bivalves, and cephalopods belonging to the phylum Mollusca. Range: Lower Cambrian to Holocene.

muscovite. A light-colored silicate (silicon + oxygen) mineral of the mica group, $KAl_3Si_3O_{10}(OH)_2$, characterized by perfect cleavage in one direction and the ability to split into thin, clear sheets.

neoglacial. A period of glacial readvance during the late Holocene Epoch. The Little Ice Age (1500s to mid-1800s) was the most recent.

neritic. Describes the ocean environment or depth zone between low tide and 200 m (660 ft), or between low tide and approximately the edge of the continental shelf. Also, describes the organisms living in that environment.

oligoclase. A silicate (silicon + oxygen) mineral of the plagioclase group, intermediate in chemical composition and crystallographic and physical characters between albite ($NaAlSi_3O_8$) and anorthite ($CaAl_2Si_2O_8$).

orogeny. A mountain-building event.

orthoclase. A colorless, white, cream-yellow, flesh-pink, or gray silicate (silicon + oxygen) mineral of the alkali feldspar group, $KAlSi_3O_8$, characterized by potassium ions in its crystal structure.

outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.

paleofluvial channel. A natural passageway or depression produced by the action of a stream or river at a particular time in the geologic past.

paleogeography. The study, description, and reconstruction of the physical landscape in past geologic periods.

paleontology. The study of the life and chronology of Earth's geologic past based on the fossil record.

paleotopography. The topographic relief of an area at a particular time in the geologic past.

parabolic dune. Crescent-shaped dune with horns or arms that point upwind.

parent material. The unconsolidated organic and mineral material from which soil forms.

parent rock. Rock from which soil, sediment, or other rock is derived.

passive margin. A continental plate boundary where no plate-scale tectonism is taking place; plates are not converging, diverging, or sliding past one another.

peat. An unconsolidated deposit of semicarbonized plant remains in a water-saturated environment, such as a bog or fen, and of persistently high moisture content (at least 75%). It is an early stage or rank in the development of coal; carbon content is about 60% and oxygen content is about 30% (moisture-free). Structures of the vegetal matter may or may not be visible, depending on the degree of organic matter degradation.

pebble. A small rounded rock, especially a waterworn stone, between 4 and 64 mm (0.16 and 2.5 in) across.

perched aquifer. An aquifer that is separated from ("perched" above) the main body of groundwater by an unsaturated zone.

periphyton. Microorganisms, primarily algae and heterotrophic microbes, that coat rocks, plants, and other surfaces at the bottom of a body of water.

permeability. A measure of the relative ease with which a fluid moves through the pore spaces of a rock or unconsolidated deposit.

plagioclase. A silicate (silicon + oxygen) mineral of the feldspar group that contains both sodium and calcium ions that freely substitute for one another; characterized by striations (parallel lines) in hand specimens.

platform. Any level or nearly level surface.

porosity. The percentage of total void space in a volume of rock or unconsolidated deposit.

potassium feldspar. A feldspar mineral rich in potassium such as orthoclase, microcline, and sanidine.

potentiometric surface. A surface representing the total head of groundwater and defined by the level to which water will rise in tightly cased wells.

prodelta. The part of a delta below the level of wave erosion.

progradation. The seaward building of land area as a result of sedimentary deposition.

pyroxene. A group of silicate (silicon + oxygen) minerals composed of magnesium and iron with the general formula $(Mg,Fe)SiO_3$; characterized by short, stout crystals in hand specimens.

quartz. The only silicate (silicon + oxygen) mineral consisting entirely of silicon and oxygen, SiO_2; silicon dioxide. Synonymous with "crystalline silica."

quartzite. A medium-grained, nonfoliated metamorphic rock composed mostly of quartz; metamorphosed quartz sandstone.

radioactivity. The spontaneous decay or breakdown of unstable atomic nuclei.

radiocarbon age. An isotopic age expressed in years and calculated from the quantitative determination of the amount of carbon-14 remaining in an organic material. Synonymous with "carbon-14 age."

radiolarian. Any actinopod (protozoan) belonging to the subclass Radiolaria, characterized by a siliceous skeleton and a marine pelagic environment. Range: Cambrian to Holocene.

radiometric age. An age (in years) calculated from the quantitative determination of radioactive elements and their decay products. Synonymous with "isotopic age."

ravinement. An irregular junction that marks a break in sedimentation, such as an erosion line occurring where shallow-water marine deposits have "scooped down into" (or "ravined") slightly eroded underlying beds; a small-scale disconformity caused by periodic invasions of the sea over a deltaic area. From the French meaning "hollowing out (by waters), gullying."

rebound. Upward flexing of Earth's crust. Synonymous with "upwarping."

recharge. The addition of water to the saturated zone below the water table.

refraction. The deflection of a ray of light or of an energy wave (such as a seismic wave) due to its passage from one medium to another of differing density, which changes its velocity.

regression. Long-term seaward retreat of the shoreline or relative fall of sea level.

relative dating. The chronological placement and ordering of rocks, events, or fossils with respect to the geologic time scale and without reference to numerical ages.

relict. Describes a topographic feature that remains after other parts of the feature have been removed or have disappeared, for example, a "relict beach ridge" or a "relict hill." Also, a landform made by processes no longer operative such as glaciated forms in the northern United States or sand dunes in rain forests.

rip current. A strong, narrow, surface or near-surface current of short duration (a few minutes to an hour or two) and high velocity (up to 2 knots), flowing seaward from the shore through the breaker zone at nearly right angles to the shoreline, appearing as a visible band of agitated water returning to the sea after being piled up on the shore by incoming waves and wind.

riprap. A layer of large, durable rock fragments placed in an attempt to prevent erosion by water and thereby preserve the shape of a surface, slope, or underlying structure.

rock. An aggregate of one or more minerals (e.g., granite), a body of undifferentiated mineral matter (e.g., obsidian), or a body of solid organic material (e.g., coal).

runup. The advance of water up the foreshore (between high- and low-water marks) of a beach, following the breaking of a wave.

rutile. A reddish-brown oxide mineral of titamium, TiO_2.

saltation. A mode of sediment movement, driven by wind or water, whereby materials move through a series of intermittent leaps or jumps.

sand. A clastic particle smaller than a granule and larger than a silt grain, with a diameter ranging from 1/16 to 2 mm (0.0025 to 0.08 in).

sand sheet. A large irregularly shaped plain of aeolian sand, lacking the discernible slip faces that are common on dunes.

saturated zone. A subsurface zone in which all the interstices are filled with water under pressure greater than that of the atmosphere; separated from the unsaturated zone (above) by the water table.

scarp. A steep cliff or topographic step resulting from displacement on a fault or as a result of slope movement or erosion. Synonymous with "escarpment."

scour. The powerful and concentrated clearing and digging action of flowing air, water, or ice.

seagrass. Flowering plants from four families (Posidoniaceae, Zosteraceae, Hydrocharitaceae, and Cymodoceaceae) all in the order Alismatales, which grow in marine environments.

sediment. An eroded and deposited, unconsolidated accumulation of rock and mineral fragments.

sedimentary. Pertaining to or containing sediment.

sedimentary rock. A rock resulting from the consolidation of loose sediment that has accumulated in layers; it may be "clastic," consisting of mechanically formed fragments of older rock; "chemical," formed by precipitation from solution; or "organic," consisting of the remains of plants and animals. One of the three main classes of rock—igneous, metamorphic, and sedimentary.

sedimentation. The process of forming or accumulating sediment into layers, including the separation of rock particles from parent rock, the transportation of these particles to the site of deposition, the actual deposition or settling of the particles, the chemical and other changes occurring in the sediment, and the ultimate consolidation of the sediment into solid rock.

sequence. A rock-stratigraphic unit that is traceable over large areas and defined by sediment associated with a major sea level transgression–regression.

shoal. A relatively shallow place in a stream, lake, sea, or other body of water.

shoaling. To become shallow gradually, to fill up or block off with a shoal, or to proceed from a greater to a lesser depth of water.

shoreface. The zone between the seaward limit of the shore and the more nearly horizontal surface of the offshore zone; typically extends seaward to storm wave depth or about 10 m (30 ft).

silica. Silicon dioxide, SiO_2, an essential constituent of many minerals, occurring as crystalline quartz, cryptocrystalline chalcedony, and amorphous opal.

silicate. A mineral group composed of silicon (Si) and oxygen (O) plus an element or elements, for example, quartz, SiO_2; olivine, $(Mg, Fe)_2SiO_4$; and pyroxene, $(Mg,Fe)SiO_3$; as well as the amphiboles, micas, and feldspars.

siliceous. Describes a rock or other substance containing abundant silica.

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay, 1/256 to 1/16 mm (0.00015 to 0.002 in) across.

silting. The deposition or accumulation of silt that is suspended throughout a body of standing water or in some considerable portion of it, especially the choking, filling, or covering with stream-deposited silt behind a dam or other place of retarded flow, or in a reservoir.

siltstone. A clastic sedimentary rock composed of silt-sized grains.

slope. The inclined surface of any part of Earth's surface, such as a hillslope. Also, a broad part of a continent descending into an ocean.

slump. A generally large, coherent slope movement with a concave failure surface and subsequent backward rotation relative to the slope.

soil. The unconsolidated portion of the Earth's crust modified through physical, chemical, and biotic processes into a medium capable of supporting plant growth.

sorted. Describes an unconsolidated sediment consisting of particles of essentially uniform size.

sorting. The dynamic process by which sedimentary particles having some particular characteristic (such as similarity of size, shape, or specific gravity) are naturally selected and separated from associated but dissimilar particles by the agents of transportation.

specific conductance. The measure of discharge of a water well per unit of drawdown.

stage. A major subdivision of a glacial epoch, particularly one of the cycles of growth and disappearance of the Pleistocene ice sheets.

strand plain. A shore built seaward by waves and currents, extending continuously for some distance along the coast.

strata. Tabular or sheetlike layers of sedimentary rock; layers are visually distinctive from other layers above and below. The singular form of the term is stratum, but is less commonly used.

stratification. The accumulation, or layering, of sedimentary rocks as strata. Tabular, or planar, stratification refers to essentially parallel surfaces. Cross-stratification refers to strata inclined at an angle to the main stratification.

stratigraphy. The geologic study of the origin, occurrence, distribution, classification, correlation, and age of rock layers, especially sedimentary rocks.

stream. Any body of water moving under gravity flow in a clearly confined channel.

stream channel. A long, narrow depression shaped by the concentrated flow of a stream and covered continuously or periodically by water.

subaerial. Describes a condition or process that exists or operates in the open air on or immediately adjacent to the land surface.

subaqueous. Describes conditions and processes, or features and deposits, that exist or are situated in or under water.

submarine. Something situated or living under the surface of the sea.

submergence. A rise of water level in relation to land, so that areas of formerly dry land become inundated; results from either a sinking of the land or rise of water level. Compare to "emergence."

subsidence. The sudden sinking or gradual downward settling of part of Earth's surface.

supertidal. Describes a feature or process at an elevation higher than normal tidal range on a given shoreface.

terrestrial. Describes a feature, process, or organism related to land, Earth, or its inhabitants.

terrigenous. Describes material or a feature derived from the land or a continent.

theory. A hypothesis that has been rigorously tested against further observations or experiments; a generally accepted tenet of science.

topography. The general morphology of Earth's surface, including relief and locations of natural and human-made features.

tourmaline. A silicate (silicon + oxygen) mineral of sodium and aluminum whose composition varies widely because of substitutions of elements; occurs as a semi-precious stone in a wide variety of colors.

trace fossil. A fossilized feature such as a track, trail, burrow, or coprolite (dung), that preserves evidence of an organism's life activities, rather than the organism itself. Compare to "body fossil."

transgression. Landward migration of the sea as a result of a relative rise in sea level.

transverse dune. A dune that is elongated perpendicular to the prevailing wind direction; the leeward slope stands at or near the angle of repose of sand, whereas the windward slope is comparatively gentle.

travertine. A chemical sedimentary rock—the spongy or less compact variety is tufa—composed of precipitated calcium carbonate (predominantly calcite and aragonite) from spring-fed, heated and/or ambient-temperature waters.

unconfined groundwater. Groundwater that has a water table; that is, water not confined under pressure beneath a confining bed.

unconformity. A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession, resulting from either a change that caused deposition to cease for a considerable span of time or erosion with loss of the previously formed record.

undercutting. The removal of material at the base of a steep slope by the erosive action of water (such as a meandering stream), sand-laden wind in a desert, or waves along the coast.

water table. The surface between the saturated zone and the unsaturated zone. Synonymous with "groundwater table" and "water level."

wave base. The depth at which wave activity no longer stirs up sediments, usually at about 10 to 20 m (30 to 70 ft) below water level.

wind tide. The change in still-water level that is caused by wind transport of the surface water.

