National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Gulf Islands National Seashore

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2019/1986

ON THE COVER
Aerial photograph of Fort Massachusetts on West Ship Island (Mississippi). The photograph was taken on 2 August 2012, a few weeks after Hurricane Isaac. Geomorphic map units pictured include beach, active overwash zone, inactive overwash zone, beach ridge complex, beach ridge swale, structures, and reclaimed land; these map units are discussed in this report. USGS photograph.

THIS PAGE
Photograph of habitats on Horn Island (Mississippi). The photograph was taken on 21 July 2015. Map units pictured include active dune complex, stable dune complex, and vegetated barrier flat; these map units are discussed in this report. Trees in the distance were killed by the Hurricane Katrina storm surge and saltwater inundation. NPS photograph by Courtney Schupp.

Gulf Islands National Seashore

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2019/1986

Courtney A. Schupp

National Park Service Geologic Resources Inventory
Geologic Resources Division
PO Box 25287
Denver, CO 80225

August 2019

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

This report is available from http://go.nps.gov/gripubs, and https://www.nps.gov/im/publication-series.htm. If you have difficulty accessing information in this publication, particularly if using assistive technology, please email irma@nps.gov

Please cite this publication as:

Schupp, C. A. 2019. Gulf Islands National Seashore: Geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2019/1986. National Park Service, Fort Collins, Colorado.

NPS 635/160210, August 2019

Contents

Figures

Tables

Executive Summary

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

This report synthesizes discussions from a scoping meeting held in 2006 and a follow-up conference call in 2016 (see Appendix A). Chapters of this report highlight and discuss the geologic setting, distinctive geologic features and processes within Gulf Islands National Seashore, geologic issues facing resource managers, the geologic history leading to the present-day landscape, and information about the previously completed GRI map data. Two posters (in pocket) illustrate these data. Refer to Appendix C for URLs.

Gulf Islands National Seashore (referred to as the "park" throughout this report) is located within the Coastal Plain physiographic province, which extends for more than 3,500 km (2,200 mi) from Cape Cod, Massachusetts, to the Mexican border. The Coastal Plain physiographic province consists of seaward-sloping lowlands and the submerged continental shelf along the Atlantic Ocean and Gulf of Mexico. The park is in the portion of the province known as the East Gulf Coastal Plain.

The park encompasses 13 units that consist of barrier islands and mainland areas along the coasts of Mississippi and Florida (National Park Service [NPS] 2018). The park's purpose is to preserve and interpret an interconnected system of coastal defense fortifications, barrier islands, wilderness, and coastal and marine ecosystems, while providing for public use and enjoyment (NPS 2016a).

This report describes the geologic connection to the park's fundamental resources and values, which were identified in the park's foundation document (NPS 2016a) and include terrestrial and marine ecosystems, barrier islands, and wilderness. In addition, many of the planning issues and concerns raised in the park's general management plan (NPS 2014) have geologic considerations that are discussed in this report; these include preserving coastal ecosystems, storm recovery and sustainability, oil and gas development, the Deepwater Horizon oil spill, and climate change.

The park hosts a diversity of coastal habitats such as forests, beaches and washover fans, seagrass beds, interior dunes, coastal marshes, interior brackish ponds and creeks, and interior sand flats. These habitats support aquatic and terrestrial plant and animal life, including federally protected species, migratory birds, and turtle nesting sites.

The park is relatively young, geologically speaking. The barrier islands were formed within the last 5,000 years. They sit atop sedimentary fluvial, estuarine, and nearshore marine strata deposited during sea level oscillations that took place during the Pliocene, Pleistocene, and Holocene Epochs—a timespan that covers the past 5.3 million years. Table 10 of this report is a geologic time scale that provides a context for the timing of geologic events that pertain to the evolution of the park's barrier islands.

The modern islands are shaped by the region's geologic framework and bathymetry, as well as interactions with coastal processes—such as storms, waves, tides, sediment transport, inlet dynamics, and sea level change—and anthropogenic activities—such as inlet dredging and shoreline engineering—that rework the Quaternary (Pleistocene and Holocene) sediments.

This report is supported by two GRI GIS data sets (gifl_geology.mxd and gims_geology.mxd) that provide coverage of the Florida and Mississippi portions of the park, excluding the mainland areas; that is, Santa Rosa Island and Perdido Key in Florida and Cat Island, East and West Ship Islands, Horn Island, and Petit Bois Island in Mississippi. Mapping for Sand Island is not included in the GRI GIS data, but figure 7 of this report illustrates ecological habitats and geomorphic features (marsh shrubland, beach dune herbland, water, and bare sand) that make up Sand Island. In addition, the GRI team produced component maps for Cat Island (cati_geology.mxd), Horn Island (hrni_geology.mxd), Petit Bois Island (pebo_geology.mxd), and Ship Island (ship_geology.mxd); these were derived from gims_geology.mxd (the digital geomorphic map for the

Mississippi portions of the park). The GRI team created the GRI GIS data using US Geological Survey (USGS) open-file reports. The GRI GIS data delineate the locations of 19 geomorphic map units (table 2).

Additional useful references are provided at the end of this report. Relevant geologic resource laws, regulations, and policies are provided in Appendix B.

Noteworthy geologic features and processes at the park include the following:

- **Geomorphic Map Units**. The digital geomorphic maps that accompany this report include 19 map units: active dune complex (map unit symbol **dn_cplx_a**), stable/stabilized dune complex (**dn_cplx_s**), active overwash zone (**ovrwsh_zn_a**), inactive overwash zone (**ovrwsh_zn_i**), beach (**beach**), beach ridge complex (**bch_rdg_cplx**), beach ridge swale (**bch_rdg_swl**), marsh (**marsh**), shoal (**shoal**), spit (**spit**), vegetated barrier flats (**veg_brr_flt**), vegetated barrier core (**veg_brr_cr**), interior wetland (**intr_wtlnd**), modified land (**mdfd_lnd**), structures (**structure**), structure zone (**strctr_zn**), reclaimed land (**rclmd_lnd**), dredge material (**drdg_mtrl**), and artificial dune (**artfcl_dn**). As a result of the dynamic nature of barrier islands, the land surface continues to change and the 2007 maps used to compile the accompanying GRI GIS data may not reflect present conditions in all locations.
- **Oceanographic Conditions**. The park's islands are wave-dominated and microtidal (less than 2 m [7 ft]). Because of the large water volume in the Mississippi Sound, tidal currents in inlets (locally called "passes") are strong. The Loop Current and the Mississippi River outflow influence circulation in the Gulf of Mexico.
- **Sediment Transport Processes**. Historically, the Mississippi barrier islands underwent net westward migration because the net beach drift and littoral current direction were defined by dominantly southeasterly winds. Island sand comes from beaches in northwest Florida and southeast Alabama, rivers that drain into Pensacola Bay and Mobile Bay, the inner shelf, and a Pleistocene headland east of Santa Rosa Island. Dredged passes interrupt the sediment transfer along shoals between islands. Cat Island beaches have no apparent external source of sand. Dune height is related to grain size and wind velocity. Dune position is related to the frequency of storm erosion. Dune vegetation helps to trap sediment.
- **Overwash and Island Migration**. Overwash (the flow of water over low parts of barriers, especially during storms) is an important process in building island elevation and width, as well as creating habitat. Washover is the material deposited by the action of overwash; washover fans are commonly built by overwash.
- **Inlets**. Storm-driven surges flow across an island and excavate an inlet. The inlet widens by erosion and collapse of the adjacent bank and deepens as tidal flow scours the channel. Inlets may form from either the seaward side (toward the Gulf of Mexico) or the landward side (adjacent to either the Mississippi Sound of the Santa Rosa Sound) of the barrier islands.
- **Wetlands**. Salt marshes, tidal flats, and freshwater interior wetlands are present in the park. Accretion rates of tidal salt marshes depend on the input of fine-grained sediment and deposition of erosion-resistant organic peat.
- **Seagrass**. Locations of seagrass beds are controlled by bathymetry and sediment type. Submerged aquatic vegetation stabilizes bottom sediment, improves water clarity, binds shallow water sediments with roots and rhizomes, and slows waves and currents.
- **Groundwater**. Groundwater is one source of water to island ponds; precipitation, inflow from bays, overwash, and breaching are other sources of water. Climate change may influence groundwater by driving saltwater intrusion, higher water tables, and changes in soil moisture. Groundwater dynamics in surficial aquifers are directly affected by rising sea levels and indirectly by the morphological changes driven by sea level rise.
- **Estuarine Sediments**. Sediments in the Mississippi Sound originated in the Appalachian Mountains and were discharged by the Mississippi River, Mobile River, and smaller regional river systems. Additional sediment is organic and locally derived from marsh decomposition. Tidal flows through the passes also carry sediment to and from the Gulf of Mexico. As a result, the central portions of the Mississippi Sound are primarily silt and clay. In the Pascagoula area (Mississippi), medium-grained sands are more prevalent. Coarse-grained sands occur near the barrier islands, whereas fine-grained muds accumulate in dredged channels.
- **Nearshore Substrate and Benthic Habitat**. The islands are surrounded by coarse-to-medium grained sand, which gets finer with increasing distance offshore (toward the Gulf of Mexico) and muddier toward the Mississippi Sound. The passes between islands are primarily medium-to-coarse grained sand. Dredged shipping channels have fine-grained mud and silt. Large, sandy bed forms occur to the south (Gulf of Mexico) side of each island; the largest ones are south of Petit Bois and Horn Islands.

- **Paleontological Resources**. Very few fossils wash ashore onto the park's barrier islands. Mollusks and microfossils occur in fluvial, estuarine, and marine environments, as shown in drill cores.

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

- **Coastal Resource Management and Planning**. The NPS has developed a variety of databases and guidance for managing coastal resources and planning for the impacts of climate change on natural and cultural resources and facilities. These resources are discussed in this report.
- **Coastal Erosion**. Variations in wave energy, sediment availability, sea level change, and human activities influence the balance between erosion and deposition. East and West Ship Islands are the most vulnerable of the Mississippi barrier islands because they are farthest from sand sources at exposed Pleistocene shore ridges and mainland beaches of northwest Florida and southeast Alabama and locally at eastern Dauphin Island and the Mobile Pass ebb-tidal delta. Subsidence of the Mississippi River Delta is causing Cat Island to lose land along all shorelines. Severe storms have caused erosional events and breaching. Coastal erosion and storm events threaten historical and archeological resources.
- **Coastal Vulnerability and Sea Level Rise**. Relative sea level rise of park areas increases westward toward the subsiding Mississippi River Delta. Sea level change and storm surge are expected to cause land loss, rising groundwater, increased risk of high intensity storm events, and potential loss of nearby freshwater ecosystems. Prolonged drought conditions, storm surges, and rising sea levels may reduce availability of freshwater resources, alter river and wetland hydrology, increase erosion, induce changes in the distribution of coastal plant and animal species, and drown marshes.
- **Hurricane Impacts and Human Responses**. Hurricanes and other major storms are important drivers of geomorphic change because winds, waves, and storm surges move sand across and off the islands. Island response to storms is controlled primarily by island width, topography, and bathymetry. Storm parameters such as path and wind speeds also change the impacts of storms. Recent hurricanes have impacted island habitats, topography, and infrastructure. Post-storm recovery of beaches and dunes correlates with island width, height of the pre-storm dunes, overwash penetration, storm frequency, and offshore bathymetry. Climate change is expected to increase hurricane intensity.
- **Dredging of Inlets**. Anthropogenic modifications of an inlet, such as dredging and jetty stabilization, disrupt an inlet's ability to perform the following functions: respond to storms, bypass sediment between islands, exchange sediment between flood and ebb-tidal deltas, migrate, and provide sediment to downdrift shorelines. Dredging occurs in Pensacola, Ship Island, and Horn Island Passes. Proposed dredging of a pass through Santa Rosa Island east of Navarre Beach would affect park resources by changing alongshore sediment transport and estuarine circulation patterns.
- **Coastal Engineering and Beach Nourishment**. Sediment has been added to beaches on West Ship Island and Perdido Key multiple times. Removal of sediment from the former Ship Island Pass has maintained a sand sink that prevents island migration. The Mississippi Coastal Improvements Program is intended to restore the Mississippi barrier islands and protect associated resources. Sand has been placed around Fort Massachusetts and on Cat Island. Sediment placement began in late 2017 within and adjacent to Camille Cut to reconnect East and West Ship Islands and to augment sediment transported alongshore toward East Ship Island. Sediment dredged in the future to maintain Horn Island Pass will be placed within park boundaries. The changes may increase sedimentation in Ship Island Pass, change estuarine circulation patterns, and create subaerial and subaqueous habitat.
- **Impacts to Wetlands**. Past modifications to wetlands, including drainage, damming, and diking, have changed the natural flow regime in several park areas.
- **Visitor Use Impacts**. Boat use, including public and private ferry systems, can increase coastal erosion and scar seagrass beds. Social trails accelerate dune erosion. The Fort Pickens Road affects island topography and is frequently damaged by storm overwash.
- **Visitor Safety**. Rip currents are caused by the interaction of nearshore bathymetry and waves; they are common along the park shoreline and pose a visitor safety concern.
- **Decline of Seagrass Beds**. Seagrass coverage is declining around the park probably because of increased turbidity and reduced water quality from human activities. The park's general management plan (NPS 2014) identifies designated seagrass bed zones that will be managed to prevent resource damage to seagrass beds from vessel groundings, anchoring, and propeller scarring.
- **Water Quality**. Estuarine water quality in the park is affected by mainland runoff, particularly in Florida.