Wisconsinan. Pertaining to the classical fourth glacial stage of the Pleistocene Epoch in North America, following the Sangamonian interglacial stage and preceding the Holocene Epoch.

zircon. A very durable silicate mineral (silicon + oxygen), $ZrSiO_4$. When cut and polished, the colorless variety provides exceptionally brilliant gemstones.

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Additional References

These additional references, resources, and websites may be of use to resource managers. Web addresses are valid as of April 2015. 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 (Lakewood, Colorado): http://nature.nps.gov/geology/

NPS Geologic Resources Inventory: http://www.nature.nps.gov/geology/inventory/.

NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://www.nature.nps.gov/geology/gip/index.cfm

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://www.nature.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

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/

Geologic monitoring manual (Young and Norby 2009) http://nature.nps.gov/geology/monitoring/index.cfm

NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://www.nps.gov/dsc/technicalinfocenter.htm

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 http://www.geology.enr.state.nc.us/

US Geological Survey: http://www.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

National geologic map database (NGMDB): http://ngmdb.usgs.gov/

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")

Publications warehouse (many publications available online): http://pubs.er.usgs.gov

Tapestry of time and terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

Water Quality Data Portals and Websites

North Carolina DENR Division of Marine Fisheries (shellfish closures due to pollution): http://portal.ncdenr.org/web/mf/proclamations-polluted-areas

North Carolina OneMap Geospatial Portal (including water quality data): http://data.nconemap.com/geoportal/catalog/main/home.page

US Environmental Protection Agency How's My Watershed? Tool: http://watersgeo.epa.gov/mywaterway/

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Cape Hatteras National Seashore, held on 3-5 April 2000. Discussions during that meeting supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://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

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 April 2015. 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 (April 2015).	**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. **Exception: 16 USC § 445c (c) – Pipestone National Monument enabling statute**. Authorizes American Indian collection of catlinite (red pipestone).	**36 CFR § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units. **Exception: 36 CFR § 7.91** allows limited gold panning in Whiskeytown. **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.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
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. **Exception:** 16 USC §90c 1(b) the non-wilderness portion of Lake Chelan National Recreation Area, where sand, rock and gravel may be made available for sale to the residents of Stehekin for local use as long as such sale and disposal does not have significant adverse effects on the administration of the National Recreation Area.	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
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. **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 13089** (coral reefs) (1998) calls for reduction of impacts to coral reefs. **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.	**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.	**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
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).

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

NPS 603/128571, May 2015

National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

www.nature.nps.gov

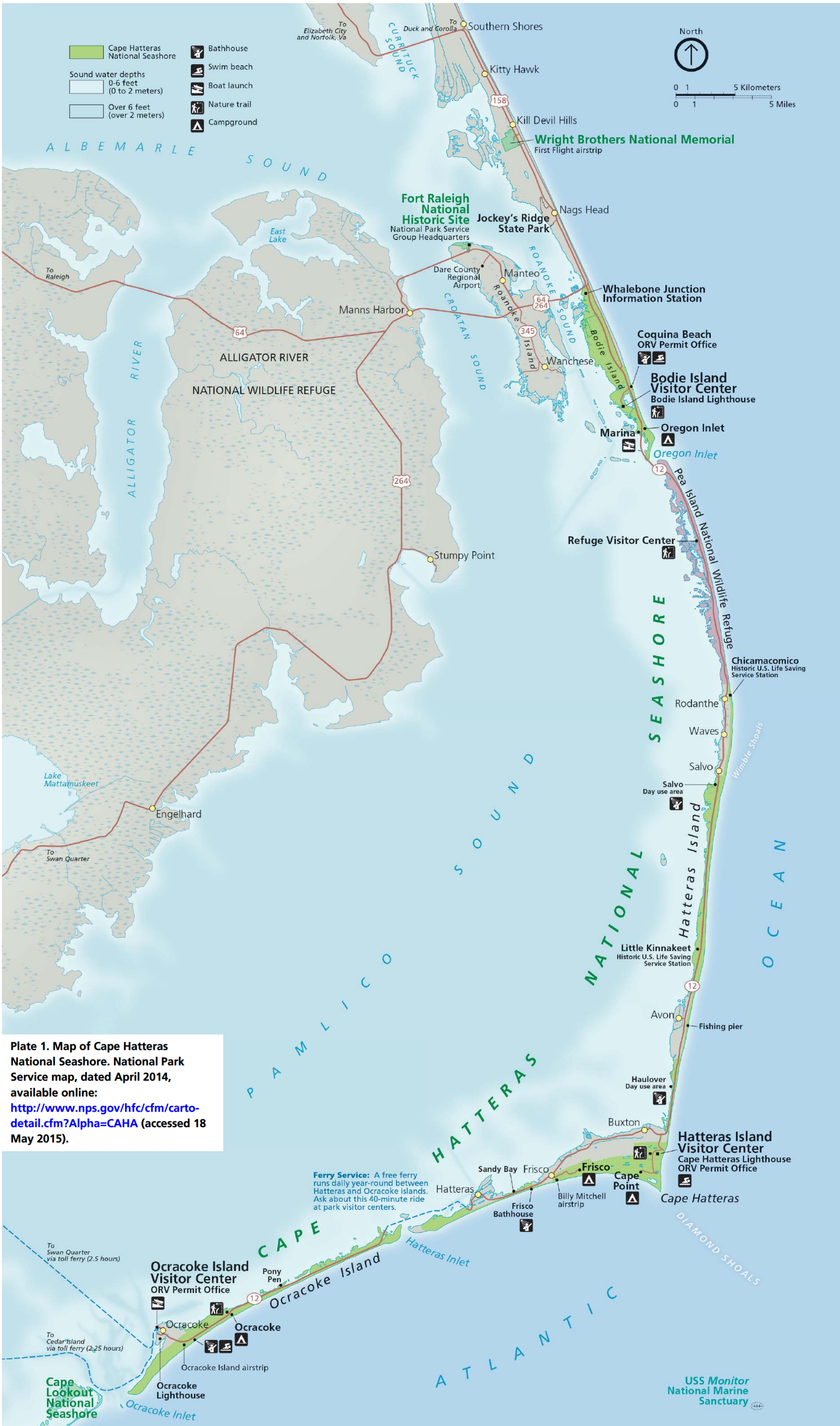


Plate 1. Map of Cape Hatteras National Seashore. National Park Service map, dated April 2014, available online: http://www.nps.gov/hfc/cfm/carto-detail.cfm?Alpha=CAHA (accessed 18 May 2015).

Geomorphic Map of Cape Hatteras National Seashore

East Carolina University Map (1:10,000 scale data)

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

Sheet 1: Kitty Hawk to Whalebone Junction Area

This map was produced by Kari Lanphier (Colorado State University) and Georgia Hybels (Colorado State University) in May 2015. It displays compiled geomorphic data prepared as part of the NPS Geologic Resources Inventory. This map is not a substitute for site-specific investigations.

The source maps used in creation of these data were originally published by East Carolina University as Ames and Riggs (2006a–j; see "Literature Cited" section in report). Riggs and Ames (2006) described the map development process.

According to the 1:10,000 scale of the source maps and U.S. National Map Accuracy Standards, features represented here are within 5 m (17 ft) of their true location.

All digital geologic data and publications prepared as part of the Geologic Resources Inventory are available at the NPS Integrated Resource Management Applications Portal (IRMA): https://irma.nps.gov/App/Reference/Search. Enter "GRI" as the search text and select a park from the unit list

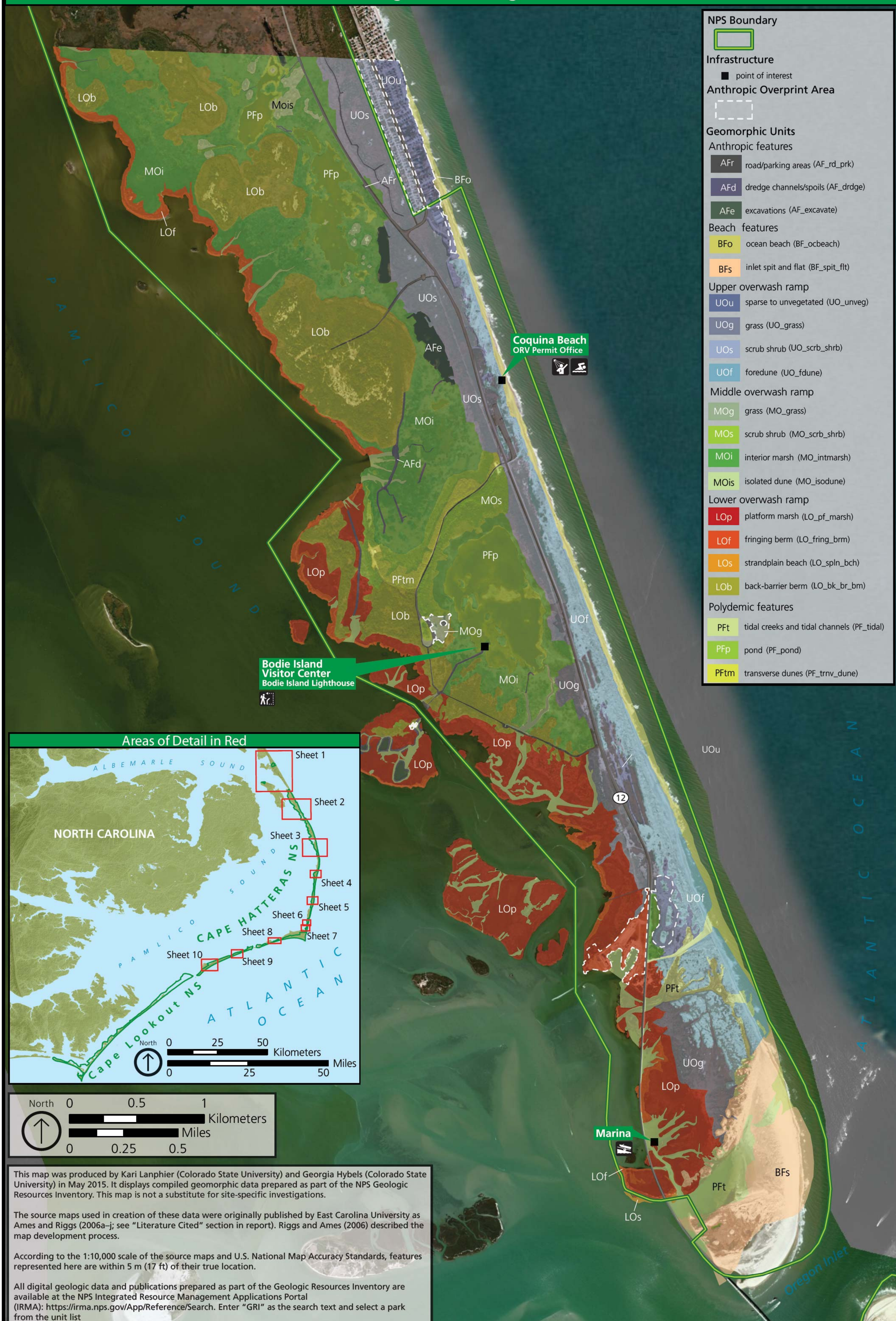
Geomorphic Map of Cape Hatteras National Seashore

East Carolina University Map (1:10,000 scale data)

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

Sheet 2: South Nags Head to Oregon Inlet Area



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Geomorphic Map of Cape Hatteras National Seashore

East Carolina University Map (1:10,000 scale data)

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

Sheet 3: New Inlet to Rodanthe Area

This map was produced by Kari Lanphier (Colorado State University) and Georgia Hybels (Colorado State University) in May 2015. It displays compiled geomorphic data prepared as part of the NPS Geologic R esources Inventory. This map is not a substitute for site-specific investigations.

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Geomorphic Map of Cape Hatteras National Seashore

East Carolina University Map (1:10,000 scale data)

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

Sheet 4: South Salvo to No Ache Island Area

This map was produced by Kari Lanphier (Colorado State University) and Georgia Hybels (Colorado State University) in May 2015. It displays compiled geomorphic data prepared as part of the NPS Geologic Resources Inventory. This map is not a substitute for site-specific investigations.

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Geomorphic Map of Cape Hatteras National Seashore

East Carolina University Map (1:10,000 scale data)

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

Sheet 5: Little Kinnakeet Area

This map was produced by Kari Lanphier (Colorado State University) and Georgia Hybels (Colorado State University) in May 2015. It displays compiled geomorphic data prepared as part of the NPS Geologic Resources Inventory. This map is not a substitute for site-specific investigations.