- **Abandoned Mineral Lands**. Abandoned mineral lands (AML) are lands, waters, and surrounding watersheds that contain facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation, including oil and gas features and operations. The "Old Quarry Trail," also known as the "Old Borrow Pit Trail," is a now–abandoned borrow pit from which material was extracted to build Highway 90. The borrow pit, which is in the Naval Live Oaks area, is not currently a restoration priority for park managers. If restoration of this area becomes a priority in the future, park managers can contact the NPS Geologic Resources Division for technical assistance.
- **Energy Development**. Offshore drilling and extraction from beneath the park through directional drilling from outside the park may occur in the future. These activities could cause ground subsidence and other threats to park resources and values. The 2010 Deepwater Horizon explosion and subsequent release of more than 800 million L (200 million gal) of oil contaminated park beaches.
- **Paleontological Resource Inventory and Protection**. Active surveys and protection efforts are not a current park management priority, but the NPS Geologic Resources Division has many resources to help in future efforts.
- **Sediment Budget Data Needs**. Park management would benefit from additional information related to the following: appropriateness of beach nourishment in certain park areas, whether the regional sediment budget is losing sand, impacts to park resources from dredging and renourishment at adjacent beaches, the natural movement of Petit Bois Island, sand transport along Santa Rosa Island, the Mississippi islands' vulnerability to sea level rise, and identification of erosional hot spots along the Mississippi–Alabama island chain.

Products and Acknowledgments

The NPS Geologic Resources Division partners with the Colorado State University Department of Geosciences to produce GRI products. The US Geological Survey developed the source maps. Content reviewers include staff from the US Geological Survey, NPS, and two universities. This chapter describes GRI products and acknowledges contributors to this report. Refer to Appendix C for URLs.

GRI Products

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

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

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

Additional information regarding the GRI, including contact information, is available at the GRI website.

Acknowledgments

Trista Thornberry-Ehrlich (Colorado State University) produced many of the graphics in this report. **Ervin Otvos** (University of Southern Mississippi) provided multiple reviews of geologic history and stratigraphy sections. Additional insights, information, and graphics were provided by **Jeff Bracewell** (NPS Gulf Coast Network), **Cass Bromley** (Gulf Islands National Seashore), **Mark Byrnes** (Applied Coastal, Inc.), **Jim Flocks** (US Geological Survey), **Gary Hopkins** (Gulf Islands National Seashore), **Jeff Paine** (Texas Bureau of Economic Geology), and **Jolene Williams** (Gulf Islands National Seashore). **Jolene Williams** (Gulf Islands National Seashore), **Linda York** (NPS Southeast Regional Office), and **Mark Ford** (NPS Regional Office) helped to clarify some "final points" and answer some "final questions" that allowed completion of the final report; their prompt responses are much appreciated.

Author

Courtney Schupp (National Park Service)

Review

Joe Donoghue (University of Central Florida)
Jim Flocks (US Geological Survey)
Mark Ford (NPS Southeast Regional Office)
Jason Kenworthy (NPS Geologic Resources Division)
Pamela Marsh (Gulf Islands National Seashore)
Mark Nicholas (Gulf Islands National Seashore)
Ervin Otvos (University of Southern Mississippi)
Jolene Williams (Gulf Islands National Seashore)
Linda York (NPS Southeast Regional Office)

Editing

Katie KellerLynn (Colorado State University)

Report Formatting and Distribution

Chelsea Bitting (NPS Geologic Resources Division)

Source Maps

Robert A. Morton (US Geological Survey)
Bryan E. Rogers (US Geological Survey)
Marilyn C. Montgomery (US Geological Survey)

GRI GIS Data Production

Stephanie O'Meara (Colorado State University)

GRI Map Poster Design

Chase Winters (Colorado State University)
Georgia Hybels (Colorado State University)

GRI Map Poster Editing

Georgia Hybels (Colorado State University)
Rebecca Port (NPS Geologic Resources Division)
Michael Barthelmes (Colorado State University)
Jason Kenworthy (NPS Geologic Resources Division)

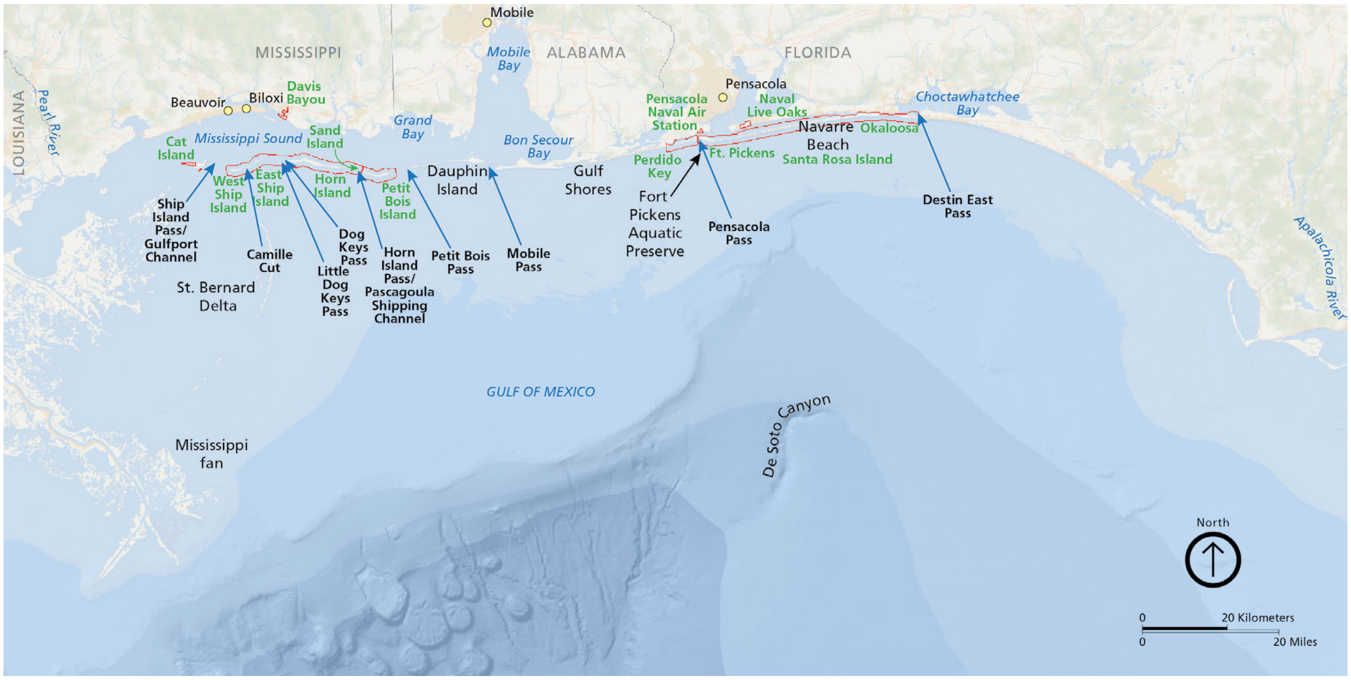

Figure 1. Location map of significant features in and nearby the park.
The features on this figure are listed and described in Table 1. This figure identifies the locations of towns (yellow dots); islands and park areas (labeled in green); natural and artificial inlets, referred to as channels, cuts, and passes (labeled in black); bathymetric features (also labeled in black), and water bodies (labeled in blue). The park boundary is delineated in red. Bathymetry is from ESRI oceans base map. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Geologic Setting and Significance

This chapter describes the regional geologic setting of the park and summarizes connections among geologic resources, other park resources, and park stories. Refer to Appendix C for URLs.

Park Establishment and Setting

Gulf Islands National Seashore (referred to as the "park" throughout this document) was authorized by the US Congress on 8 January 1971 (16 USC § 459h-3). The park's purpose is to preserve and interpret an interconnected system of coastal defense fortifications, barrier islands, wilderness, and coastal and marine ecosystems in Mississippi and northwest Florida, while providing for public use and enjoyment (NPS 2016a). Table 1 of this report provides a list of significant geomorphic features in the park. Figure 1 is a location map of these features.

The park has portions in Florida and Mississippi. The Florida units of the park include Fort Barrancas (at the Pensacola Naval Air Station) and Fort Pickens, as well as the Naval Live Oaks, Santa Rosa, Okaloosa, and Perdido Key areas (figs. 1, 2, and 3). Fort Barrancas and Naval Live Oaks are on the mainland. The other Florida units are on Santa Rosa Island and Perdido Key. The Mississippi units of the park consist of five islands (West and East Ship, Horn, Sand [also known as "West Petit Bois"], and Petit Bois, as well as part of Cat Island. The Davis Bayou unit is on the mainland (figs. 1, 2, and 4).

The park preserves both natural and cultural resources along the Gulf of Mexico—a large sedimentary basin that extends roughly 1,600 km (1,000 mi) from the western coast of Florida to the US–Mexico border (Williams et al. 2012). The park is more than 160 km (100 mi) long and encompasses 56,322 ha (139,175 ac); 80% of the park's area is submerged or intertidal. Park resources range from remote wilderness islands with limited visitation to readily accessible white sand beaches and historic sites. The natural environment supports both terrestrial and aquatic plant and animal communities. These complex communities characterize the northern Gulf Coast and include bayou, salt marsh, live oak, and southern magnolia forests (NPS 2014).

Adjacent urban development has increased the importance of the park as a refuge for species with special status, including federal threatened and endangered species, and state species of special concern. Critical habitat for several special-status species has been designated within the park by the US Fish and Wildlife Service. Habitats such as seagrass beds, migratory bird habitat, and turtle nesting sites are at risk from the pressures of outside development, increased visitation, and greater storm frequency in the Gulf of Mexico (NPS 2014). Between 2011 and 2014, annual average visitation was almost 5 million visitors (NPS 2016a).

Florida Units

In general, the legislated boundary along the landward (north) side of Santa Rosa Island and Perdido Key is the southern boundary of the Intracoastal Waterway—a shipping channel that the US Army Corps of Engineers (USACE) maintains via dredging. On the Gulf of Mexico (south) side of the islands, the boundary is 2 km (1 mi) beyond the low tide line (see posters, in pocket). All waters within the boundaries of the Florida portion of the park are Florida Outstanding Waters (Jolene Williams, Gulf Islands National Seashore, environmental protection specialist, GRI review comments, 3 September 2017).

Most of Santa Rosa Island is only a few hundred meters wide (see poster, in pocket). This long, thin barrier runs east–west for about 76 km (47 mi) from Pensacola Pass to East Pass near Destin, Florida (fig. 1). The waters adjacent to Santa Rosa Island are included in the boundary; some of the submerged lands underlying those waters are owned by the State of Florida. The Fort Pickens Aquatic Preserve surrounds the western end of Santa Rosa Island and the eastern end of Perdido Key (fig. 1). The preserve encompasses approximately 14,000 ha (34,000 ac) of submerged lands and extends 5 km (3 mi) offshore (18-20 Florida Administrative Code). It was established in 1970 to preserve biological resources. The preserve is jointly managed by the National Park Service and Florida Department of Environmental Protection.

Perdido Key is approximately 24 km (15 mi) long. The National Park Service manages the easternmost 11 km (7 mi) of the key.

In Florida, park lands are separated and dissected by many notable water bodies and rivers. Santa Rosa Sound is a 58-km- (36-mi-) long lagoon tapering in width from 3 km (2 mi) near its western end to less than 0.4 km (0.25 mi) eastward. It has an average depth of 3 m (9 ft) within the park. The sound connects on the north to Pensacola Bay and on the west to Big Lagoon (see poster, in pocket). Big Lagoon—which is 1.2 km (0.75 mi) wide and, within the park, has an average water depth of 2.3 m (7.5 ft)—is an estuary between Perdido Key and the Pensacola Naval Air Station (fig. 3). The major tributaries to Pensacola Bay and Perdido Bay are the Escambia, Blackwater, Yellow, and Perdido

Table 1. Significant geomorphic features at Gulf Islands National Seashore.

Features are listed in geographic order from west to east. Refer to figure 1 for locations.

Name	Type	Description
St. Bernard lobe of the Mississippi River Delta	River delta	Growth of the delta lobe between 3,800 and 1,800 years ago deposited sediments to the south and east of Cat Island and interrupted the development of Cat and the Ship Islands. The resulting mainland-ward extension of the delta, shoaling, and marsh development stranded the barrier islands of western Mississippi and southeastern Louisiana within the emerging marshlands.
Cat Island	Island	The westernmost island in the park is losing area as a result of continued coastal erosion, compaction, and subsidence of the adjacent Mississippi River Delta complex.
Ship Island Pass / Gulfport Channel	Pass	The pass separating Cat and West Ship Islands is 8 km (5 mi) wide. It was created in 1899 and then relocated to the west in 1993. The old channel persists as a beach nourishment source and impoundment to trap sediment.
West Ship Island	Island	The island was migrating westward and rotating in a northeastward direction. Visitors access the island via public ferry and private vessel. Beach nourishment projects protect Fort Massachusetts on the western end of the island.
Camille Cut	Pass	East and West Ship Islands were breached in 1969, and later hurricanes widened Camille Cut. As part of the Mississippi Coastal Improvements Program, the breach will be filled, which is expected to change water circulation patterns in the Mississippi Sound.
East Ship Island	Island	The two Ship Islands are the most vulnerable of the Mississippi barrier islands on account of their distance from sand sources and diminished sand supply from Dog Keys Pass that serves as a major "sediment sink" toward the Gulf of Mexico. High long-term erosion rates may in part be a result of an old channel that runs beneath the middle of the island in an offshore direction; the channel is exposed on the adjacent inner shelf.
Dog Keys Pass	Pass	The pass separating East Ship and Horn Islands is the widest pass in the Mississippi barrier island chain. It is a sediment sink, reducing sediment transport to East Ship Island.
Horn Island	Island	Horn Island's relict beach ridges are the highest elevations in the Mississippi barrier chain. Horn Island has migrated westward. It was designated as wilderness in 1978.
Sand Island	Island	Sand Island, part of DA-10, was created with sediment dredged from the Pascagoula Channel beginning in 1917 and receives sediment approximately every 18 months during channel maintenance. It is a functioning barrier island managed by the NPS and contributes some sand to the westward-directed littoral drift.
Horn Island Pass / Pascagoula Channel	Pass	The pass separating Horn and Petit Bois Islands is dredged to provide access for the Pascagoula Channel.
Petit Bois Island	Island	The island is rotating in a northeastward direction. The vegetated beach ridge complex on the eastern end has added stability and limited the expansion of Petit Bois Pass. It was designated as wilderness in 1978.
Petit Bois Pass	Pass	The pass separating Petit Bois and Dauphin Islands does not have a maintained ship channel.
Dauphin Island	Island	Approximately 5,500 to 5,100 years ago, Dauphin Island contributed sediment to a shoal platform that isolated Mississippi Sound from the Gulf of Mexico and supported Mississippi barrier island emergence. Dauphin and Petit Bois Islands were one island until breached in the early 1700s.
Perdido Key	Island	Perdido Key was part of the mainland Holocene coastal plain and was artificially separated from the mainland by a dredged channel. The ocean shore has historically accreted with sediment being transported from the inner shelf onshore, and also eastward along the shore.
Pensacola Pass	Pass	The channel was dredged in 1883 and is migrating westward. It has been deepened several times. Dredging has accelerated erosion along Perdido Key and Santa Rosa Island. The pass is a net sediment sink, receiving sediment from Pensacola Beach to the east and from Perdido Key to the west.
Santa Rosa Island	Island	The eastern half of the island, including the Santa Rosa and Okaloosa areas of the park, receives sediment from an eroding headland to the east. The western end of the Fort Pickens area of the park is accreting as a result of westward sediment transport. The narrow portions of the Fort Pickens area are frequently overwashed during storms, and erosion is occurring on both the Gulf of Mexico and Santa Rosa Sound sides of the island.

Table 1 (continued). Significant geomorphic features at Gulf Islands National Seashore.

Name	Type	Description
East Pass	Pass	The pass is a maintained ship channel that delineates the eastern boundary of Santa Rosa Island, near the Okaloosa area of the park. It formed when the island breached during storms in 1928 and 1929. The channel is migrating eastward.

Rivers (fig. 2). Pensacola Bay, Big Lagoon, and Santa Rosa Sound are connected to the Gulf of Mexico through Pensacola Pass (fig. 1), which has a width of 1.2 km (0.75 mi) and a maximum depth of 18 m (60 ft).

Along the Florida units within the park, the regional coastal slope is between 0.624% and 1.032%, which is steeper than along the Mississippi units, where the slope is between 0.14% and 0.27% (Pendleton et al. 2004).

At the park's southern boundary, which is located about 2 km (1 mi) out into the Gulf of Mexico, water depth averages 5 m (15 ft) off Perdido Key, 6 m (20 ft) off Fort Pickens, and more than 9 m (30 ft) off the Santa Rosa Area (NPS 2014). The maximum range for the diurnal tides at the Pensacola Bay entrance station (see fig. 3) is 0.8 m (3 ft), and the maximum current speed is 2.1 m (6.9 ft) per second, or 4.1 knots (NPS 2014).

Generally, the islands have broad, sandy beaches on the north (sound) side, and dunes and beaches on the south (Gulf of Mexico) side (see poster, in pocket). Park beaches are composed primarily of white quartz sand, with higher levels of clay along the Mississippi beaches (Foxworth et al. 1962; Hatt et al. 2016). On the sound side, the low tide terrace (relatively level bench or steplike surface) typically extends up to several hundred meters into the sound and is usually subtidal (Stone et al. 2004).

Along Santa Rosa Island, dunes are typically 2 m (7 ft) high, although some are more than 6 m (20 ft) high (fig. 5) (Houser et al. 2015b). Foredunes on Perdido Key are generally 4–5 m (12–16 ft) high (Sankar 2015). The continued existence of dune fields depends on several factors: sediment supply via alongshore transport or artificial nourishment, island width, dune field width, continuity of the dune complex, and inner-shelf bathymetry (Sankar 2015).

Mississippi Units

In 1978, Congress designated Horn and Petit Bois Islands as wilderness, thus creating one of the few nationally designated barrier island wilderness areas in the National Park System. The wilderness ends at the mean high tide line and does not extend over submerged lands within the park boundary. In general, the boundary of the Mississippi units of the park extends 2 km (1 mi) from the mean low tide lines of the northern and southern shorelines and is contiguous from West Ship Island to Petit Bois Island. Unlike the park areas in Florida, all of the submerged lands, except around Cat Island, within the park boundary are part of the park. The boundary extends from the Mississippi–Alabama state line to the east boundary of the Gulfport Channel (fig. 1). The Pascagoula Channel is excluded from the park boundary.

Also known as "West Petit Bois Island" or "Spoil Island," Sand Island, which is located within the park's water boundaries, is within USACE Disposal Area 10 (DA-10) (Clark 2014). Sand Island is composed of dredge spoil that the USACE deposited just prior to park establishment; additional spoil has been added periodically to the island since park establishment. Sand Island is about 2 km (1 mi) long, 580 m (180 ft) wide, and has an unnaturally high elevation of 9 m (30 ft). The island's east–west recurved and truncated beach ridges are highly elevated (Anderson et al. 2016b).

The Mississippi Sound, which is located between the mainland and barrier islands, is a shallow estuary that extends about 150 km (90 mi) along the southern coasts of Mississippi and Alabama (figs. 1 and 2). The sound is 10 to 19 km (6 to 12 mi) wide. Its southern border is defined by Cat, East and West Ship, Horn, Petit Bois, and Dauphin Islands, all of which are narrow barrier islands located between about 15 and 19 km (9 and 12 mi) from the mainland. With the exceptions of Dauphin Island and portions of Cat Island, these barrier islands are part of the park. The sound deepens gradually from the mainland shore toward the islands. The average mean low water depth of the sound is 3 m (10 ft), and most of the area is less than 6 m (20 ft) deep (NPS 2014).

Inlets between islands (locally known as "passes") are generally 5 m (16 ft) deep or less. For example, a natural channel in Dog Keys Pass between East Ship Island and Horn Island leading toward Biloxi is approximately 4.6 m (15.1 ft) deep (USACE 2016a). By contrast, passes that contain navigation channels may be 9 to 20 m (30 to 65 ft) deep (Byrnes et al. 2013). In Mississippi, the USACE maintains dredged navigation channels that extend into the Mississippi Sound from Gulfport, Pascagoula/Bayou Casotte, Biloxi, and Bayou La Batre (USACE 2016a).