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Geomorphic Map of Cape Hatteras National Seashore

East Carolina University Map (1:10,000 scale data)

National Park Service
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Sheet 6: North Buxton Inlet Area

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Geomorphic Map of Cape Hatteras National Seashore

East Carolina University Map (1:10,000 scale data)

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

Sheet 7: South Buxton Inlet Area

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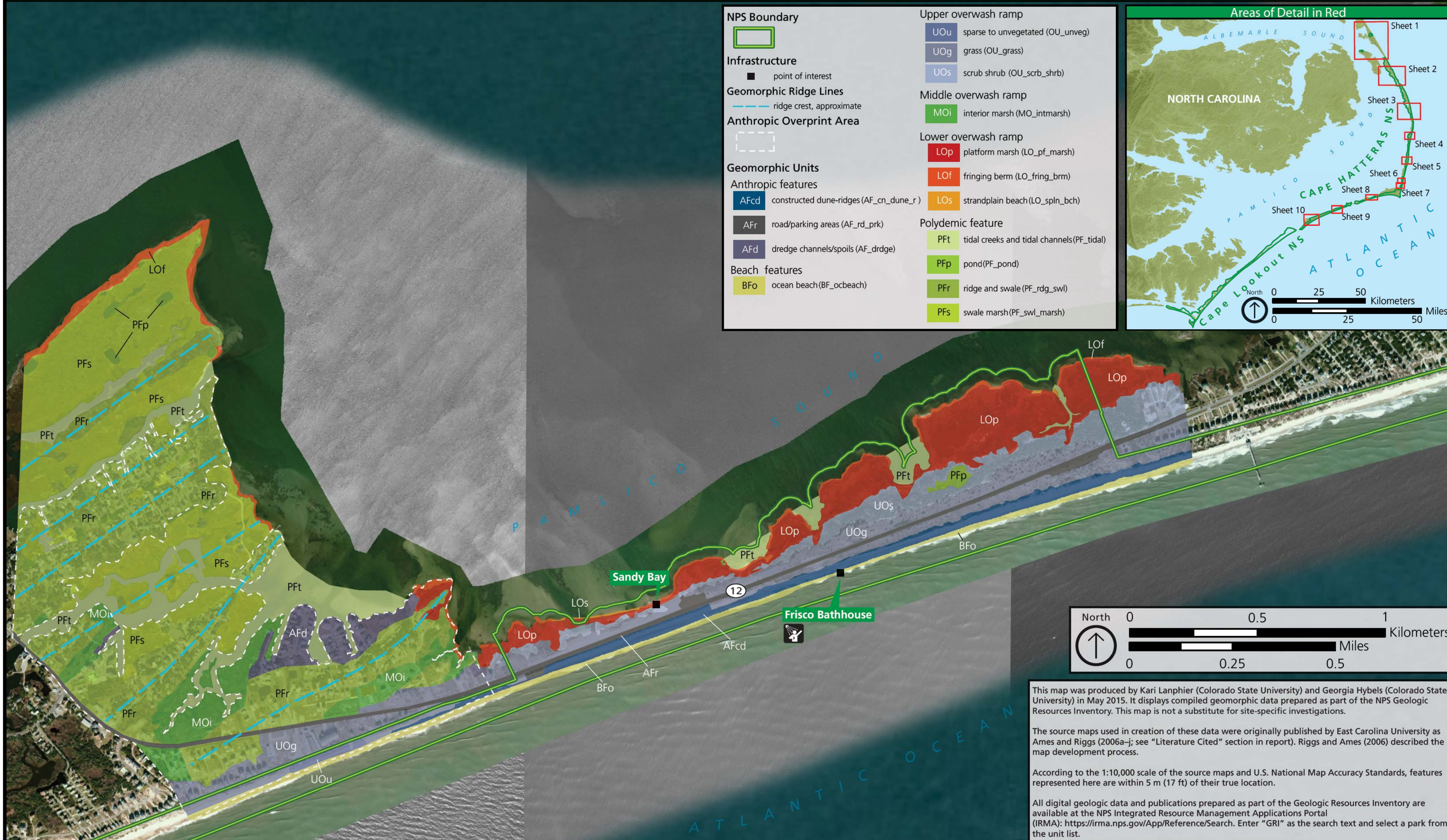
Geomorphic Map of Cape Hatteras National Seashore

East Carolina University Map (1:10,000 scale data)

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

Sheet 8: Hatteras Village to Frisco Area



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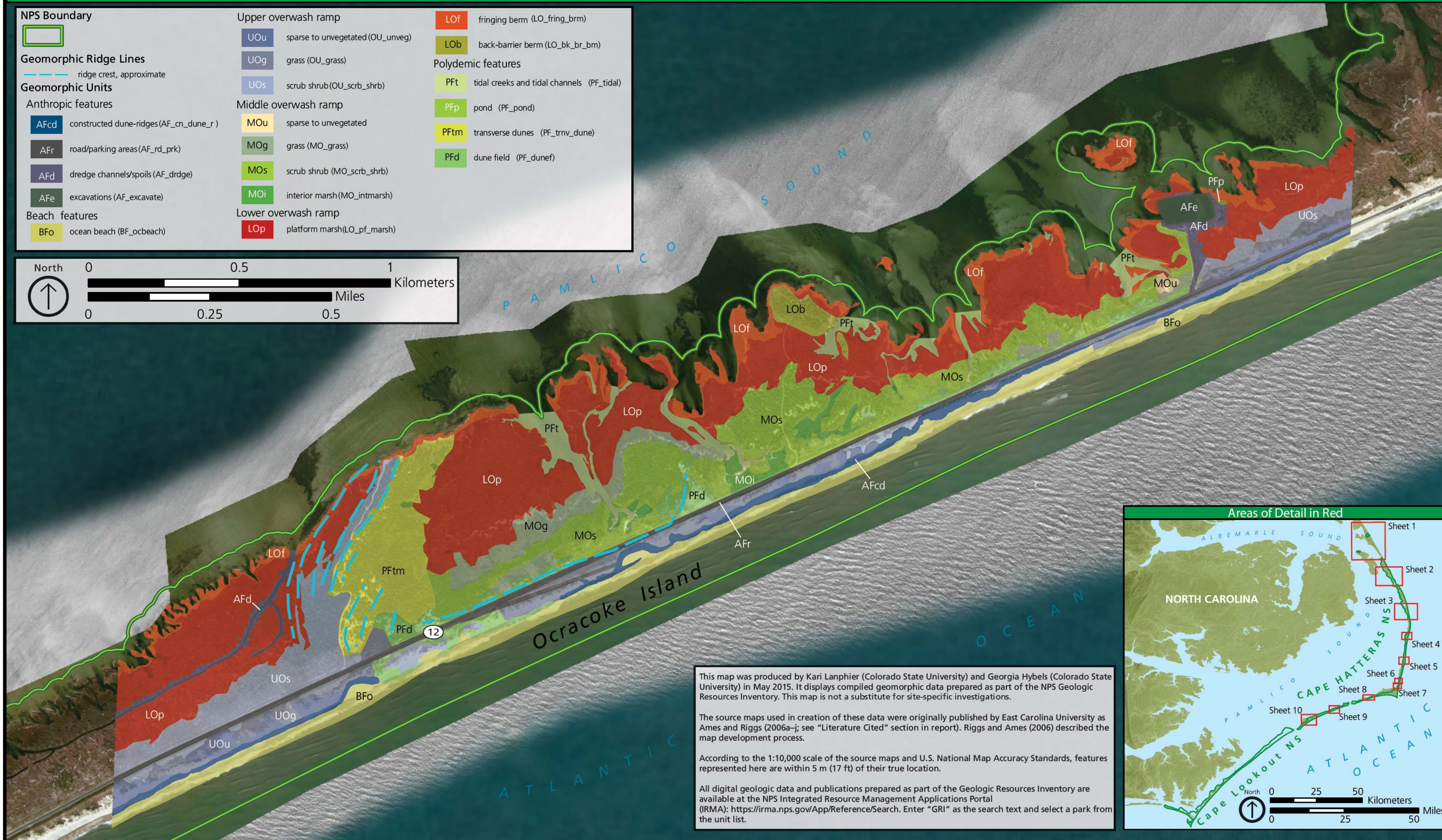
Geomorphic Map of Cape Hatteras National Seashore

East Carolina University Map (1:10,000 scale data)

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

Sheet 9: Great Swash to Quork Hammock Areas



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Geomorphic Map of Cape Hatteras National Seashore

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Natural Resource Stewardship and Science

Sheet 10: Ocracoke Village to The Plains Area

This map was produced by Kari Lanphier (Colorado State University) and Georgia Hybels (Colorado State University) in May 2015. It displays compiled geomorphic data prepared as part of the NPS Geologic Resources Inventory. This map is not a substitute for site-specific investigations.

The source maps used in creation of these data were originally published by East Carolina University as Ames and Riggs (2006a–j; see "Literature Cited" section in report). Riggs and Ames (2006) described the map development process.

According to the 1:10,000 scale of the source maps and U.S. National Map Accuracy Standards, features represented here are within 5 m (17 ft) of their true location.

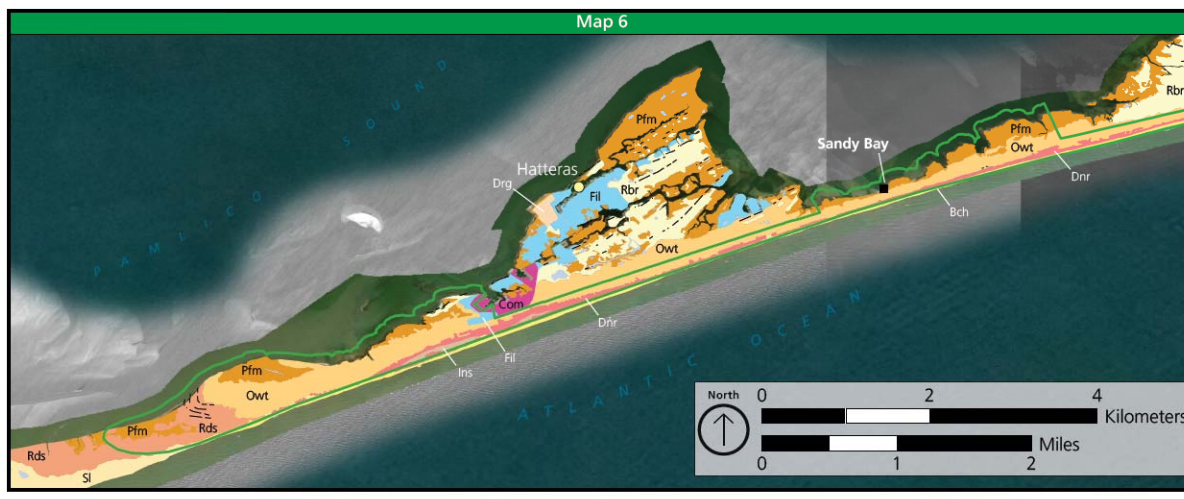
All digital geologic data and publications prepared as part of the Geologic Resources Inventory are available at the NPS Integrated Resource Management Applications Portal (IRMA): https://irma.nps.gov/App/Reference/Search. Enter "GRI" as the search text and select a park from the unit list.

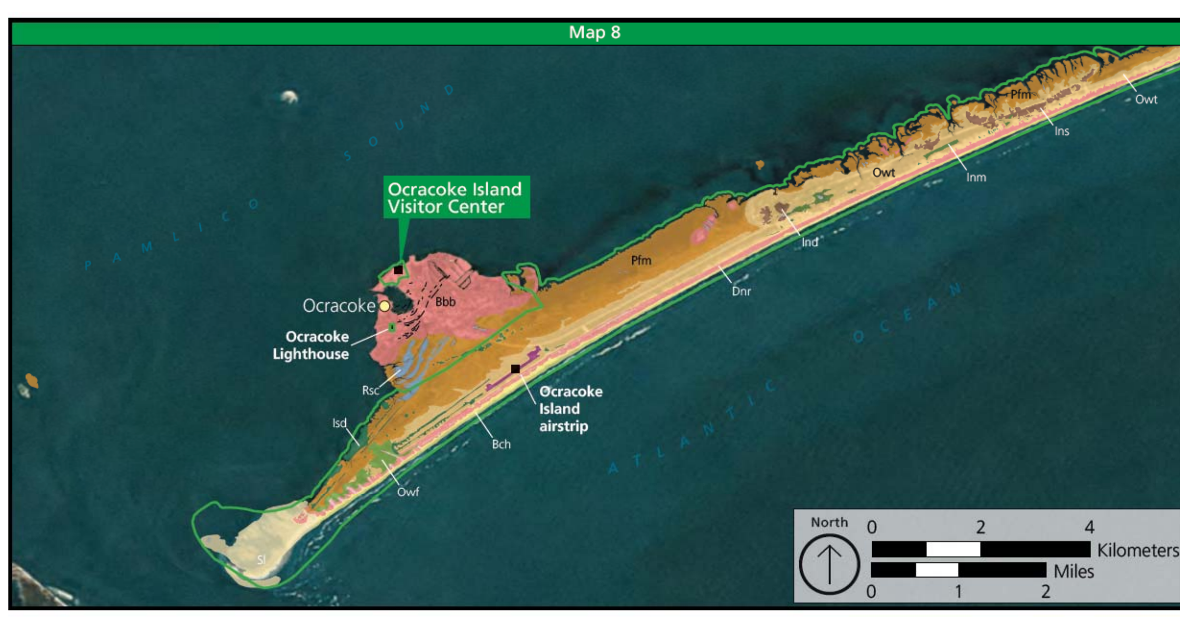
Geomorphic Map of Cape Hatteras National Seashore

North Carolina Geological Survey Map (1:24,000 scale data)

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science





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The source maps used in creation of these data were originally published by the North Carolina Geological Survey as Hoffman et al. (2007a–f; see "Literature Cited" section in report). Hoffman et al. (2007g) described the map development process.