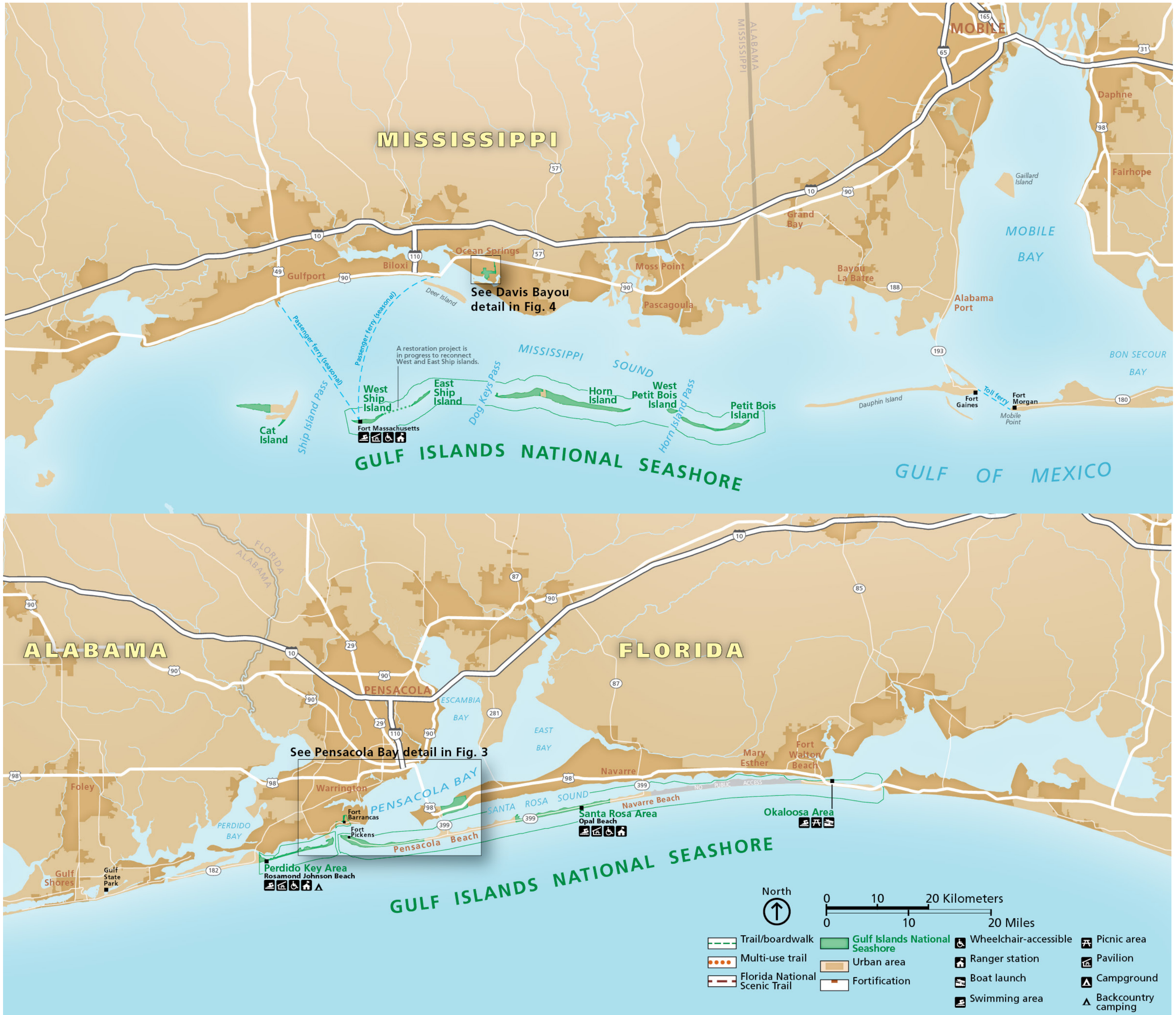

Figure 2. Location map of Gulf Islands National Seashore. The park consists of wilderness and easily accessible areas along the coasts of Mississippi and northwest Florida. The park is more than 160 km (100 mi) long and contains 56,322 ha (139,175 ac); 80% of the park's area is submerged or intertidal. NPS graphic available at the Harpers Ferry Center cartography website.

Figure 3. Location map for Fort Barrancas, Fort Pickens, and Naval Live Oaks.
Most Florida areas are accessible by car and include historic forts and beautiful beaches. NPS graphic available at the Harpers Ferry Center cartography website.

Figure 4. Location map of Davis Bayou area.
Most of the Mississippi units of the park are located on barrier islands accessible only by boat, but the Davis Bayou area is located on the mainland near Ocean Springs, Mississippi; it is accessible by car. NPS graphic available at the Harpers Ferry Center cartography website.

Within the Mississippi Sound, the east-to-west alongshore currents are driven by wind (Cipriani and Stone 2001). The diurnal tides have a mean range of 0.46 m (1.53 ft) at Gulfport Harbor (NOAA 2017). The tides are strongly influenced by local bathymetry, local river discharges, and winds (Jarrell 1981, as cited in USACE 2016a). Offshore bathymetry causes tide-driven circulation to be strong and clockwise in the eastern portion of the Mississippi Sound and weaker and counter-clockwise in the western parts of the sound (Kjerfve and Sneed 1984, as cited in USACE 2016a).

Offshore Petit Bois Island, the seafloor slopes southward at 0.2%; offshore Cat Island, the seafloor slope is gentler and dips at 0.04% to the southeast (Twichell et al. 2011).

Surface elevations of the Mississippi barrier islands are usually less than 2 m (5 ft) above mean sea level (MSL) (fig. 6). Because Mississippi barrier islands are wider than the Florida islands, they have a greater variety of interior habitats that include interior dunes, coastal marshes, interior brackish ponds and creeks, and interior sand flats. The ocean beaches are wider than the sound-side beaches. Most dunes are less than 4 m (13 ft) high, although relict beach ridges on Horn Island reach 8 m (26 ft) (Ervin Otvos, University of Southern Mississippi, professor emeritus, written communication, 26 February 2007, as cited in NPS 2007). Cat Island has high aeolian (wind-formed) dunes, and strand plain (prograded shore built seaward) ridges that run in an east–west direction and rise 0.6 to 2.5 m (2 to 8.2 ft) above sea level (Otvos and Carter 2008).

Nearshore Geomorphology and Geologic Framework

The modern Gulf Islands are shaped by the region's geologic framework and by interactions with relative sea level, sediment supply, meteorological-oceanographic conditions, and human modifications including dredging, sediment diversion, and coastal engineering structures.

The Mississippi–Alabama shelf is slowly subsiding. It is bounded by the Mississippi River Delta to the west and by DeSoto Canyon (fig. 1), which is offshore of the Florida Panhandle, to the east (Sydow and Roberts 1994). The shelf dips southward and extends to about 80 km (50 mi) south of Mobile Bay. It has a very low slope of 0.1% out to a depth of 20 m (65 ft), and then flattens out to a slope of 0.04%. The sand sheet covering most of the shelf is composed of moderately sorted medium-grained sand up to 2 m (7 ft) thick; the sand sheet is thicker where shoals have formed under modern conditions (Flocks et al. 2011a).

Shoals are important nearshore features in terms of sand storage, wave attenuation, and habitat. Both shore-parallel shoals (north and south Perdido shoals), which occur between fluvial channels and represent stillstands (stable shorelines), and nearshore shore-oblique sand ridges, which form during storm conditions in depths of less than 20 m (65 ft), occur offshore of Florida and Alabama (McBride et al. 1999). In Florida, the shoreface along Santa Rosa Island has shore-attached ridges that extend approximately 2 km (1 mi) offshore to a depth of about 15 m (49 ft), in a southeast direction (25° from shore normal); they do not appear to migrate in response to short-term events such as storms (Houser 2012).

Shore-parallel sand ridges, which average 2 m (7 ft) high with lengths as much as 2.6 km (1.6 mi), lie on the mid- and outer shelf area east of Mobile Bay (Parker et al. 1992; Flocks et al. 2011a). These sand ridges have been relatively stable over at least the past century (Flocks et al. 2011b; Twichell et al. 2011) and possibly since sea level rise approached present levels about 6,000 to 4,000 years ago (Flocks et al. 2014). The Perdido shoals are within this ridge field; it contains shoals up to 10 km (6 mi) long with relief up to 5 m (16 ft) (McBride et al. 2004; Flocks et al. 2011a). The Perdido shoals have a base of Pleistocene oxidized clay overlain by a transgressive (the spread of sea over land) sequence consisting of clasts (fragments of preexisting rocks) and shell lag. Over this is a fining-upward sequence of sand and bivalves from flooded estuarine conditions, to increasing marine conditions, to open marine environment (McBride et al 2004). A thin (less than 1-m- [3-ft-] thick) layer of muddy sand lies between the shoals (Flocks et al. 2014).

Hard bottom (exposed rock or other hard surfaces) occurs farther offshore along the mid-shelf, with outcrops up to 1.5 m (4.9 ft) high. The isolated escarpments or fields of rock rubble are composed of fossiliferous sandstone, coquina, and carbonate-cemented sandstones (Schroeder et al 1988, Parker et al 1992). Beyond mid-shelf, pinnacle reefs are found along the shelf break; their formation and location are described in the "Geologic History" chapter.

Along the Mississippi coast, offshore shoals occur adjacent to Ship Island Pass and Petit Bois Pass in water depths of 4 to 20 m (13 to 70 ft) (Twichell et al. 2011). Offshore of Petit Bois Pass, the shore-oblique sand ridges are stable and trend parallel to slightly oblique to the prevailing wave climate (Flocks et al. 2015). The ridges increase in size from east to west. They are composed of poor to moderately sorted, medium-grained shelly sand (Flocks et al. 2011b, 2014, 2015). Shoal systems on the inner shelf contribute to

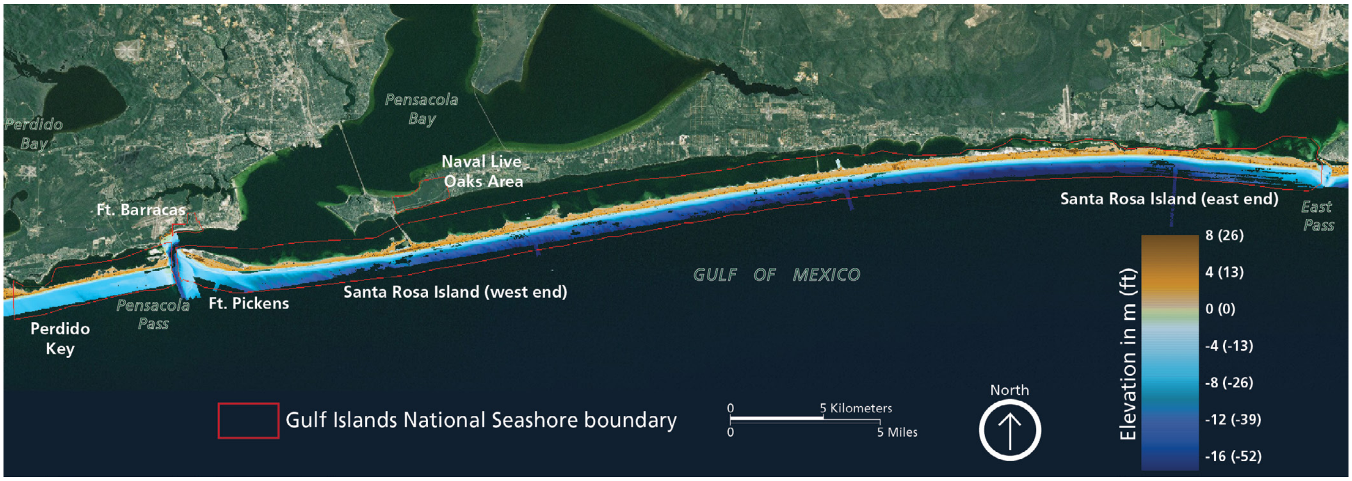

Figure 5. Map of Florida portion of the park.
Along Santa Rosa Island, dunes provide the highest elevations. They are typically 2 m (7 ft) high, although some are more than 6 m (20 ft) high. Foredunes on Perdido Key are generally 4–5 m (12–16 ft) high. The park boundary is delineated in red. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using NOAA data.

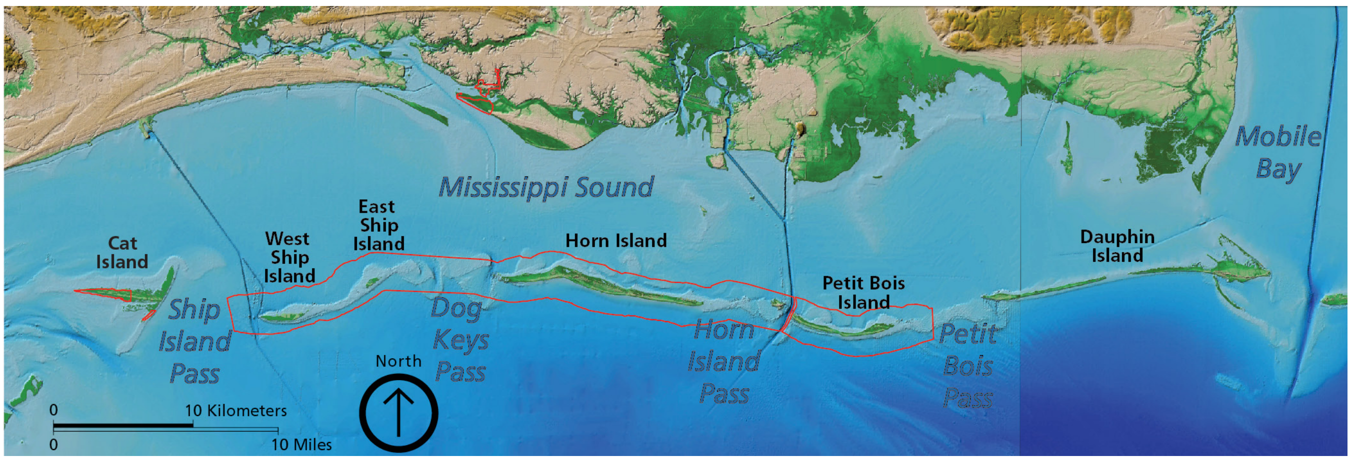

Figure 6. Map of Mississippi portion of the park.
Surface elevations of the Mississippi barrier islands are less than those of the Florida islands (see fig. 5). Elevations on Mississippi islands are generally less than 2 m (5 ft) above mean sea level. Because the Mississippi barrier islands are wider than the Florida islands, they have a greater variety of interior habitats. The park boundary is delineated in red. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using NOAA data.

shoreline protection and habitat, although their depth below normal wave base minimizes their migration and contribution of sand to the littoral sediment transport system (Flocks et al. 2011b).