According to the 1:24,000 scale of the source maps and U.S. National Map Accuracy Standards, features represented here are within 12 m (40 ft) of their true location.

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NPS Boundary

Infrastructure
- city
- point of interest

Geomorphic Ridge Lines
- approximate

Geomorphic Units
Intertidal Features
- Bch — Beach (beach)

Spit Complex
- Sl — Sand Flat (sand_flat)
- Rds — Ridge and Swale (ridge_swale)
- Pfm — Marsh Platform (pf_marsh)

Intertidal and Supratidal Feature
- Dnb — Dune Saddles (dnesadl_bch)

Supratidal Features
Fore-Island Dune Complex Subgroup
- Dnr — Dune Ridges (dunerdg)
- Ins — Dune Ridges, Interdune Swale (intswale_dr)
- Dnd — Dune Ridges, Dune Saddles (dnesadl_dr)

Overwash Complex Subgroup
- Owt — Overwash Flat (owflat)
- Owo — Overwash Flat, Overwash Channels (owflt_owchn)
- Owf — Overwash Fans (owfan)
- Isd — Isolated Dunes (isodune)
- Ind — Interior Dune (intdune)
- Inm — Interior Marsh (intmarsh)
- Bbb — Back-Barrier Berm (bk_br_bm)

Relict Features
- Rbr — Relict Beach Ridge Complex (rel_bch_rdge)
- Rsc — Relict Spit Complex (rel_spit)
- Water Body (water)

Anthropogenic Features
- Apl — Airport/Landing Strip (airport_land)
- Com — Commercial/Industrial Facility (comm_indust)
- Drg — Dredge/Spoil (drdge - intdune)
- Fil — Filled (filled)
- Ecs — Erosion Control Structure (ersn_ctrl_st)
- Exc — Excavation (excavate)
- Dke — Dike (dike)
- Wfi — Waterfowl Impoundment (wtrfwl_impnd)

Cape Hatteras National Seashore: Geomorphic Map Unit Properties Table (East Carolina University Map; 1:10,000 scale)

Group	Subgroup	Map Unit (Symbol)	Geologic Description	Geologic and Environmental Features and Processes	Geologic Resource Management Issues	Geologic History and Habitat
BEACH FEATURES (BF)		Ocean Beach (BF_ocbeach) Inlet Spit and Flat (BF_spit_flt)	Beach: a sand body that extends from the wet/dry line to the base of a dune field, scarped dune, or island berm crest. Inlet Spit and Flat: subparallel sand ridges adjacent to modern or paleo-inlets. Characterized by curved ridge structures on gently ramped flats.	**Sediment Transport Processes**—Units are frequently inundated during storms and high tides. Ridges form in response to overflow conditions. Barrier islands are continuously reshaped by the constant movement of sand by wind, waves, and currents. Storm winds move sand into the island interior and estuary, and build dunes. Overwash builds island elevation, expands marsh platforms and estuarine shoals, and creates and maintains early-succession habitat. **Inlets**—Created when storms drive surges across and through the island from the ocean or estuarine side. It widens by erosion and collapse of the adjacent bank, and deepens as flow scours the channel. They provide sediment to the back-barrier system through the growth of spits and delta deposits, which become platform marshes when the inlet closes. **Barrier Island Evolution and Behavior**—Sediment availability and shoreline erosion patterns are influenced by the geologic framework of older stratigraphic units occurring beneath and seaward of the shoreface. **Barrier Island System Units**—Predominantly sand. **Paleontological Resources**—Fossils may wash ashore or be exposed.	**Shoreline Erosion**—Ocean shoreline change rates range from -2 m/yr to 2 m/yr. Erosion rates and breach potential are highest north of Rodanthe, southern Pea Island, the Buxton and Isabel inlet areas, and northeastern Ocracoke Island. **Coastal Vulnerability and Sea-Level Rise**—Erosion, overwash, and inlet formation will continue to change island morphology. Sea-level rise may accelerate shoreline erosion, landward migration, and conversion of tidal wetlands to open water. **Hurricane Impacts and Human Responses**—Storms move sand across and off the island, create overwash and breaches, and drive landward migration. Overwash adds saline water to surficial aquifers and groundwater. **Inlet Modifications—**Inlet modifications disrupt the inlet's ability to provide sediment to downdrift shorelines. Newly opened inlets are often closed artificially to maintain the highway infrastructure. The Oregon Inlet terminal groin and revetment stopped erosion of northern Pea Island, but soundward accretion of the Bodie Island spit has narrowed and deepened the inlet. Oregon Inlet stabilization causes shoreline erosion of up to 4 m/yr on Pea Island. **Recreational and Watershed Land Use**—ORV use disturbs beach ecosystems, damages backshore vegetation, limits seaward dune development, and prevents post-storm dune recovery. **Coastal Engineering and Shoreline Armoring**—Seawalls, bulkheads, and other structures to inhibit wave action are expensive and accelerate erosion in front of the structures. Temporary soft stabilization (sandbags) have similar effects but are permitted in North Carolina. There have been 17 recorded beach nourishment projects in the park. Most nourishment sand is sourced from inlet deltas and channels; its removal destabilizes the inlets and impacts regional sediment budgets. Between 1962 and 2011, over 7.8 million m^3 of sediment were emplaced on park beaches. **Highway 12 Transportation Corridor**—Highway 12 is very vulnerable to shoreline erosion and storm overwash, and has been repeatedly damaged in numerous places in the last few decades. Debate over how to replace the route is ongoing. **Paleontological Resource Inventory, Monitoring, and Protection**— Beachcombers are allowed to collect unoccupied shells at Cape Hatteras National Seashore, but NPS policy states that fossils cannot be collected from NPS lands.	Beach unit is among the most indicative features of modern barrier island geomorphological processes. Spit and flat features are indicative of sand accretion during periodic overflow events and evolve in patterns. Cultural artifacts may wash ashore. Habitat: Shorebird foraging. Wrack consisting of offshore algae (*Sargassum* spp.), dune grasses, submerged aquatic vegetation, and estuarine marsh grasses. Inlet spits support *Spartina patens* grasses, mixed grasses, and scrub shrub.

Group	Subgroup	Map Unit (Symbol)	Geologic Description	Geologic and Environmental Features and Processes	Geologic Resource Management Issues	Geologic History and Habitat
OVERWASH-PLAIN FEATURES	UPPER OVERWASH RAMP (UO)	Sparse to Unvegetated (UO_unveg) Grass (UO_grass) Scrub Shrub (UO_scrb_shrb)	Upper overwash ramp begins at the island berm crest with a slightly undulating surface and slopes of varying degrees to the middle overwash ramp, lower overwash ramp, or adjacent estuary. Small isolated dunes are present locally. Sparse to unvegetated: dominated by salty groundwater with a surface of xeric vegetation. Vegetative cover increases successively away from the beach to grass- and shrub-dominated areas on the upper ramp. Shrub: communities expand oceanward on very wide ramps with dune fields or ridges.	**Sediment Transport Processes**—Barrier islands are continuously reshaped by the constant movement of sand by wind, waves, and currents. Overwash builds island elevation, expands marsh platforms and estuarine shoals, and creates and maintains early-succession habitat. **Inlets**—Created when storms drive surges across and through the island from the ocean or estuarine side. It widens by erosion and collapse of the adjacent bank, and deepens as flow scours the channel. They provide sediment to the back-barrier system through the growth of spits and delta deposits, which become platform marshes when the inlet closes. **Freshwater Aquifers**—Units have a relatively deep freshwater table or salty groundwater; farther from the beach, freshwater dominates and the water table rises. The dunes near Theoff Point at the southern end of Bodie Island are favorable for fresh groundwater development because they are unlikely to be inundated by salt water or overwash. **Barrier Island System Units**—Predominantly sand with shell gravel pavements that may contain paleontological resources.	**Shoreline Erosion**—Ocean shoreline change rates range from -2 m/yr to 2 m/yr. Erosion rates and breach potential are highest north of Rodanthe, southern Pea Island, the Buxton and Isabel inlet areas, and northeastern Ocracoke Island. **Coastal Vulnerability and Sea-Level Rise**—Erosion, overwash, and inlet formation will continue to change island morphology. Sea-level rise may accelerate shoreline erosion and landward migration. **Hurricane Impacts and Human Responses**—Storms move sand across and off the island, create overwash and breaches, and drive landward migration. Overwash adds saline water to surficial aquifers and groundwater. **Highway 12 Transportation Corridor**—Highway 12 is very vulnerable to shoreline erosion and storm overwash, and has been repeatedly damaged in numerous places in the last few decades. Debate over how to replace the route is ongoing.	Units record landward changes in morphology and vegetation in overwash ramp areas. Successive landform development and vegetation give important relative age dates for island development. Cultural artifacts may wash ashore. Habitat: Xeric vegetation dominated by firewheel (*Gaillardia pulchella*), prickly pear cactus (*Opuntia* spp.), and scattered eastern red cedar (*Juniperus virginiana*), lichens, moss. Grass flat communities include sea oats (*Uniola paniculata*), salt meadow hay (*Spartina patens*), broomstraw rush (*Andropogon scoparius*), pennywort (*Hydrocotyle bonariensis*), sea rocket (*Cakile edentula*). Shrub habitat dominated by salt myrtle (*Baccharis halimifolia*), wax myrtle (*Myrica cerifera*), yaupon holly (*Ilex vomitoria*), marsh elder (*Iva frutescens*), bayberry (*Myrica pensylvanica*), eastern red cedar (*Juniper virginiana*), salt meadow hay (*Spartina patens*), cat brier (*Smilax* spp.), poison ivy (*Toxicodendron radicans*), Virginia creeper (*Parthenocissus quinquefolia*).
OVERWASH-PLAIN FEATURES	UPPER OVERWASH RAMP (UO)	Foredune (UO_fdune) Urban (UO_urbdune)	Foredune: natural features forming along the uppermost portion of the overwash plain with irregular geometry and variable size. Absent in areas where constructed dunes disrupt the natural sediment-supply process.	**Sediment Transport Processes**—Barrier islands are continuously reshaped by the constant movement of sand by wind, waves, and currents. Storm winds move sand into the island interior and estuary, and build dunes. Overwash builds island elevation. **Barrier Island System Units**—Predominantly sand.	**Coastal Vulnerability and Sea-Level Rise**—Erosion, overwash, and inlet formation will continue to change island morphology. Sea-level rise may accelerate shoreline erosion and landward migration. **Hurricane Impacts and Human Responses**—Units are continuously evolving through blowouts, cut and fill structures, and scarping. Sand inundation associated with active dunes. **Recreational and Watershed Land Use**—ORV use disturbs beach ecosystems, damages backshore vegetation, limits seaward dune development, and prevents post-storm dune recovery. **Coastal Engineering and Shoreline Armoring**—Seawalls, bulkheads, and other structures to inhibit wave action are expensive and accelerate erosion in front of the structures. Temporary soft stabilization (sandbags) have similar effects but are permitted in North Carolina. There have been 17 recorded beach nourishment projects in the park. Most nourishment sand is sourced from inlet deltas and channels; its removal destabilizes the inlets and impacts regional sediment budgets. Between 1962 and 2011, over 7.8 million m^3 of sediment were emplaced on park beaches.	Natural dunes are rare in modern developed beach areas and serve as models for the evolution of barrier island systems. Habitat: Locally vegetated by sea oats (*Uniola paniculata*) and on the lee side by salt meadow hay (*Spartina patens*), sea rocket (*Cakile edentula*), goldenrod (*Solidago sempervirens*), wax myrtle (*Myrica cerifera*), eastern red cedar (*Juniper virginiana*), and pennywort (*Hydrocotyle bonariensis*).
OVERWASH-PLAIN FEATURES	MIDDLE OVERWASH RAMP (MO)	Sparse to Unvegetated (MO_unveg) Grass (MO_grass) Scrub Shrub (MO_scrb_shrb) Forest (MO_forest)	Middle overwash ramp is relatively flat, with a dry to damp surface. This unit occurs only on relatively wide islands. Vegetation succession goes from unvegetated to grass to shrub to forest (if storm events are infrequent, ocean shoreline recession is slow, and/or a protective dune field is present).	**Sediment Transport Processes**—Overwash builds island elevation, expands marsh platforms and estuarine shoals, and creates and maintains early-succession habitat. **Freshwater Aquifer**—Supply is recharged through rainfall and depleted through residential use, evapotranspiration from the surface and vegetation, and surface drainage from wetlands. Groundwater systems and aquifers can be affected by impoundments, weather conditions, and water withdrawal; these influences alter hydrologic processes, wetland function, and the distribution, composition, diversity, and structure of vegetation communities. **Barrier Island System Units**—Predominantly sand. Erosion resistance is low to moderately low where forested.	**Hurricane Impacts and Human Responses**—Units are often slightly wet and inundated during storm events. Units are associated with infrequent, but pervasive, storm events that destroy or bury existing stabilizing vegetation. Overwash adds saline water to surficial aquifers and groundwater. Rainwater adds fresh water to surficial aquifers and groundwater.	Units form as a function of island size, sediment supply, overwash frequency, vegetation patterns, and island morphology. Unvegetated areas represent new overwash fans following major storm events. May contain cultural resources. Habitat: Grass species include salt meadow hay (*Spartina patens*) and broom straw (*Andropogon scoparius*). Scrub shrub species include salt myrtle (*Baccharis halimifolia*), wax myrtle (*Myrica cerifera*), yaupon holly (*Ilex vomitoria*), marsh elder (*Iva frutescens*), bayberry (*Myrica pensylvanica*), eastern red cedar (*Juniper virginiana*), salt meadow hay (*Spartina patens*), cat brier (*Smilax* spp.), poison ivy (*Toxicodendron radicans*), Virginia creeper (*Parthenocissus quinquefolia*). Forest species include pine (*Pinus* spp.), live oak (*Quercus virginiana*), eastern red cedar (*Juniper virginiana*), wax myrtle (*Myrica cerifera*), yaupon holly (*Ilex vomitoria*), cat brier (*Smilax* spp.), poison ivy (*Toxicodendron radicans*), and muscadine grape (*Vitus rotundifolia*).

Group	Subgroup	Map Unit (Symbol)	Geologic Description	Geologic and Environmental Features and Processes	Geologic Resource Management Issues	Geologic History and Habitat
OVERWASH-PLAIN FEATURES	MIDDLE OVERWASH RAMP (MO)	Interior Marsh (MO_intmarsh)	Unit contains sandy, organic-rich soil with a high, fluctuating water table. Grades into platform marsh areas with a gentle decline in elevation, ranging from <1 m (39 in) to a few centimeters above mean sea level.	**Sediment Transport Processes**—Frequently flooded by wind and storm tides and estuarine water flowing through tidal channels. Overwash builds island elevation, expands marsh platforms and estuarine shoals, and creates and maintains early-succession habitat. **Freshwater Aquifer**—Supply is recharged through rainfall and depleted through residential use, evapotranspiration from the surface and vegetation, and surface drainage from wetlands. Groundwater systems and aquifers can be affected by impoundments, weather conditions, and water withdrawal; these influences alter hydrologic processes, wetland function, and the distribution, composition, diversity, and structure of vegetation communities. **Barrier Island System Units**—Predominantly sand and peat. Erosion resistance is low. **Paleontological Resources**—May contain pollen spores and other recent organic remains.	**Hurricane Impacts and Human Responses**—Overwash adds saline water to surficial aquifers and groundwater. Rainwater adds fresh water to surficial aquifers and groundwater.	Unit is interstitial between the middle overwash ramp and dry grass flat areas. Unit has a sandy substrate, in contrast to the peaty substrates of platform marsh areas. Habitat: Algal mats, marsh vegetation including smooth cordgrass (*Spartina alterniflora*), salt meadow hay (*Spartina patens*), black needlerush (*Juncus roemerianus*), saltgrass (*Distichlis spicata*), sea oxeye (*Borrichia frutescens*), soft-stemmed bulrush (*Scirpus robustus*), sawgrass (*Cladium jamaicense*), common reed (*Phragmites australis*), giant cordgrass (*Spartina cynosuroides*), cattail (*Typha angustiflora*), depending on groundwater salinity.
		Isolated Dunes (MO_isodune) Ringed Dunes and Beach Ridges (MO_rdune_br) Urban Dune (MO_urbandune) Paleo-inlet Spit (MO_p_inl_spt)	Isolated Dunes: common in unvegetated areas of the middle ramp, often on algal flats. Ringed Dunes: complicated geometries that form when isolated dunes are stabilized by vegetation through a process of dry-season sand trapping followed by wet-season reworking. Paleo-inlet Spits: subparallel ridges adjacent to inlets with curved ridge structures at oblique angles to the shoreline.	**Barrier Island System Units**—Predominantly sand.	**Hurricane Impacts and Human Responses**—Units associated with sand inundation and can be prone to major storm flooding.	Units are typically fleeting and constantly evolving naturally and under human influence. Paleounits record past overflow and blowout events. Ringed dunes form around stabilized structures, such as Ocracoke Village. Habitat: Isolated dunes may be stabilized by salt meadow hay (*Spartina patens*) or scrub shrub. Isolated ringed dunes may contain salt meadow hay (*Spartina patens*) and sea oxeye (*Borrichia frutescens*).
	LOWER OVERWASH RAMP (LO)	Platform Marsh (LO_pf_marsh)	The lower overwash ramp is a wet, flat, intertidal surface extending toward the back-barrier estuary, with strong vegetation zonation determined by salinity gradients. Marsh contains a <1-m- (3-ft-) thick peat or sandy peat substrate that is permanently water saturated. This unit often has tidal creek networks and occasional small ponds. Grades gently to a scarp abutting the estuary and a low fringing berm.	**Inlets**—Created when storms drive surges across and through the island from the ocean or estuarine side. It widens by erosion and collapse of the adjacent bank, and deepens as flow scours the channel. They provide sediment to the back-barrier system through the growth of spits and delta deposits, which become platform marshes when the inlet closes. **Estuaries**—Some sediment contributions is derived from erosion of the marsh shoreline. **Freshwater Aquifer**—Supply is recharged through rainfall and depleted through residential use, evapotranspiration from the surface and vegetation, and surface drainage from wetlands. Groundwater systems and aquifers can be affected by impoundments, weather conditions, and water withdrawal; these influences alter hydrologic processes, wetland function, and the distribution, composition, diversity, and structure of vegetation communities. **Barrier Island System Units**—Predominantly sand and peat. Frequently inundated and may locally contain quicksand or thick muck. **Paleontological Resources**—May preserve pollen.	**Coastal Vulnerability and Sea-Level Rise**—Erosion, overwash, and inlet formation will continue to change island morphology. Sea-level rise may accelerate shoreline erosion, landward migration, and conversion of tidal wetlands to open water. **Hurricane Impacts and Human Responses**—Unit is constantly water saturated and should be avoided for infrastructure. Overwash adds saline water to surficial aquifers and groundwater. Rainwater adds fresh water to surficial aquifers and groundwater. High rainfall and flooding increases nutrients and sediments to the estuary, reduces estuarine salinity, and causes phytoplankton blooms. **Recreational and Watershed Land Use**—Toxic and nuisance algal blooms may occur in tidal creeks, marshes, and ponds on Ocracoke Island due to runoff or septic system leachate.	Wrack causes depressions, where it kills underlying marsh vegetation and may eventually form ponds that vary from hypo- to hypersaline in wet/dry seasons. May preserve cultural artifacts. Habitat: Decaying wrack deposits kill marsh platform vegetation, but are locally recolonized by sea oxeye (*Borrichia frutescens*), annual marsh glasswort (*Salicornia bigelovii*), perennial marsh glasswort (*Salicornia virginica*), saltgrass (*Distichlis spicata*), wax myrtle (*Myrica cerifera*), marsh elder (*Iva frutescens*), salt myrtle (*Baccharis halimifolia*).

Group	Subgroup	Map Unit (Symbol)	Geologic Description	Geologic and Environmental Features and Processes	Geologic Resource Management Issues	Geologic History and Habitat
OVERWASH-PLAIN FEATURES	LOWER OVERWASH RAMP (LO)	Fringing Berm (LO_fring_brm) Strandplain Beach (LO_spln_bch) Back-Barrier Berm (LO_bk_br_bm)	Fringing Berms: up to 1 m (3 ft) in height and 1 to 3 m (3 to 9 ft) wide. These storm deposits are shore parallel <10 m (30 ft) from the edge of the platform marsh. Berm consists of mixed sand and peat. Strandplain Beaches: occur in eroded scarps and are often temporary or seasonal due to storm patterns. Back-Barrier Berms: form at the interface between estuarine and ocean storm–dominated systems and occur as ridges subparallel to the overwash plain. Berms are <2 m (6 ft) high and 25 m (77 ft) wide, and may have arcuate morphologies.	**Sediment Transport Processes**—Low-lying areas are prone to inundation and some units are associated with storm surge events. Storm winds move sand into the island interior and estuary. Overwash builds island elevation, and expands marsh platforms and estuarine shoals. **Inlets**—Created when storms drive surges across and through the island from the ocean or estuarine side. It widens by erosion and collapse of the adjacent bank, and deepens as flow scours the channel. They provide sediment to the back-barrier system through the growth of spits and delta deposits, which become platform marshes when the inlet closes. **Barrier Island System Units**—Predominantly peat and sand.	**Shoreline Erosion**—Estuarine shoreline change rates range from -1.2 m/yr (marsh) to 0.2 m/yr (beach). Estuarine erosion at Fort Raleigh NHS threatens infrastructure and cultural resources. The northern side of Ocracoke Village is eroding at 1.2 m/yr due to storm wind and waves from Pamlico Sound. **Coastal Vulnerability and Sea-Level Rise**—Erosion, overwash, and inlet formation will continue to change island morphology. Sea-level rise may accelerate shoreline erosion, landward migration, and conversion of tidal wetlands to open water. **Hurricane Impacts and Human Responses**—Storms move sand across and off the island, create overwash and breaches, and drive landward migration. **Recreational and Watershed Land Use—**Constructed dune ridges have altered the park's ecosystem and geologic structure, minimized overwash and inlet formation, modified habitat and back-barrier estuarine processes. They have resulted in narrower beaches, steeper shoreface, increased wave energy hitting the shoreface, marsh scarps, and decreased sound productivity.	Fringing berm buffers the lower overwash ramp from the sound and records timing of storm surge events. Units are strongly associated with storm events and may be present only temporarily. They record the evolution of the low-lying back-barrier area. Habitat: Barren peat surfaces become colonized by *Salicornia bigelovii*, berms dominated by salt meadow hay (*Spartina patens*), giant cordgrass (*Spartina cynosuroides*), wax myrtle (*Myrica cerifera*), salt myrtle (*Iva frutescens*), black needlerush (*Juncus roemerianus*). Algal mats on strandplain beaches. Back-barrier berms provide habitat for eastern red cedar (*Juniper virginiana*), salt meadow hay (*Spartina patens*), salt myrtle (*Iva frutescens*), marsh elder (*Iva frutescens*), wax myrtle (*Myrica cerifera*), and yaupon holly (*Ilex vomitoria*). Higher forested areas have pine (*Pinus* spp.), live oak (*Quercus virginiana*), eastern red cedar (*Juniper virginiana*), salt myrtle (*Baccharis halimifolia*), marsh elder (*Iva frutescens*), wax myrtle (*Myrica cerifera*), and yaupon holly (*Ilex vomitoria*).
POLYDEMIC FEATURES (PF)		Tidal Creeks and Tidal Channels (PF_tidal) Pond (PF_pond)	Tidal Creeks and Channels: form in platform marshes, may be fed by tides or fresh groundwater from higher island elevations. Overwash plain deposits may bury headwaters of creeks. Where tidal creeks erode between platform marsh segments, the classic molar-tooth geomorphology forms. Tidal channels are 3 to 4 m (9 to 12 ft) deep, with steeply scarped peat shorelines. Ponds: formation, water composition, and duration in the general overwash plain vary. Many ponds are present as a function of the patterns, frequency, and abundance of storms and precipitation.	**Freshwater Aquifer**—Supply is recharged through rainfall and depleted through residential use, evapotranspiration from the surface and vegetation, and surface drainage from wetlands. Groundwater systems and aquifers can be affected by impoundments, weather conditions, and water withdrawal; these influences alter hydrologic processes, wetland function, and the distribution, composition, diversity, and structure of vegetation communities. **Barrier Island System Units**—Predominantly peat and sand. Erosion resistance is nonexistent. **Paleontological Resources**—May contain pollen.	**Shoreline Erosion**—Estuarine shoreline change rates range from -1.2 m/yr (marsh) to 0.2 m/yr (beach). **Coastal Vulnerability and Sea-Level Rise**—Erosion, overwash, and inlet formation will continue to change island morphology. Sea-level rise may accelerate shoreline erosion, landward migration, and conversion of tidal wetlands to open water. **Hurricane Impacts and Human Responses** Overwash adds saline water to surficial aquifers and groundwater. Rainwater adds fresh water to surficial aquifers and groundwater. High rainfall and flooding increases nutrients and sediments to the estuary, reduces estuarine salinity, and causes phytoplankton blooms. **Recreation and Watershed Land Use**—Toxic and nuisance algal blooms may occur in tidal creeks, marshes, and ponds on Ocracoke Island due to runoff or septic system leachate.	Tidal creeks and channels are major forces of landscape change, eroding the upper platform areas. Ponds are constantly changing based on abundance of water and vary from open water to marshes and dried algal flats. May contain cultural resources. Habitat: Perimeter areas may contain soft-stemmed bulrush (*Scirpus robustus*), sawgrass (*Cladium jamaicense*), giant cordgrass (*Spartina cynosuroides*), cat tail (*Typha angustiflora*), common reed (*Phragmites australis*), and black needle rush (*Juncus roemerianus*). Ponds may contain algal mats and other marsh vegetation.
POLYDEMIC FEATURES (PF)		Transverse Ridges (PF_trnv_dune) Dune Flat (PF_dune_flat)	Transverse Ridges: long, low, straight ridges forming transverse to the long trend of a barrier island. Unit forms when temporarily ponded waves of storm surge rework dune sands or by truncation of a large dune system. Dune Flats: form in areas of abundant sand supply as broad, rolling flat areas (elevation 2 to 3 m [6 to 9 ft] higher than the island berm) downwind of the island berm. Maximum relief of sand flat areas is <2 m (6 ft).	**Sediment Transport Processes**—Units are associated with active overwash and aeolian processes and are prone to sand and water inundation. **Barrier Island System Units**—Predominantly sand.	**Coastal Vulnerability and Sea-Level Rise**—Erosion, overwash, and inlet formation will continue to change island morphology. Sea-level rise may accelerate shoreline erosion, landward migration, and conversion of tidal wetlands to open water. **Hurricane Impacts and Human Responses**—Storms move sand across and off the island, create overwash and breaches, and drive landward migration. Overwash adds saline water to surficial aquifers and groundwater. Rainwater adds fresh water to surficial aquifers and groundwater.	Transverse dune ridges suggest former inlet locations. Dune flats record the anthropogenic impacts of urbanization on the barrier islands, as they become vegetated and stabilized when the sand supply is truncated by roads, structures, and other changes. Long-standing, stable dune flats support cultural resources at Kitty Hawk and Whalebone Junction. Habitat: Vegetation ranges from nonexistent to some areas stabilized by sea oat (*Uniola paniculata*), salt meadow hay (*Spartina patens*), scrub shrubs such as salt myrtle (*Baccharis halimifolia*), marsh elder (*Iva frutescens*), wax myrtle (*Myrica cerifera*), yaupon holly (*Ilex vomitoria*), and eastern red cedar (*Juniper virginiana*). The oldest, forested areas contain pine (*Pinus* spp.), live oak (*Quercus virginiana*), eastern red cedar (*Juniper virginiana*), cat brier (*Smilax* spp.), poison ivy (*Toxicodendron radicans*), and muscadine grape (*Vitus rotundifolia*). Unit supports broad damp areas dominated by algae and freshwater marsh plants. Other species include salt meadow hay (*Spartina patens*), forests of pine (*Pinus* spp.), yaupon holly (*Ilex vomitoria*), and live oak (*Quercus virginiana*).