Ridge and swale bathymetry also exists in the nearshore of Santa Rosa Island in Florida, and likely controls alongshore variation in beach and dune morphology, which in turn controls island response to hurricane impacts and response to sea level rise (Houser 2012). Maritime forests and back-barrier marsh occur along the wider portions of Santa Rosa Island. Sand ridges occur offshore. Seagrass beds occur on the sound side. In contrast, the narrow portions of Santa Rosa Island contain small discontinuous dunes and are susceptible to storm-driven overwash and breaching (Houser 2012). Seaward of the narrow portions, the shoreface has swales (low areas) that produce a steep shoreface and beachface profile, creating a safety hazard for swimmers (Houser 2012).

Alongshore variations in storm surge, erosional hotspots (Schupp et al. 2006; Stockdon et al. 2007), sediment supply (Lentz and Hapke 2011), and island response to extreme storms (Belknap and Kraft 1985; Riggs et al. 1992, 1995, 1996) have also been linked to nearshore bathymetry, which in turn is controlled in part by the geologic framework (McNinch and Luettich 2000; Cooper and Navis 2004; McNinch 2004; Schupp et al. 2006).

Geologic Significance and Connections

The park's cultural resources—including one of the most complete collections of structures relating to the evolution of seacoast defense in the United States—reflect its coastal setting. Publicly accessible sites represent a continuum of development from the Spanish colonization of the 18th century through World War II (NPS 2014). The terrestrial and submerged cultural resources located throughout the park represent a 5,000-year continuum of human use, including archeological and historic sites such as middens and occupation sites, early Spanish settlements, shipwrecks, forts built as part of a US fortification effort to protect all major harbors after the War of 1812, and batteries and artillery from the early 1900s to World War II. The park also encompasses underwater sites such as D'Iberville French Warehouse Site off East Ship Island, Fort McRee, and shipwrecks (NPS 2014). The Naval Live Oaks area of the park on the mainland is also part of this history; the federal government established the tree farm in 1828 for the purpose of supplying shipbuilding materials (NPS 2014). The sites are in a wide range of coastal environments, including elevated mainland areas, eroding bluffs, and exposed low-lying barrier islands (Toscano 2004). These resources are important for enhancing the knowledge of past habitation along the northern Gulf Coast.

Most of the prehistoric archeological sites within the park are Woodland period sites (1000 BCE–1000 CE); middens are characteristically found in the Naval Live Oaks area, but other sites are scattered throughout the park including Davis Bayou and the Santa Rosa area. Several Mississippian period sites (550 CE–1500 CE) also have been tentatively identified in the park, primarily as seasonal and short-term camps. The subsistence strategy during both periods was based on hunting, gathering, and fishing in this coastal area (NPS 2014).

The archeological record along the present-day beaches is minimal. Much of the ancient shoreline available for human use is now submerged, and the sediments along with any archeological resources they contained have likely been reworked by waves, excavated and moved alongshore, and buried by other sediments. Archeological resources are sometimes washed onto the beaches of the park, in which cases they may have been eroded from a number of locations thus their original context cannot always be known. On Cat Island, waves and storm tides erode older beach ridges and spits, exposing buried archeological sites in the swash zone (Wharton et al. 2014).

The higher Pleistocene barrier ridges and terraces that occur on the mainland offered better locations for permanent settlements because of reduced exposure to erosion and storms, as well as proximity to beaches and islands for short-term activities. The elevated ridges along inlets and lagoons also provided small areas for occupation, resulting in accumulations of occupational debris (Wharton et al. 2014).

In addition to erosion of ridges, bluffs, and the coastal shelf, inlet dredging and sea level rise can affect submerged and coastal cultural sites; dredging and sea level rise are discussed in the "Geologic Resource Management Issues" chapter.

Geologic Features and Processes

These features and processes are significant to the park's landscape and history. Refer to Appendix C for URLs.

Most of the geologic features and processes in the park can be classified as "coastal." They occur in a transition zone between terrestrial and submerged environments and, as such, have characteristics of both. Coastal environments may be shaped by waves, tides, wind, and the geologic framework. Coastal change in the Gulf Islands region is a product of geologic and oceanographic factors in combination with human modifications and climate-driven changes.

The NPS manages 88 coastal—including ocean, seashore, and lakeshore—parks with more than 18,000 km (11,200 mi) of shoreline (Curdts 2011). Of that total, 370 km (230 mi) are within Gulf Islands National Seashore (Curdts 2011). In addition, more than 120 parks are close to a coast and vulnerable to sea level rise, lower lake levels, salt water intrusion, and inundation during coastal storms, even though some do not manage a shoreline (Beavers et al. 2016a). The NPS Geologic Resources Division Coastal Geology website provides additional information. The "Geologic Resource Management Issues" chapter of this report discusses topics associated with coastal resource management.

The following significant features and processes were identified during the 2006 scoping meeting (summarized in NPS 2007), the 2016 conference call (Appendix A provides a list of participants), and during research and writing of this GRI report. The geomorphic features in the GRI GIS data are highlighted first. These features, which are represented by 19 map units, are listed in table 2.

- Geomorphic Map Units
- Oceanographic Conditions
- Sediment Transport Processes
- Overwash and Island Migration
- Inlets
- Wetlands
- Seagrass
- Groundwater
- Estuarine Sediments
- Nearshore Substrate and Benthic Habitat
- Paleontological Resources

Geomorphic Map Units

This report is supported by two GRI GIS data sets (gifl_geology.mxd and gims_geology.mxd), which cover the Florida and Mississippi portions of the park (excluding the mainland). In addition, four component maps—Cat Island (cati_geology.mxd), Horn Island (hrni_geology.mxd), Petit Bois Island (pebo_geology.mxd), and Ship Island (ship_geology.mxd)—were derived from gims_geology.mxd. Two posters (in pocket) illustrate these data and include the locations of 19 geomorphic map units (table 2). Mapping for Sand Island is not part of the GRI GIS data, but figure 7 illustrates ecological habitats and geomorphic features of that island. General information about geologic maps and the source maps for the GRI GIS data is provided in the "Geologic Map Data" chapter.

Oceanographic Conditions

The park's islands are wave-dominated and microtidal (less than 2 m [7 ft]). The mean tide is 0.38 m (1.2 ft) along Perdido Key (Browder and Dean 2000) and 0.5 m (1.6 ft) in Mississippi (Twichell et al. 2013). Within the park, mean significant wave height is 0.6 m (2 ft) along the Florida units (Pendleton et al. 2004) and 0.8 m (3 ft) along the Mississippi islands (Hubertz and Brooks 1992), where waves approach from the southeast at a mean angle of 139°.

Because of the large water volume in the Mississippi Sound, tidal currents in passes to the Gulf of Mexico are strong, ranging from 0.5 to 1.0 m (1 to 3 ft) per second and 1.8 to 3.5 m (5.9 to 11 ft) per second on flood and ebb tides, respectively (Foxworth et al. 1962, as cited in Byrnes et al. 2013). The mean tidal range along Perdido Key is 0.38 m (1.2 ft) (Foster et al. 1999).

Loop Current

The Loop Current and the Mississippi River outflow influence circulation in the Gulf of Mexico. The Loop Current is a warm current that flows northward into the Gulf of Mexico through the Yucatan Channel (strait between Mexico and Cuba), and then turns eastward before exiting the Gulf of Mexico through the Florida Straits and joining the Gulf Stream, a warm and fast ocean current. This current produces numerous eddies, meanders, and inclusions (NPS 2014). West of the Loop Current, the central shelf of the Gulf of Mexico is influenced by outflow of the Mississippi River.

Table 2. GRI GIS geomorphic map units.

Descriptions in this table reflect input from GRI reviewers and may vary from the descriptions provided in guis_geology.pdf.

*Locations are based on the GRI GIS data and reflect conditions during mapping in 2007.

Geomorphic Feature	Map Unit Symbol	Description	Park Location*	Figure
Active Dune Complex	dn_cplx_a	Barren to sparsely vegetated mounds or ridges of windblown sand that form hummocky topography landward of the beach.	Cat Island West Ship Island Horn Island Petit Bois Island Santa Rosa Island Perdido Key	8
Stable/ Stabilized Dune Complex	dn_cplx_s	Mounds or ridges of windblown sand that are typically densely vegetated with salt-tolerant grasses. The vegetated dunes form hummocky topography landward of the beach. The sand in these dunes is protected by vegetation and is not moving.	Cat Island West Ship Island Horn Island Santa Rosa Island Perdido Key	9, 13
Active Overwash Zone	ovrwsh_ zn_a	Land frequently flooded by high water and ocean waves generated by storms. Typically low lying with sparse vegetation. Composed of sand with patches of shell at the surface.	Cat Island East and West Ship Islands Horn Island Petit Bois Island	10
Inactive Overwash Zone	ovrwsh_ zn_i	Historically overwashed and flooded by storm surge, such as during Hurricane Katrina in 2005. These areas are not frequently flooded by high water or ocean waves but are still vulnerable to flooding from extreme storms. The former washover sand is commonly reworked into low, hummocky dunes that may be densely vegetated with salt-tolerant grasses	Cat Island East and West Ship Islands Horn Island Petit Bois Island Santa Rosa Island Perdido Key	9
Beach	beach	Mostly unvegetated strip of sand parallel to the shore that extends from the water to the seaward edge of the dunes or crest of a washover terrace. The seaward part of the beach is regularly inundated by wave run-up during high-water phases of the tidal cycle.	Cat Island East and West Ship Islands Horn Island Petit Bois Island Santa Rosa Island Perdido Key	9, 10
Beach Ridge Complex	bch_rdg_ cplx	Sets of long, continuous ridges formed parallel to the ocean shore by sand that is deposited by a combination of wave run-up and the wind. The unit is typically vegetated with salt-tolerant grasses.	Cat Island East and West Ship Islands Horn Island Petit Bois Island	14
Beach Ridge Swale	bch_rdg_ swl	Topographic depressions within the beach ridge complex **(bch_rdg_cplx)**. It may be dry or intermittently wet (with pond freshwater after heavy rain).	Cat Island West Ship Island Horn Island Petit Bois Island	14
Marsh	marsh	Low vegetated wetlands that support plant assemblages tolerant of saltwater. It is typically found along the sides of barrier islands protected from ocean waves or along the margins of tidal creeks.	Cat Island Horn Island Petit Bois Island Santa Rosa Island Perdido Key	8, 14
Shoal	shoal	Prominent subtidal platforms surrounding the upland core of a barrier island. Composed of mobile sand. Typically covered with large bed forms constructed by ocean waves and currents.	East and West Ship Islands	10

Table 2 (continued). GRI GIS geomorphic map units.