Group	Subgroup	Map Unit (Symbol)	Geologic Description	Geologic and Environmental Features and Processes	Geologic Resource Management Issues	Geologic History and Habitat
POLYDEMIC FEATURES (PF)		Dune Field (PF_dunef) Sparse to Unvegetated Dune Field (PF_dune_unvg) Grassy Dune Field (PF_dune_grss) Forested Dune Field (PF_dune_fors) Urbanized Dune Field (PF_dune_urb)	Dune Fields: form atop dune flats when sand supply is sufficient. Dune heights range from 3 to 25 m (9 to 77 ft) or more. Dune morphology varies with formation process and wind direction. Dune vegetation varies from nonexistent to forested and urbanized, depending on sand supply. Infrastructure has stabilized dune areas at Kill Devil Hills, Nags Head Cove, the northern end of Jockey's Ridge, Kitty Hawk, and the southern half of the Seven Sisters dune field.	**Barrier Island System Units**—Predominantly sand. **Paleontological Resources**—May contain paleontological resources (paleosol horizons).	**Recreational and Watershed Land Use**—Constructed dune ridges have altered the park's ecosystem and geologic structure, minimized overwash and inlet formation, modified habitat and back-barrier estuarine processes. They have resulted in narrower beaches, steeper shoreface, increased wave energy hitting the shoreface, marsh scarps, and decreased sound productivity. Along the barrier segment between Avon and Buxton, this has resulted in substantial island narrowing and four relocations of Highway 12.	Large sand supplies (from paleo–Roanoke River delta deposits) record previous climatic conditions and sea-level stands that built sediment-rich or complex barrier island segments. Unit features prominently in photographs by the Wright brothers. Kill Devil Hill was used by the Wright brothers and is now stabilized. Contains cultural resources (buried soil profiles that may record early settlement) Habitat: Prior to 1930s stabilization efforts, dunes were virtually void of vegetation except some minor salt meadow hay (*Spartina patens*). Heavy forests on the Nags Head Woods dune field, unit supports mixed hardwood and pine forest with a scrub shrub perimeter.
POLYDEMIC FEATURES (PF)		Algal Flat (PF-algal_flt) Ridge and Swale (PF_rdg_swl) Swale Marsh (PF_swl_marsh) Paleo-inlet Spit (PF_p_inl_spt)	Algal Flats: dominate the lower supratidal portion of the overwash area and form in ephemeral ponds or depressions. Unit persists in highly fluctuating salinity. Ridges and Swales: subparallel couplets of low, regular sand ridges (<3 m [9ft] high) and adjacent shallow swales.	**Sediment Transport Processes**—Storm winds move sand into the island interior and estuary, and build dunes. Overwash builds island elevation. **Capes and Cape-Associated Shoals**—Alongshore sediment transport is toward the tip of Cape Hatteras, so that the sediment loads from the south and from the north meet and are deposited at Diamond Shoals. **Inlets**—Created when storms drive surges across and through the island from the ocean or estuarine side. It widens by erosion and collapse of the adjacent bank, and deepens as flow scours the channel. They provide sediment to the back-barrier system through the growth of spits and delta deposits, which become platform marshes when the inlet closes. **Estuaries**—The sounds provide habitat for birds, seagrass, oysters, and mid-Atlantic fish. Most sand in Core Sound and central and eastern Pamlico Sound is derived from barrier islands and offshore sediments carried through inlets and overwash fans. Additional major contributions are from rivers, shoreline erosion and biogenic production. **Barrier Island System Units**—Predominantly sand and peat. Algal flats are frequently flooded by waters of varying salinity.	**Shoreline Erosion**—Estuarine shoreline change rates range from -1.2 m/yr (marsh) to 0.2 m/yr (beach). **Coastal Vulnerability and Sea-Level Rise**—Erosion, overwash, and inlet formation will continue to change island morphology. Sea-level rise may accelerate shoreline erosion, landward migration, and conversion of tidal wetlands to open water. **Hurricane Impacts and Human Responses**—Overwash adds saline water to surficial aquifers and groundwater. Rainwater adds fresh water to surficial aquifers and groundwater. **Recreational and Watershed Land Use**—Toxic and nuisance algal blooms may occur in Hatteras Island swales that are impacted by runoff or septic system leachate. Groundwater withdrawals can disrupt habitat by limiting plant species richness and diversity in nearby swales.	Algal mats can persist in conditions ranging from freshwater to hypersaline. No ridge and swale structure is forming today on the northern Outer Banks, but unit provides important age dates for sea-level highstand events. Units are among the oldest landforms present on the barrier islands. Many swales are dredged as navigational channels. May contain evidence of early settlements (<500 years old). Habitat: Perimeter of algal flats contains annual marsh glasswort (*Salicornia bigelovii*), perennial marsh glasswort (*Salicornia virginica*), saltgrass (*Distichlis spicata*), and sea oxeye (*Borrichia frutescens*). Sand ridges are heavily vegetated with mixes of pine and hardwood. Swales are dominated by wetland vegetation.
ANTHROPOGENIC FEATURES (AF)		Constructed Dune Ridges (AF_cn_dune_r) Constructed Interior Dune Ridges (AF_cn_idune)	Constructed Dune Ridges and Interior Dune Ridges: linear, ocean-parallel sand ridges built by bulldozers, then artificially vegetated with grass. Generally about 15 m (45 ft) wide at the base and up to 5 m (15 ft) high.	**Barrier Island System Units**—Predominantly sand.	**Shoreline Erosion**—Ocean shoreline change rates range from -2 m/yr to 2 m/yr. Erosion rates and breach potential are highest north of Rodanthe, southern Pea Island, the Buxton and Isabel inlet areas, and northeastern Ocracoke Island. **Coastal Vulnerability and Sea-Level Rise**—Erosion, overwash, and inlet formation will continue to change island morphology. Sea-level rise may accelerate shoreline erosion. **Hurricane Impacts and Human Responses**—Storms erode protective dunes. **Recreational and Watershed Land Use**—Constructed dune ridges have altered the park's ecosystem and geologic structure, minimized overwash and inlet formation, modified habitat and back-barrier estuarine processes. They have resulted in narrower beaches, steeper shoreface, increased wave energy hitting the shoreface, marsh scarps, and decreased sound productivity. Along the barrier segment between Avon and Buxton, this has resulted in substantial island narrowing and four relocations of Highway 12.	Units are out of equilibrium and are rapidly scarped on the ocean side and breached by storm surges. Units protect buildings and roads by preventing storm overwash and inlet migration. Units began in the 1930s with Works Progress Administration and Civilian Conservation Corps work camps. Habitat: Vegetation planted on these units includes sea oats (*Uniola paniculata*), American beachgrass (*Ammophila breviligulata*), salt meadow hay (*Spartina patens*). Older ridges become vegetated with salt myrtle (*Baccharis halimifolia*), marsh elder (*Iva frutescens*), wax myrtle (*Myrica cerifera*), yaupon holly (*Ilex vomitoria*), and eastern red cedar (*Juniper virginiana*).

Group	Subgroup	Map Unit (Symbol)	Geologic Description	Geologic and Environmental Features and Processes	Geologic Resource Management Issues	Geologic History and Habitat
ANTHROPOGENIC FEATURES (AF)		Road/Parking Areas (AF_rd_prk) Dredge Channels/Spoils (AF_drdge) Excavations (AF_excavate) Anthropic Overprint (AF_an_overpr)	Paved Areas: include roads, highways, and parking lots. Dredge Channels and Pits: sediment removal areas with most dredged material pumped offsite or deposited adjacent to the dredged area. Dredge often appears as linear ridges or rounded mounds. Excavations: artificially round or rectangular water features (including marinas and harbors) where sand was mined for constructed dune features. Anthropogenic Overprint: includes major urban areas with dense patterns of structures, parking lots, and roads.	**Barrier Island System Units**—Predominantly soil, sand, and gravel.	**Inlet Modifications**—The US Army Corps of Engineers sealed the 2003 Hurricane Isabel Inlet breach using sand dredged from the federally maintained ferry channel between Hatteras and Ocracoke islands. Sand dredged from Oregon Inlet was deposited offshore from 1960 to 1983, and was artificially bypassed to Pea Island beaches between 1983 and 2009. **Recreational and Watershed Land Use**—Impervious surface increases pollutant and nutrient runoff, degrading estuarine habitat. Constructed drainage ditches affect water distribution and quality on Bodie and Hatteras islands. Toxic and nuisance algal blooms may occur in nutrient-enriched drainage ditches on Bodie Island. **Coastal Engineering and Shoreline Armoring**—Seawalls, bulkheads, and other structures to inhibit wave action are expensive and accelerate erosion in front of the structures. Temporary soft stabilization (sandbags) have similar effects but are permitted in North Carolina. There have been 17 recorded beach nourishment projects in the park. Most nourishment sand is sourced from inlet deltas and channels; its removal destabilizes the inlets and impacts regional sediment budgets. Between 1962 and 2011, over 7.8 million m^3 of sediment were emplaced on park beaches. **Highway 12 Transportation Corridor**—Highway 12 is very vulnerable to shoreline erosion and storm overwash, and has been repeatedly damaged in numerous places in the last few decades. Debate over how to replace the route is ongoing.	Units record the human presence on the barrier islands. Units associated with urban development and access to natural areas. Anthropogenic unit includes cemeteries, monuments, Coast Guard stations, and camp grounds. Habitat: Inundated dredged areas contain salt myrtle (*Baccharis halimifolia*), marsh elder (*Iva frutescens*), salt meadow hay (*Spartina patens*), giant cordgrass (*Spartina cynosuroides*), and scrub shrub. Above the supratidal zone, dredged areas contain wax myrtle (*Myrica cerifera*), yaupon holly (*Ilex vomitoria*), northern bayberry (*Myrica pensylvanica*), pine (*Pinus* spp.), eastern red cedar (*Juniper virginiana*), salt meadow hay (*Spartina patens*), cat brier (*Smilax* spp.), and poison ivy (*Toxicodendron radicans*).