Geomorphic Feature	Map Unit Symbol	Description	Park Location*	Figure
Spit	spit	Narrow, mostly unvegetated strip of sand at the end of a barrier island that extends the island alongshore. Spits form because of recent deposition by waves and currents.	Cat Island East and West Ship Islands Horn Island Petit Bois Island	14
Vegetated Barrier Flats	veg_brr_flt	Low, relatively flat interior part of the barrier island that is densely vegetated in some places and sparsely vegetated in other places, both by salt-tolerant grasses and by fresh and brackish species. May be referred to as a marsh.	Horn Island Petit Bois Island	8
Vegetated Barrier Core	veg_brr_cr	Low, stable interior part of the barrier island that is sparsely to densely vegetated by plants, including trees, that have adapted to fresher groundwater settings, as well as drought-tolerant vegetation such as cacti that have adapted to the high drainage rates of the sand substrate.	Santa Rosa Island Perdido Key	11
Interior Wetland	intr_wtlnd	Nontidal inundated barrier island swales that support plant assemblages tolerant of brackish water and freshwater, including some shrubs and trees. May be referred to as marsh.	Santa Rosa Island Perdido Key	11, 13
Modified Land	mdfd_lnd	Areas where the land surface has been significantly altered for residential and commercial development, including paved roads, parking lots, and infrastructure.	Santa Rosa Island Perdido Key	11
Structures	structure	Miscellaneous manmade features, including buildings, docking piers, roads, and walkways, and shoreline-protection structures such as groins and bulkheads.	Cat Island West Ship Island Horn Island Santa Rosa Island Perdido Key	12
Structure Zone	strctr_zn	Areas of closely spaced manmade features along the shore, including piers, walkways, boat docks and shoreline protection structures, such as riprap, groins, and bulkheads.	Santa Rosa Island	none
Reclaimed Land	rclmd_lnd	Former land areas that were eroded and rebuilt by emplacement of dredged material.	West Ship Island	12
Dredge Material	drdg_mtrl	Land areas formed by the disposal of sediment that was dredged from adjacent navigation channels and commonly placed along the margins of the channels.	Cat Island Santa Rosa Island Perdido Key	12
Artificial Dune	artfcl_dn	Low linear ridge of sand constructed in the back beach parallel to the shore to reduce overwash of the barrier island. Includes planted vegetation and other means designed to trap windblown sand. Commonly associated with residential and commercial development.	Santa Rosa Island	9

Sediment Transport Processes

Prevailing southeast winds and resulting longshore currents cause the islands to migrate westward. The mature medium sands in the barrier islands originated in the Appalachian Mountains and were carried downstream to form shore bluffs as well as other fluvial, deltaic, estuarine, and marine features before being recycled into barrier island sediments (Otvos and Carter 2013). Interruptions to natural sediment transport, and the resulting impacts on island dynamics, are described in several sections of the "Geologic Resource Management Issues" chapter.

Wave Transport

Winds drive the net east-to-west sand transport along the islands (fig. 15). Wave energy re-suspends sediment and promotes alongshore transport. Storms can move major volumes of sediment when winds and associated waves and currents are forceful enough to cause both longshore transport and sand movements through the passes between the islands (Byrnes et al. 2010).

Cross-shore sediment transport determines the magnitude and direction of net transport. When waves are breaking, sediment tends to be transported offshore; during calm conditions with non-breaking waves, transport is assumed to be onshore (Aagaard et al. 2002).

Aeolian (Wind) Transport and Dune Building

Wind transports sand both offshore and onshore, forming sand sheets and dunes. Aeolian transport can be relatively high along the Gulf Islands because the beaches are dissipative, that is, they have a wide gently sloping beach and a wide surf zone with nearshore bars, little air flow disturbance, and the greatest potential for large foredunes (Short and Hesp 1982).

Sea oats and other dune plants equipped with elaborate stem and root systems play a vital role in holding sand in place. Growth of dune vegetation is, in turn, controlled by wave action and soil salinity. The height of the foredune line ("primary dunes") is controlled chiefly by grain size and wind velocity. Primary dunes serve as the first line of defense from storms (Falls 2001). The seaward dune position depends upon the frequency of storms, which erode the dune face, and the rate at which these scarps can heal by wind transport and vegetation growth (Leatherman 1988). On eroding shorelines, dune-system survival depends on the relative rates of dune migration and shoreline retreat.

A study on Santa Rosa Island found that alongshore variation in beach and dune form is controlled by nearshore bathymetry; the transverse bars control the aeolian transport potential and available sediment supply to the dunes (Houser and Hamilton 2009).

Dune development is controlled by many factors including wind that moves sediment between the beach and back-shore, tidal range, sediment type and availability, the beach and nearshore morphodynamics, storm waves and surge that cause erosion and overwash, and vegetation to capture the sediment (Houser and Ellis 2013, and references therein). At wider sections of Santa Rosa Island, longitudinal dunes align with the dominant summer winds and offer protection from wind and salt spray (NPS 2007).

Determining the age of the dunes would allow investigators to identify when the dunes moved from the Gulf of Mexico side to their present position and what events or climatological activity affected them, which would in turn provide insight on what might trigger their movement in the future. Staff at the park or Gulf Coast Network may want to develop a monitoring plan for those dunes (Chris Houser, Texas A&M University, geology professor, conference call, 16 May 2016).

Sediment Sources and Movement along the Mississippi Barrier Islands

The nearshore seafloor along the Mississippi barrier islands is covered by sand down to 24 m (79 ft) water depth (McBride and Byrnes 1995). The primary sources of sediment to the Mississippi barrier islands are exposed Pleistocene shore ridges and mainland beaches of northwest Florida and southeast Alabama (Otvos and Giardino 2004; Stone et al. 2004). Local sources are eastern Dauphin Island and the Mobile Pass ebb-tidal delta (Otvos and Giardino 2004). The ebb-tidal delta off the mouth of Mobile Bay is composed primarily of sediments derived from beach and nearshore sources east of Mobile Pass (Byrnes et al. 2010) as well as sediment carried from Mobile Bay toward the Gulf of Mexico by ebb tides and swept in from the Gulf by heavier wave action (Otvos 1981a). Some of the Mississippi island sediments are from the inner continental shelf, where they were previously deposited by rivers during the Pleistocene glacial stages (Otvos 1970; Rucker and Snowden 1988). The "Geologic History" chapter describes the evolution of the barrier islands during the Pleistocene Epoch. In marshes, for example at Davis Bayou, soils continue to form as grassy vegetation and wetland plant material accumulates and slowly decomposes (NPS 2014).

The Mississippi beaches include more clay than the Florida beaches because the comparatively long, far-reaching drainage of the Pearl River transports clay-rich waters (Hatt et al. 2016). Additionally, some of the fine-grained suspended sediment from the Mississippi River outflow is carried along the Mississippi–Alabama shelf. Reflecting their sources, the Mississippi islands' foreshore and nearshore deposits are well- to very well–sorted, fine- and medium-grained sand, with diameters between 0.25 and 0.49 mm (0.01 and 0.02 in) (Otvos 1973a). Sediment on the Ship Islands is coarsest (0.45 mm [0.018 in]) on the sound side and finest (0.22 mm [0.009 in]) in the ocean surf zone. On East Ship and West Ship Islands, the beach face is composed of coarse sand (Cipriani and Stone 2001), beach ridges are composed of medium- to fine-grained sand, and the shelf deposit is topped by mud (Twichell et al. 2011). Sand Island, which was initially built with dredged sediments, is composed mostly of quartz sand mixed with calcareous (containing calcium carbonate) shell fragments (Anderson et al. 2016b). The sand is poorly graded, fine- to medium-grained quartz with less than 5% fine sediments (Otvos and Carter 2008). The modern ebb-tidal deltas between the Mississippi barrier islands have a median grain size range of 0.16–0.23 mm (0.006–0.009 in) and are estimated to be composed of 94%–99% sand (Twichell et al. 2011).

Along Cat Island beaches, littoral transport diverges just north of the primary beach ridge complex (Byrnes et al. 2012), moving sand from the eastern end of the ridges to each of the two spits at the north and south ends of Cat Island (Rucker and Snowden 1988, as cited in Byrnes et al. 2012). An external source of sand to Cat Island beaches is not apparent (Byrnes et al. 2013).

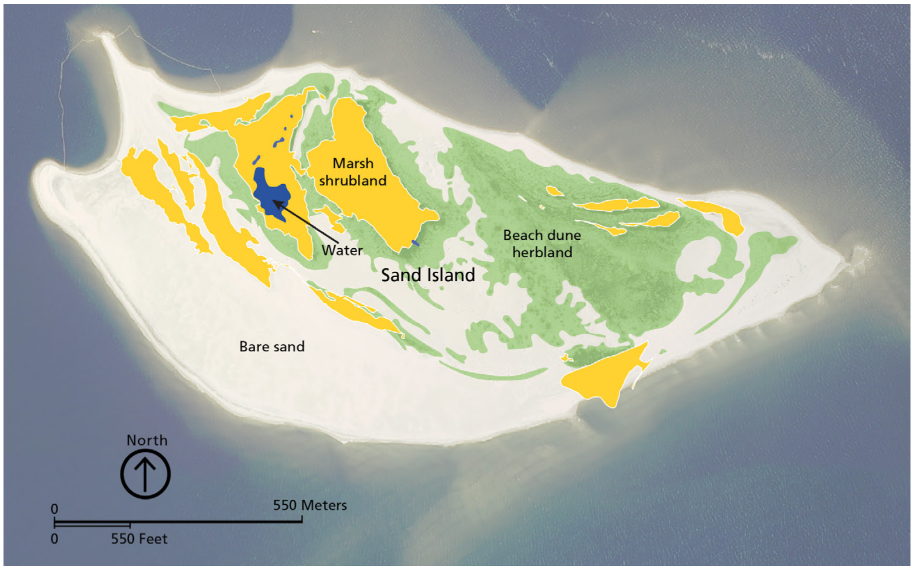

Figure 7. Geomorphic/habitat map of Sand Island.
The map illustrates ecological habitats and geomorphic features of Sand Island (also known as "West Petit Bois Island"), which is part of the USACE Disposal Area 10 (DA-10). Interior wetlands are present on the island. The island has areas of marsh shrubland (yellow), beach dune herbland (green), water (blue), and bare sand (white). Mapping of Sand Island is not included in the GRI GIS data. Graphic by Trista Thornberry-Ehrlich (Colorado State University) based on Anderson et al. (2016a, figure 2) and NPS data from May 2013 courtesy of Jolene Williams (Gulf Islands National Seashore).

Figure 8. Photograph of an active dune complex.
Active Dune Complex (dn_cplx_a) was mapped on the sound side of Horn Island. It is backed by the geomorphic map unit, Vegetated Barrier Flat (veg_brr_flt), which hosts salt-tolerant grasses and other fresh and brackish species. The vegetated barrier flat shown in the photograph is densely vegetated, though some are sparsely vegetated. In the GRI GIS data, Vegetated Barrier Flat (veg_brr_flt) is distinguished from a Marsh (marsh) by its location at the interior of a barrier island. The geomorphic map unit for a marsh was mapped as occurring along the sides of barrier islands that are protected from ocean waves or along the margins of tidal creeks. NPS photograph by Courtney Schupp taken 15 July 2015.

Figure 9. Photograph showing stabilization project on West Ship Island.
As part of the stabilization of Fort Massachusetts on West Ship Island, the beach was renourished and dune grasses were planted. The following geomorphic map units are visible in the photograph: Stable Dune Complex (dn_cplx_s), Artificial Dune (artfcl_dn) (constructed and planted with rows of grasses), Inactive Overwash Zone (ovrwsh_zn_i), and Beach (beach). The photograph is taken looking eastward with the Gulf of Mexico visible on the right. NPS photograph by Courtney Schupp taken on 22 July 2015.

Figure 10. Photograph of Petit Bois Island.
The east end of Petit Bois Island (Mississippi) was mapped as an Active Overwash Zone (ovrwsh_zn_a map unit) with Beach (beach) and Shoal (shoal) geomorphic units visible in the distance (looking eastward). NPS photograph by Courtney Schupp taken on 21 July 2015.

Figure 11. Photograph of roadside in the Fort Pickens area.
Fort Pickens is at the western end of Santa Rosa Island. An Interior Wetland (intr_wtlnd) within a Vegetated Barrier Core (veg_brr_cr) was mapped adjacent to a road, which is Modified Land (mdfd_lnd). NPS photograph by Courtney Schupp taken on 26 December 2016.

Figure 12. Photograph of Fort Massachusetts.
Fort Massachusetts and the dock on the Mississippi Sound side of West Ship Island are part of the Structure (structure) geomorphic map unit. The fort is fronted by Reclaimed Land (rclmd_lnd) and Dredge Material (drdg_mtrl). Photograph is taken looking southward. NPS photograph by Courtney Schupp taken on 22 July 2015.

Figure 13. Photographs of Sand Island.
Sand Island (also known as "Western Petit Bois Island") was created with dredge spoils but now functions as a barrier island complete with vegetated dunes. Sand Island was not mapped as part of the GRI project. It is managed by the National Park Service and is an important part of the regional sediment dynamics. Figure 7 is a geomorphic/habitat map of Sand Island based on mapping by Anderson et al. (2016a). Top: NPS photograph from Ford (2013). Bottom: NPS photograph by Courtney Schupp taken 21 July 2015.