Cape Hatteras National Seashore: Geomorphic Map Unit Properties Table (North Carolina Geological Survey Map; 1:24,000 scale)

Group	Subgroup	Map Unit (Symbol)	Geologic Description	Geologic and Environmental Features and Processes	Geologic Issues	Geologic History and Habitat
INTERTIDAL FEATURES		Beach (beach)	Area between the ocean shoreline (wet/dry line) and the toe of the Fore-island Dune Complex with a narrow, steep profile.	**Sediment Transport Processes**—Barrier islands are continuously reshaped by the constant movement of sand by wind, waves, and currents. Overwash builds island elevation and creates and maintains early-succession habitat. **Capes and Cape-Associated Shoals**—Alongshore sediment transport is toward the tip of Cape Hatteras, so that the sediment loads from the south and from the north meet and are deposited at Diamond Shoals. **Barrier Island Evolution and Behavior**—Sediment availability and shoreline erosion patterns are influenced by the geologic framework of older stratigraphic units occurring beneath and seaward of the shoreface. **Barrier Island System Units**—Predominantly sand. Periodic flooding during storms and high lunar tides, especially near inlets. **Paleontological Resources**—Fossils may wash ashore or be exposed.	**Shoreline Erosion**—Ocean shoreline change ranges from -2 m/yr to 2 m/yr. Erosion rates and breach potential are highest north of Rodanthe, southern Pea Island, the Buxton and Isabel inlet areas, and northeastern Ocracoke Island. **Coastal Vulnerability and Sea-Level Rise**—Erosion, overwash, and inlet formation will continue to change island morphology. Sea-level rise may accelerate shoreline erosion and landward migration. **Hurricane Impacts and Human Responses**—Storms move sand across and off the island, create overwash and breaches, and drive landward migration. **Inlet Modifications**—Modifications disrupt sediment transport to downdrift shorelines. Newly opened inlets are often closed artificially to maintain the highway infrastructure. The Oregon Inlet terminal groin and revetment stopped erosion of northern Pea Island, but soundward accretion of the Bodie Island spit has narrowed and deepened the inlet. Oregon Inlet stabilization causes shoreline erosion of up to 4 m/yr on Pea Island. **Recreational and Watershed Land Use**—ORV use disturbs beach ecosystems, damages backshore vegetation, limits seaward dune development, and prevents post-storm dune recovery. **Coastal Engineering and Shoreline Armoring**—Seawalls and other structures to inhibit wave action are expensive and accelerate erosion in front of the structures. Temporary soft stabilization (sandbags) have similar effects but are permitted in North Carolina. Most nourishment sand is sourced from inlet deltas and channels; its removal destabilizes the inlets and impacts regional sediment budgets. Between 1962 and 2011, over 7.8 million m^3 of sediment were emplaced on park beaches. **Highway 12 Transportation Corridor**—Highway 12 is very vulnerable to shoreline erosion and storm overwash, and has been repeatedly damaged in numerous places in the last few decades. Debate over how to replace the route is ongoing. **Paleontological Resource Inventory, Monitoring, and Protection**—Beachcombers are allowed to collect unoccupied shells at Cape Hatteras National Seashore, but NPS policy states that fossils cannot be collected from NPS lands.	Beach unit is among the most indicative features of modern barrier island geomorphological processes. Spit and flat features are indicative of sand accretion during periodic overflow events and evolve in patterns. Cultural artifacts may wash ashore. Habitat: Active wave area habitat for shorebirds and other marine life.

Group	Subgroup	Map Unit (Symbol)	Geologic Description	Geologic and Environmental Features and Processes	Geologic Issues	Geologic History and Habitat
INTERTIDAL FEATURES	SPIT COMPLEX	Sand Flat (sand_flat) Ridge and Swale (ridge_swale)	Sand Flats: unvegetated, low (<1 m [4 ft]) elevation and relief; merge with the beach along the shoreline. Ridge and Swale: components situated lateral to sand flats, merging toward the interior and trending subparallel to the axis of the barrier island; curve toward the back of the island closer to the inlet.	**Sediment Transport Processes**—Sand flats are subject to regular tidal flooding and overwash. Barrier islands are continuously reshaped by the constant movement of sand by wind, waves, and currents. Storm winds move sand into the island interior and estuary and build dunes. Overwash builds island elevation and creates and maintains early-succession habitat. **Capes and Cape-Associated Shoals**—Alongshore sediment transport is toward the tip of Cape Hatteras, so that the sediment loads from the south and from the north meet and are deposited at Diamond Shoals. **Freshwater Aquifer**—Supply is recharged through rainfall and depleted through residential use, evapotranspiration from the surface and vegetation, and surface drainage from wetlands. Groundwater systems and aquifers can be affected by impoundments, weather conditions, and water withdrawal; these influences alter hydrologic processes, wetland function, and the distribution, composition, diversity, and structure of vegetation communities. The dunes near Theoff Point at the southern end of Bodie Island are favorable for fresh groundwater development because they are unlikely to be inundated by salt water or overwash. **Barrier Island System Units**—Predominantly sand. Ridge and swale areas represent older and more stable portions of the spit complex.	**Coastal Vulnerability and Sea-Level Rise**—Erosion, overwash, and inlet formation will continue to change island morphology. Sea-level rise may accelerate shoreline erosion and landward migration. **Hurricane Impacts and Human Responses**—Storms move sand across and off the island, create overwash and breaches, and drive landward migration. **Inlet Modifications**—Soundward accretion of the Bodie Island spit has narrowed and deepened the stabilized Oregon Inlet. **Recreational and Watershed Land Use**—ORV use disturbs beach ecosystems, damages backshore vegetation, limits seaward dune development, and prevents post-storm dune recovery. Toxic and nuisance algal blooms may occur in Hatteras Island swales that are impacted by runoff or septic system leachate. Groundwater withdrawals can disrupt habitat by limiting plant species richness and diversity in nearby swales. **Highway 12 Transportation Corridor**—Highway 12 is very vulnerable to shoreline erosion and storm overwash, and has been repeatedly damaged in numerous places in the last few decades. Debate over how to replace the route is ongoing.	Sand flats are generally associated with first development of Fore-island Dune Complex. Habitat: Algae crusts, episodic ponded water.
INTERTIDAL FEATURES		Marsh Platform (pf_marsh)	Unit is present along tidal creeks as low-lying areas (<1 m [2 to 3 ft] elevation) and developed in depressions between relict ridges or behind former sand flats. Approximately 1 m (several feet) of localized peat development during sea-level rise.	**Sediment Transport Processes**—Marsh areas are subject to regular tidal flooding and storm overwash. Barrier islands are continuously reshaped by the constant movement of sand by wind, waves, and currents. Storm winds move sand into the estuary. Overwash builds island elevation, expands marsh platforms and estuarine shoals, and creates and maintains early-succession habitat. **Inlets**—Created when storms drive surges across and through the island from the ocean or estuarine side. It widens by erosion and collapse of the adjacent bank, and deepens as flow scours the channel. They provide sediment to the back-barrier system through the growth of spits and delta deposits, which become platform marshes when the inlet closes. **Barrier Island System Units**—Predominantly peat and sand (from overwash). **Paleontological Resources**—May contain pollen.	**Shoreline Erosion**—Estuarine shoreline change rates range from -1.2 m/yr (marsh) to 0.2 m/yr (beach). The northern side of Ocracoke Village is eroding at -1.2 m/yr due to storm wind and waves from Pamlico Sound. **Coastal Vulnerability and Sea-Level Rise**—Erosion, overwash, and inlet formation will continue to change island morphology. Sea-level rise may accelerate shoreline erosion, landward migration, and conversion of tidal wetlands to open water. **Hurricane Impacts and Human Responses**—Storms move sand across and off the island, create overwash and breaches. Overwash adds saline water to surficial aquifers and groundwater. Rainwater adds fresh water to surficial aquifers and groundwater. High rainfall and flooding increases nutrients and sediments to the estuary, reduces estuarine salinity, and causes phytoplankton blooms. **Recreational and Watershed Land Use** —Toxic and nuisance algal blooms may occur in tidal creeks, marshes, and ponds on Ocracoke Island due to runoff or septic system leachate.	Marsh elevations correspond to sea level and are sensitive to sediment supply. May contain cultural resources. Habitat: Grasses such as *Juncus* and *Spartina patens*.
INTERTIDAL AND SUPRATIDAL FEATURE	BEACH AND FORE-ISLAND DUNE COMPLEX	Dune Saddle (dnesadl_bch)	Gaps or breaks along dune ridges in beach and fore-island dune systems with elevations <3 m (10 ft).	**Sediment Transport Processes**—Barrier islands are continuously reshaped by the constant movement of sand by wind, waves, and currents. Storm winds move sand into the island interior and build dunes. Overwash builds island elevation and creates and maintains early-succession habitat. **Inlets**—Created when storms drive surges across and through the island from the ocean or estuarine side. It widens by erosion and collapse of the adjacent bank, and deepens as flow scours the channel. They provide sediment to the back-barrier system through the growth of spits and delta deposits, which become platform marshes when the inlet closes. **Barrier Island System Units**—Predominantly sand.	**Coastal Vulnerability and Sea-Level Rise**—Erosion, overwash, and inlet formation will continue to change island morphology. **Hurricane Impacts and Human Responses**—Saddles represent potential high-water flow pathways that are vulnerable to coastal flooding during storms. Storms move sand across and off the island, create overwash and breaches. Overwash adds saline water to surficial aquifers and groundwater. Rainwater adds fresh water to surficial aquifers and groundwater.	Important features for predicting future overwash channels or inlets. Habitat: May provide local protection from prevailing winds.

Group	Subgroup	Map Unit (Symbol)	Geologic Description	Geologic and Environmental Features and Processes	Geologic Issues	Geologic History and Habitat
SUPRATIDAL FEATURES	FORE-ISLAND DUNE COMPLEX	Dune Ridges (dunerdge)	Unit is present as prominent, linear, shore-parallel sand ridges separated by swales. As many as three distinct ridges crop out locally, with heights generally <7 m (20 ft). Toe elevations are 2 to 3 m (6 to 8 ft) toward the ocean and 1 to 3 m (4 to 8 ft) toward the island interior.	**Barrier Island System Units**—Predominantly sand.	**Coastal Vulnerability and Sea-Level Rise**—Erosion, overwash, and inlet formation will continue to change island morphology. Sea-level rise may accelerate shoreline erosion. **Hurricane Impacts and Human Responses**—Storms move sand across and off the island, create overwash and breaches. Overwash adds saline water to surficial aquifers and groundwater. Rainwater adds fresh water to surficial aquifers and groundwater. **Recreational and Watershed Land Use**—Constructed dune ridges have altered the park's ecosystem and geologic structure, minimized overwash and inlet formation, modified habitat and back-barrier estuarine processes. They have resulted in narrower beaches, steeper shoreface, increased wave energy hitting the shoreface, marsh scarps, and decreased sound productivity. Along the barrier segment between Avon and Buxton, this has resulted in substantial island narrowing and four relocations of Highway 12.	Form prominent and extensive portions of Fore-island Dune Complex, important sediment supply for the system. May contain cultural resources (artifacts). Habitat: None documented.
	FORE-ISLAND DUNE COMPLEX, DUNE RIDGE	Interdune Swale and Dune Ridge (intswale_dr) Dune Saddle and Dune Ridge (dnesadl_dr)	Swales: closed, relatively low-lying areas in dune complexes with bases <3 m (10 ft) in elevation. Saddles: gaps or breaks along dune ridge lines with an elevation threshold of <2 m (10 ft).	**Sediment Transport Processes**—Barrier islands are continuously reshaped by the constant movement of sand by wind, waves, and currents. Storm winds move sand into the island interior and estuary, and builds dunes. Overwash builds island elevation, expands marsh platforms and estuarine shoals, and creates and maintains early-succession habitat. **Inlets**—Created when storms drive surges across and through the island from the ocean or estuarine side. It widens by erosion and collapse of the adjacent bank, and deepens as flow scours the channel. They provide sediment to the back-barrier system through the growth of spits and delta deposits, which become platform marshes when the inlet closes. **Barrier Island System Units**—Predominantly sand.	**Shoreline Erosion**—Erosion rates and breach potential are highest north of Rodanthe, southern Pea Island, the Buxton and Isabel inlet areas, and northeastern Ocracoke Island. **Coastal Vulnerability and Sea-Level Rise**—Erosion, overwash, and inlet formation will continue to change island morphology. Sea-level rise may accelerate shoreline erosion. **Hurricane Impacts and Human Responses**—Dune saddles represent potential high-water flow pathways or breach points that are vulnerable to coastal flooding during storms. Storms create overwash and breaches. Overwash adds saline water to surficial aquifers and groundwater. Rainwater adds fresh water to surficial aquifers and groundwater. **Recreational and Watershed Land Use**—Toxic and nuisance algal blooms may occur in Hatteras Island swales that are impacted by runoff or septic system leachate. Groundwater withdrawals can disrupt habitat by limiting plant species richness and diversity in nearby swales.	Important features for predicting future overwash channels or inlets; if they remain stable, swales may become marshy areas. Habitat: May provide local protection from prevailing winds.
	OVERWASH COMPLEX	Overwash Flat (owflat) Overwash Flat and Overwash Channel (owflt_owchn)	Overwash Flats: long-term accumulations of sand overwash behind the Fore-island Dune Complex, often in lobate forms. Overwash Channels: linear features associated with cuts through the fore-island dune.	**Sediment Transport Processes**—Associated with overwash during seasonal high tides and storm events. Barrier islands are continuously reshaped by the constant movement of sand by wind, waves, and currents. Overwash builds island elevation, expands marsh platforms and estuarine shoals, and creates and maintains early-succession habitat. **Barrier Island System Units**—Predominantly sand.	**Shoreline Erosion**—Ocean shoreline change rates range from -2 m/yr to 2 m/yr. Erosion rates and breach potential are highest north of Rodanthe, southern Pea Island, the Buxton and Isabel inlet areas, and northeastern Ocracoke Island. **Coastal Vulnerability and Sea-Level Rise**—Erosion, overwash, and inlet formation will continue to change island morphology. Sea-level rise may accelerate shoreline erosion and landward migration. **Hurricane Impacts and Human Responses**—Units are frequently reworked during storms.	Flats are deposited as lobes in discrete events, then reworked by wind, water, and humans into large flats. Habitat: Early-succession. Shorebird foraging. If stable for a sufficiently long period, can support vegetation.
		Overwash Fan (owfan)	Well defined locally as individual lobes from discrete storm events. Often with associated channels.	**Sediment Transport Processes**—Barrier islands are continuously reshaped by the constant movement of sand by wind, waves, and currents. Overwash builds island elevation, expands marsh platforms and estuarine shoals, and creates and maintains early-succession habitat. **Barrier Island System Units**—Forms during storm events and is prone to flooding. Predominantly sand.	**Hurricane Impacts and Human Responses**—Storms move sand across and off the island, create overwash and breaches, and drive landward migration.Overwash adds saline water to surficial aquifers and groundwater. **Recreational and Watershed Land Use**—Constructed dune ridges have minimized overwash and inlet formation.	Unit records discrete storm events (obvious on satellite imagery) and can be used to date overwash events during island development. Cultural resources (artifacts) may wash ashore during storms. Habitat: Early-succession. Shorebird foraging. If stable for a sufficiently long period, can support vegetation.
		Isolated Dunes (isodune)	Isolated dunes occur in the overwash flat area and/or farther inward as remnants of former fore-island dune ridges or as sand accumulations due to local traps.	**Barrier Island System Units**—Predominantly sand. Unit is localized and can be associated with anthropogenic features.	**Hurricane Impacts and Human Responses**—Storms move sand across and off the island, create overwash and breaches, and drive landward migration **Recreational and Watershed Land Use**—Constructed dune ridges have altered the park's ecosystem and geologic structure, minimized overwash and inlet formation, modified habitat and back-barrier estuarine processes. They have resulted in narrower beaches, steeper shoreface, increased wave energy hitting the shoreface, marsh scarps, and decreased sound productivity. Along the barrier segment between Avon and Buxton, this has resulted in substantial island narrowing and four relocations of Highway 12.	Isolated unit can be remnant of former dune ridge or form as a result of sand trapping by vegetation or fencing. Interior dune sand source is enigmatic; its identification requires more research. Habitat: Vegetation may trap sand, forming isolated dunes.

Group	Subgroup	Map Unit (Symbol)	Geologic Description	Geologic and Environmental Features and Processes	Geologic Issues	Geologic History and Habitat
SUPRATIDAL FEATURES		Interior Dunes (intdune) Interior Marsh (inmarsh) Back-Barrier Berm (bk_br_brm)	Interior Dunes: large-scale dunes that are the highest points of some islands (3 to 30 m [10 to 90 ft] elevation). Can occur as single ridges or be more laterally extensive. Interior marshes: develop adjacent to water bodies, often in swales of relict beach ridge complexes or interior lowlands. Berms: subtle linear features adjacent to and slightly higher than marsh platforms. Up to 3 m (10 ft) high with complex internal morphology.	**Inlets**—Created when storms drive surges across and through the island from the ocean or estuarine side. It widens by erosion and collapse of the adjacent bank, and deepens as flow scours the channel. They provide sediment to the back-barrier system through the growth of spits and delta deposits, which become platform marshes when the inlet closes. **Barrier Island System Units**—Interior Dunes and Back-Barrier Berm are sand. Interior Marsh is organic-rich sandy soil. **Paleontological Resources**—May contain pollen.	**Hurricane Impacts and Human Responses**—Dune unit can inundate local areas with sand deposits. Units should be avoided for recreation due to active dune formation or delicate marsh habitat. Rainwater adds fresh water to surficial aquifers and groundwater. **Recreational and Watershed Land Use**—Toxic and nuisance algal blooms may occur in swales on Hatteras Island, and in tidal creeks, marshes, and ponds on Ocracoke Island, that are impacted by runoff or septic system leachate. Groundwater withdrawals can disrupt habitat by limiting plant species richness and diversity in nearby swales.	Interior dune sand source is enigmatic; its identification requires more research. Marshes may be freshwater, berms tend to form in broad arcs of apparent relict flood tidal deltas, possibly due to the reworking of delta sand bodies by wave action. Habitat: Vegetation stabilizes interior dunes, providing habitat for plants preferring well-drained conditions. Marsh vegetation is prominent. Berms support leafy vegetation.
RELICT FEATURES		Relict Beach Ridge Complex (rel_bch_rdge) Relict Spit Complex (rel_splt) Water Body (water)	Relict Beach Ridges: crop out as sets of parallel ridges and swales in interior portions of islands. Elevation reaches 0 m (30 ft). Relict Spits: subtle arcuate-shaped ridges and swales in back-island areas with no active inlet connection. Water Bodies: ponds, streams, and other perennial water features; does not include ephemeral features.	**Capes and Cape-Associated Shoals**—Alongshore sediment transport is toward the tip of Cape Hatteras, so that the sediment loads from the south and from the north meet and are deposited at Diamond Shoals. **Freshwater Aquifer**—Supply is recharged through rainfall and depleted through residential use, evapotranspiration from the surface and vegetation, and surface drainage from wetlands. Groundwater systems and aquifers can be affected by impoundments, weather conditions, and water withdrawal; these influences alter hydrologic processes, wetland function, and the distribution, composition, diversity, and structure of vegetation communities. The high and wide island mass at Buxton Woods are favorable for fresh groundwater development because they are unlikely to be inundated by salt water or overwash. **Barrier Island System Units**—Predominantly sand, and peat in local marshes. Erosion resistance is very low to low if vegetated.	**Hurricane Impacts and Human Responses**—Rainwater adds fresh water to surficial aquifers and groundwater. **Recreational and Watershed Land Use**—Toxic and nuisance algal blooms may occur in drainage ditches on Bodie Island, in swales on Hatteras Island, and in tidal creeks, marshes, and ponds on Ocracoke Island, that are impacted by runoff or septic system leachate. Groundwater withdrawals can disrupt habitat by limiting plant species richness and diversity in nearby swales.	At least 13 sequences of relict beach ridges are mappable locally. Habitat: Marsh vegetation in interior areas, leafy vegetation on dunes.
ANTHROPOGENIC FEATURES		Airport/Landing Strip (airport_land) Commercial/Industrial Facility (comm_indust)	Airport: includes buildings and pavement near Buxton, Ocracoke, and Wright Brothers memorial areas. Commercial Facilities: includes marinas, ferry terminals, parking lots, and buildings.	**Barrier Island System Units**—Predominantly sand, gravel, and building materials. Historical structures such as lighthouses and guard houses are associated with these units.	**Recreational and Watershed Land Use**—Impervious surface increases pollutant and nutrient runoff, degrading estuarine habitat. **Coastal Engineering and Shoreline Armoring**—Seawalls, bulkheads, and other structures to inhibit wave action are expensive and accelerate erosion in front of the structures. Temporary soft stabilization (sandbags) have similar effects but are permitted in North Carolina.	Units record the history of human presence on the barrier islands. Habitat: Plants and animals adaptable to human presence.
		Dredge/Spoil (drdge) Filled (filled)	Dredge/Spoil: includes features of positive relief with obvious source areas within waterways. There have been five recorded dredging projects within or immediately adjacent to the park. Fill Areas: often include wetlands and exhibit linear boundaries and atypically high elevations.	**Estuaries**—Most sand in Core Sound and central and eastern Pamlico Sound is derived from barrier islands and offshore sediments carried through inlets and overwash fans. Additional major contributions are from rivers, shoreline erosion and biogenic production. **Barrier Island System Units**—Predominantly sand and clay. Erosion resistance is moderate to low.	**Inlet Modifications**—The US Army Corps of Engineers sealed the 2003 Hurricane Isabel Inlet breach using sand dredged from the federally maintained ferry channel between Hatteras and Ocracoke islands. Sand dredged from Oregon Inlet was deposited offshore from 1960 to 1983, and was artificially bypassed to Pea Island beaches between 1983 and 2009. **Coastal Engineering and Shoreline Armoring**—Most nourishment sand is sourced from inlet deltas and channels; its removal destabilizes the inlets and impacts regional sediment budgets. Between 1962 and 2011, over 7.8 million m^3 of sediment were emplaced on park beaches.	Dredge spoil subject to wave modification and vegetation as natural processes overprint anthropogenic changes. Habitat: Fill areas often abut and/or overprint former marsh areas. The sounds provide habitat for birds, seagrass, oysters, and mid-Atlantic fish.

Group	Subgroup	Map Unit (Symbol)	Geologic Description	Geologic and Environmental Features and Processes	Geologic Issues	Geologic History and Habitat
ANTHROPOGENIC FEATURES		Erosion Control Structure (ersn_ctrl_st) Excavation (excavate) Dike (dike) Waterfowl Impoundment (wtrfwl_impnd)	Erosion Control Structures: may include hardening, riprap, and other artificial sediment traps. There are 48 coastal engineering structures in or immediately adjacent to the park. Excavation Areas: known from imagery and witness accounts, typically serving as spoil sources. There are 5 dredging projects in or immediately adjacent to the park. Dikes: built for several waterfowl impoundment areas in Pea Island National Wildlife Refuge.	**Estuaries**—Most sand in Core Sound and central and eastern Pamlico Sound is derived from barrier islands and offshore sediments carried through inlets and overwash fans. Additional major contributions are from rivers, shoreline erosion and biogenic production. **Freshwater Aquifer**—Groundwater systems and aquifers can be affected by impoundments, weather conditions, and water withdrawal; these influences alter hydrologic processes, wetland function, and the distribution, composition, diversity, and structure of vegetation communities **Barrier Island System Units**—Predominantly sand and fill.	**Hurricane Impacts and Human Responses**—Structures may fail under extreme storm conditions. **Inlet Modifications**—The US Army Corps of Engineers sealed the 2003 Hurricane Isabel Inlet breach using sand dredged from the federally maintained ferry channel between Hatteras and Ocracoke islands. **Coastal Engineering and Shoreline Armoring**—Seawalls, bulkheads, and other structures to inhibit wave action are expensive and accelerate erosion in front of the structures. Temporary soft stabilization (sandbags) have similar effects but are permitted in North Carolina. Most nourishment sand is sourced from inlet deltas and channels; its removal destabilizes the inlets and impacts regional sediment budgets. Between 1962 and 2011, over 7.8 million m^3 of sediment were emplaced on park beaches. **Recreational and Watershed Land Use**—Constructed drainage ditches affect water distribution and quality on Bodie and Hatteras islands. Toxic and nuisance algal blooms may occur in nutrient-enriched drainage ditches on Bodie Island.	Units document human attempts to stop, slow, or reverse natural barrier island processes. Habitat: Plants and animals adaptable to human presence, waterfowl use impoundment areas.