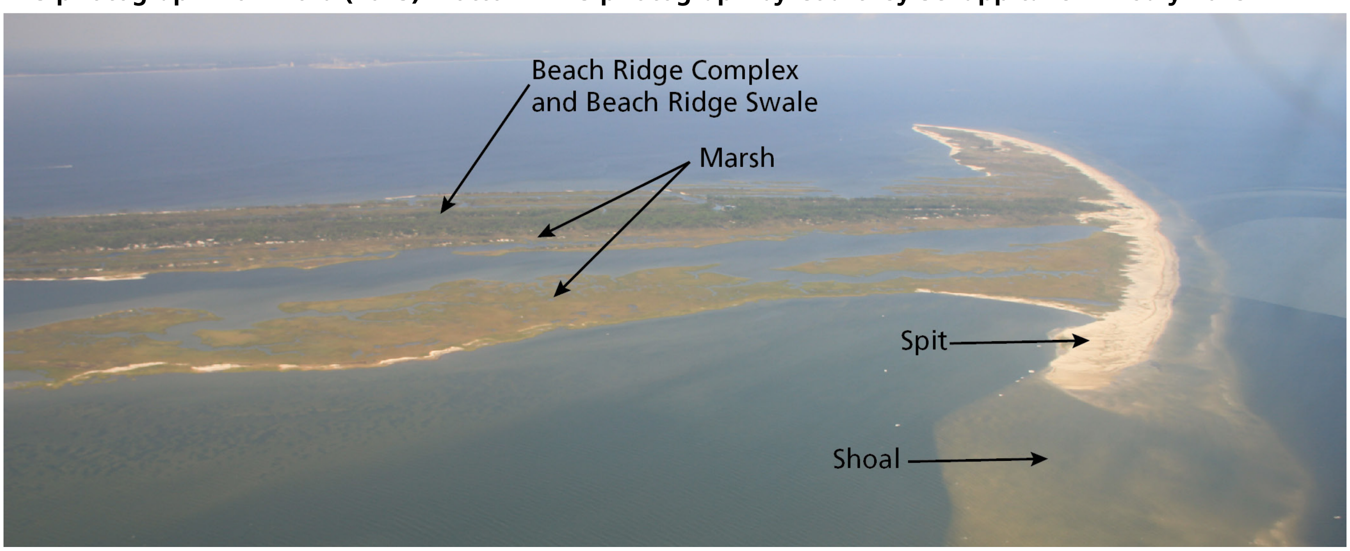

Figure 14. Aerial photograph of Cat Island.
This photograph was taken on 2 September 2012, following Hurricane Isaac. The east–west-trending portion of the island includes the following map units: Beach Ridge Complex (bch_rdg_cplx), Beach Ridge Swale (bch_rdg_swl), and Marsh (marsh). Intertidal marsh buries the subsided, youngest Holocene beach ridge plain in the southern part of the island. The southeastern peninsula is a Spit (spit) that is reworked by storms. Shoals are visible at the southern end of the spit. The northeastern peninsula, visible in the top half of the photograph, is covered by secondary dunes and aeolian sand sheets. North is toward the top of the photograph. USGS online publications directory.

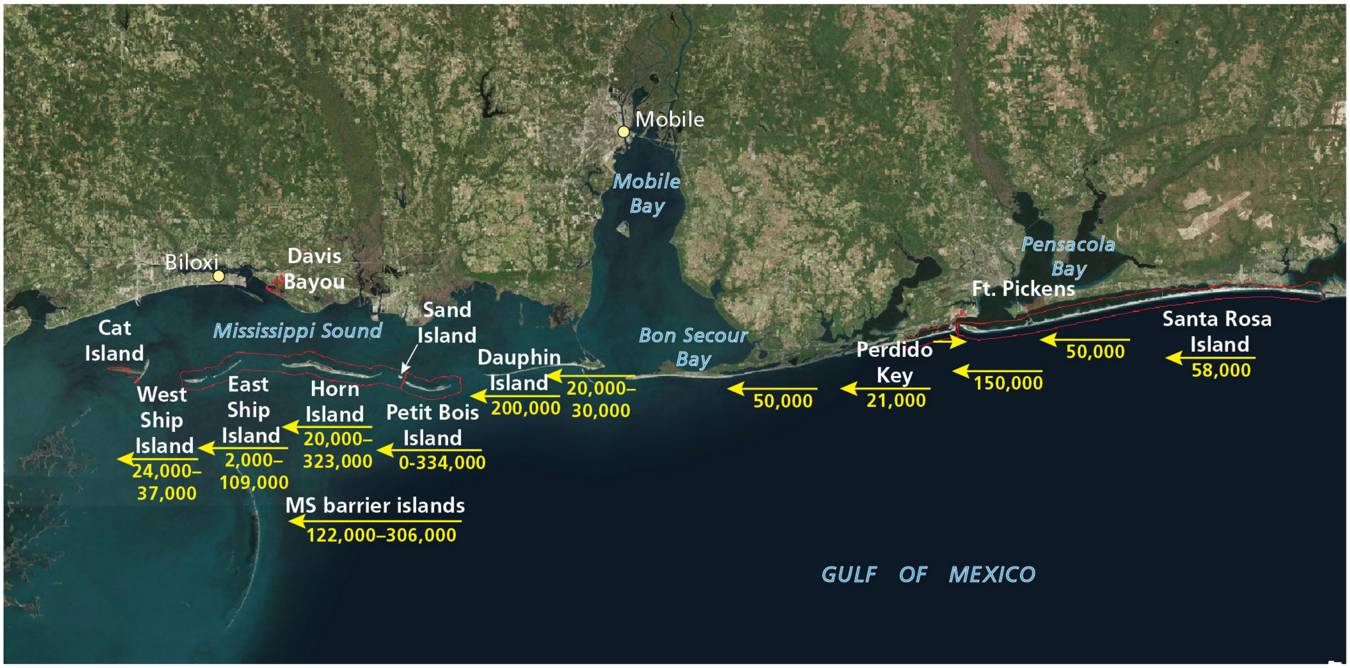

Figure 15. Graphic showing sediment transport along the park's barrier islands.
Net transport of sediment along the park's barrier islands is east to west. The graphic shows the range of annual sediment transport rates in cubic meters (m^3) per year. A small, unquantified westward transport cell occurs at the eastern end of Perdido Key. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using estimates from Hardin et al. (1976), Stone et al. (1992), Shabica et al. (1993), Douglass (1994), Stone and Stapor (1996), Cipriani and Stone (2001), Rosati et al. (2007), USACE (2009), Byrnes et al. (2012), Morang et al. (2012), Byrnes et al. (2013) as listed in Table 3 of this report.

within a narrow zone 9 to 11 m (30 to 36 ft) deep in the Gulf of Mexico and 3 to 5 m (10 to 16 ft) deep in the Mississippi Sound (Byrnes et al. 2013). Estimates of the net westward annual transport rate (fig. 15, table 3) vary widely but may be as high as 306,000 m3 (400,000 yd3) per year (Byrnes et al. 2013). The beach and nearshore areas along the eastern ends of the islands are erosional and serve as sediment sources; the western ends of the islands serve as sediment sinks where sand is deposited as elongated sand spits and ebb shoals in the adjacent passes (Byrnes et al. 2013). Sand Island also contributes some sand to the westward littoral drift, mitigating the loss of sediment through the Intracoastal Waterway from the ebb-tidal delta to offshore areas (Otvos and Carter 2008).

Transport rates decrease toward the western end of the system (fig. 15, table 3) (USACE 2016a). This has caused Petit Bois, Horn, and Ship Islands to migrate westward at rates of 25.7, 28.7, and 8.5 m (84.3, 94.2, and 28 ft) per year, respectively, for the period 1847–2010 (figs. 16, 17, 18, and 19) (Byrnes et al. 2012). Some sediment moves in the reverse direction at the eastern ends of the islands but the impact on net sediment transport is localized and minor (Byrnes et al. 2013). Some cross-shore sediment transport also occurs on the beaches of eastern Petit Bois and Ship Islands (Byrnes et al. 2013). Offshore of Alabama, a portion of the fine-grained sediment fraction travels seaward from Mobile Bay to the large Mobile ebb-tidal delta, and from there to the Mississippi barrier islands to the west. The silt and clay content does not settle on the high-energy beaches (Byrnes et al. 2010).

Sediment Sources and Movement along the Florida Barrier Islands

The continental shelf off west Florida has little sediment input, compared to the Mississippi islands, and is primarily composed of quartz sands in the nearshore. The rivers that drain into Pensacola Bay transport sand-rich sediment from upstream areas, which during higher sea levels were coastal areas. Because not much clay is mixed with the quartz content, the sand on the Florida islands is whiter than on other Gulf beaches. Santa Rosa Island, for example, is composed of approximately 99% medium-grained quartz sand. Island and shoreline ridge deposits were deposited by wind and are made of marine sand. Because Mississippi River clays rarely travel as far as Florida, Florida waters have greater water clarity (NPS 2014). Surficial sediment along Perdido Key also consists primarily of medium-grain quartz sand of 0.2 to 0.4 mm (0.008 to 0.02 in), but with small amounts of organic matter (Sankar 2015).

Table 3. Estimates of alongshore sediment transport rates.

GRI reviewers noted that estimates by Byrnes et al. (2013) are significantly larger than other sources. Future research is needed to explain this difference.

Location	Transport rate (m3/yr)	Transport rate (yd3/yr)	Data Sources
Santa Rosa Island (Santa Rosa area)	58,000	76,000	Stone and Stapor (1996)
Santa Rosa Island (Fort Pickens area)	50,000	65,000	Stone and Stapor (1996)
Pensacola Bay entrance	150,000	196,000	Stone et al. (1992); Stone and Stapor (1996)
Perdido Key	21,000	27,000	Stone and Stapor (1996)
Gulf Beach, Florida	50,000	65,000	Hardin et al. (1976)
Dauphin Island	200,000	262,000	Douglass (1994)
Dauphin Island (western end)	30,600	40,000	Deltares (2013)
Dauphin Island (eastern end)	7,600	10,000	Deltares (2013)
Dauphin Island (eastern end)	20,000–30,000	26,000–39,000	Douglass (1994)
Mississippi barrier islands	122,000	160,000	Shabica et al. (1993)
Mississippi barrier islands	306,000	400,000	Byrnes et al. (2013)
Petit Bois Island	0–60,000	0–78,000	Cipriani and Stone (2001)
Petit Bois Island (eastern end)	7,600	10,000	Deltares (2013)
Petit Bois Island (western end)	57,000	75,000	Deltares (2013)
Petit Bois Island	20,000–60,000	26,000–78,000	Morang et al. (2012)
Petit Bois Island	226,000	296,000	Rosati et al. (2007); USACE (2009)
Petit Bois Island	334,000	437,000	Byrnes et al. (2013)
Horn Island (eastern and western ends)	15,000	20,000	Deltares (2013)
Horn Island	20,000–60,000	26,000–78,000	Morang et al. (2012)
Horn Island	24,000–65,000	31,000–85,000	Cipriani and Stone (2001)
Horn Island (central portion)	76,000	100,000	Deltares (2013)
Horn Island	313,000–323,000	409,000–423,000	Byrnes et al. (2013)
Ship Islands	<40,000	<52,000	Morang et al. (2012)
East Ship Island	2,000–13,000	2,600–17,000	Cipriani and Stone (2001)
East Ship Island	38,000	50,000	Deltares (2013)
East Ship Island	109,000	143,000	Byrnes et al. (2013)
West Ship Island	24,000–37,000	31,000–48,000	Cipriani and Stone (2001)
West Ship Island	38,000	50,000	Deltares (2013)

The park's Florida barrier islands have three discrete sediment transport cells: Perdido Key, western Santa Rosa Island, and eastern Santa Rosa Island (fig. 15, table 3) (Stone et al. 1992).

The Perdido Key area of the park annually receives about 58,000 m3 (76,000 yd3) of sediment that is reworked from the inner shelf and transported directly onshore, resulting in a sediment surplus of about 37,000 m3 (48,000 yd3) per year (Stone and Stapor 1996). That sediment is delivered to the eastern few kilometers of Perdido Key via net easterly transport, and to the area extending from eastern Perdido Key to Perdido Pass via net westward transport (Stone et al. 1992). Along the eastern half of Perdido Key, 130,000 m3 (170,000 yd3) per year of sediment has been overwashed across the barrier or transported eastward toward Pensacola Pass, and does not appear to be lost offshore (Stone and Stapor 1996). About 21,000 m3 (27,000 yd3) of sediment is transported westward toward Perdido Pass, where it is deposited (Stone and Stapor 1996). The historical sediment surplus is evidenced by accretion along Perdido Key, but the truncation of the seaward ends of the beach ridges indicates that shelf sediment

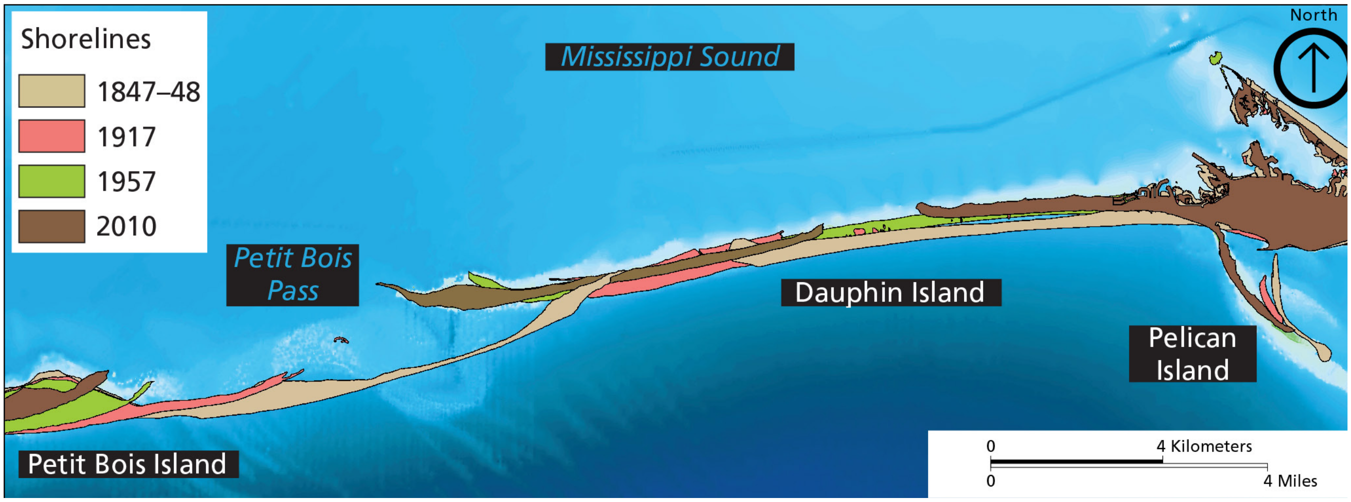

Figure 16. Map showing movement of eastern Petit Bois Island, 1847–2010.
Figure modified from Byrnes et al. (2013, figure 6). Reprinted with permission from Mark Byrnes (Applied Coastal, Inc.).

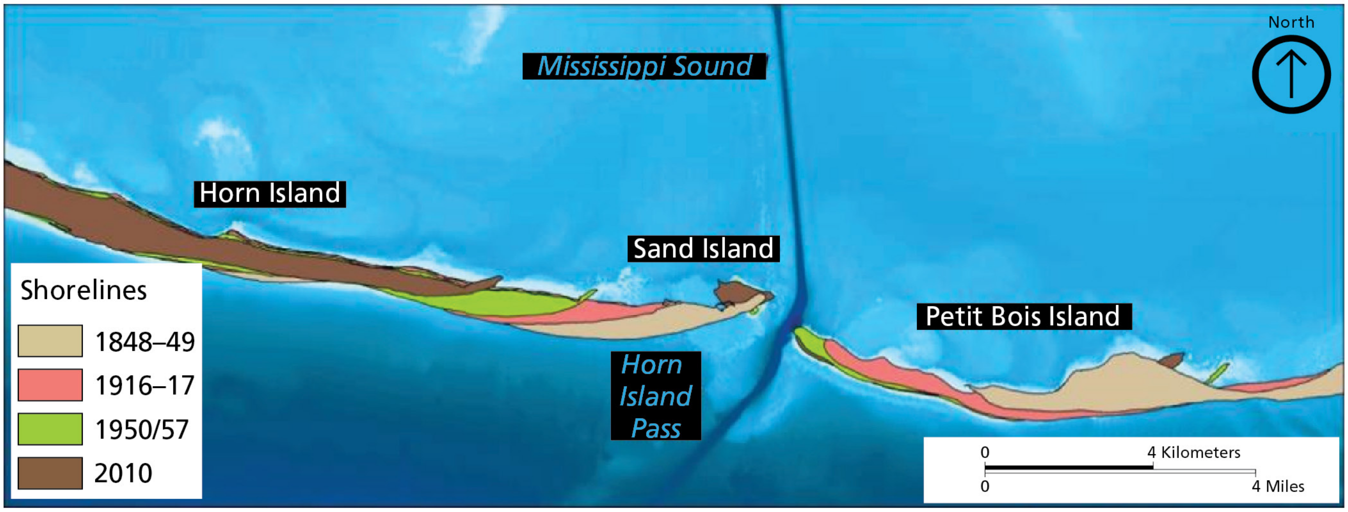

Figure 17. Map showing movement of western Petit Bois and eastern Horn Islands, 1848–2010.
Figure modified from Byrnes et al. (2013, figure 7). Reprinted with permission from Mark Byrnes (Applied Coastal, Inc.).

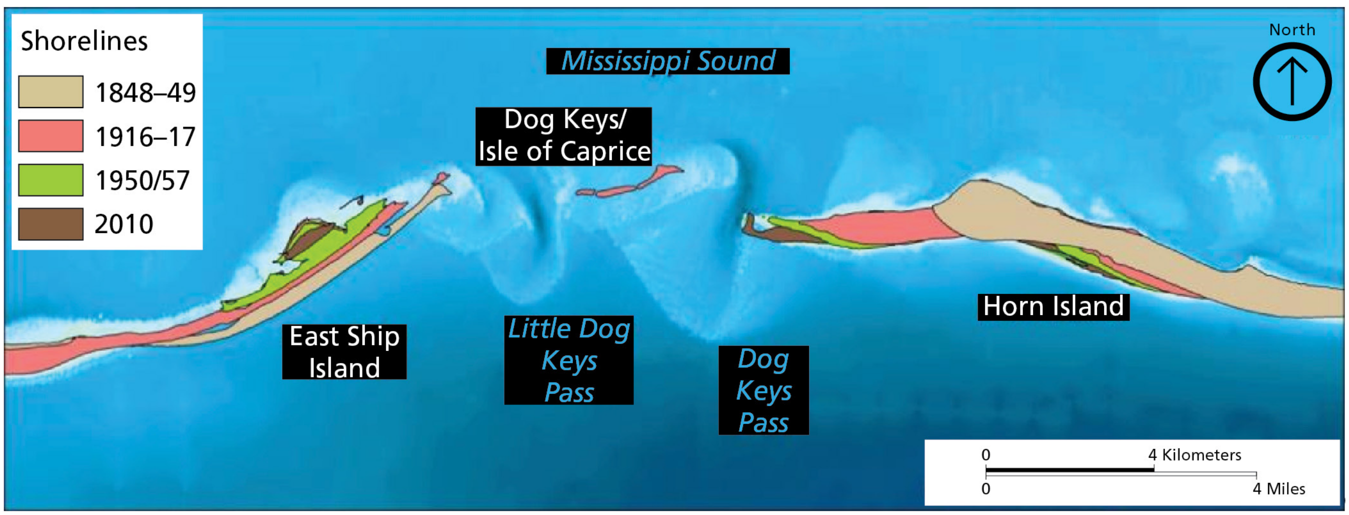

Figure 18. Map showing movement of western Horn and East Ship Islands, 1848–2010.
Figure modified from Byrnes et al. (2013, figure 8). Reprinted with permission from Mark Byrnes (Applied Coastal, Inc.).

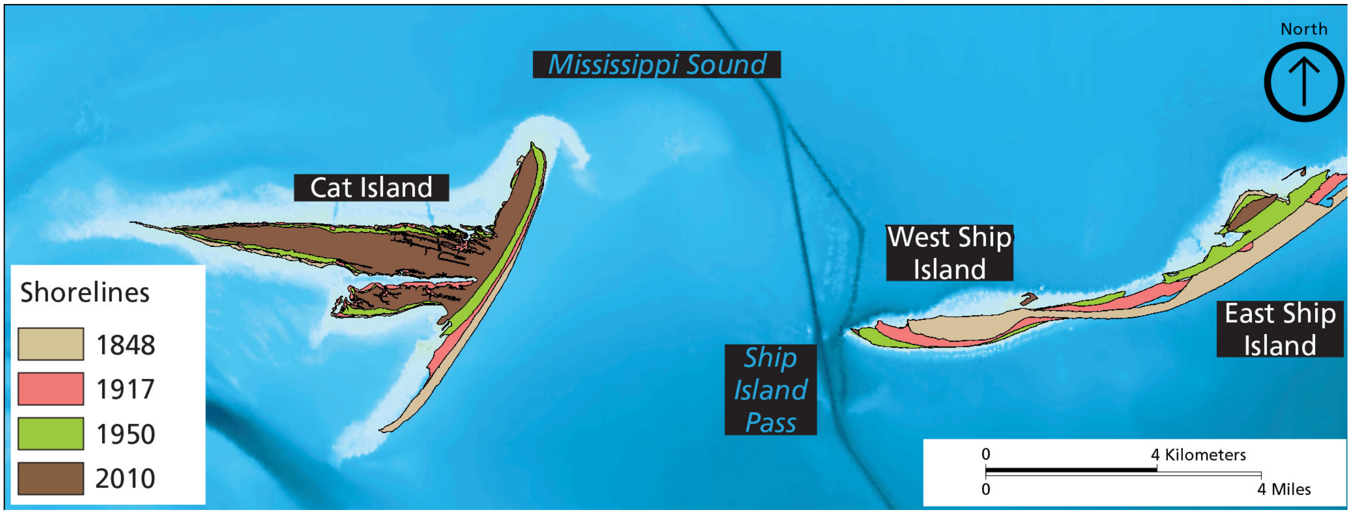

Figure 19. Map showing movement of West Ship and Cat Islands, 1848–2010.
Figure modified from Byrnes et al. (2013, figure 9). Reprinted with permission from Mark Byrnes (Applied Coastal, Inc.).

is being depleted. This trend is equally apparent along the remainder of the coast westward toward Mobile Bay (Stone and Stapor 1996).

The sediment along Pensacola Beach on Santa Rosa Island tends to remain between Pensacola Beach and Pensacola Pass. Apparently, very little sediment naturally bypasses the pass in either direction (Browder and Dean 1999). Pensacola Pass is a net sediment sink, receiving sediment from Pensacola Beach to the east and from Perdido Key to the west (fig. 15, table 3) (Stone et al. 1992).

The eastern half of Santa Rosa Island, including the Santa Rosa and Okaloosa areas of the park, receives sediment from the Pleistocene barrier island complex along Grayton–Mirimar Beach (east of Destin, Florida; see fig. 1) via net westward transport that decreases in magnitude in a downdrift (westward) direction (Stone and Stapor 1996).

Inter-Island Connectivity

Subaqueous and intertidal barrier platforms, in combination with tidal deltas, are critical components of the alongshore sand transport system that moves sediment from island to island. The shoals (submerged ridges, banks, or bars of sand) act as stepping stones in inlet bypassing. These features are important components of the littoral sediment transport system. The connectivity is easily interrupted by deepening navigation channels, which act to flush sand away from the littoral zone and into deeper bottom areas, and by the permanent disposal of dredge spoil in deeper Gulf of Mexico waters. Subaqueous sand resources are also critical to post-storm regeneration of islands (Otvos and Carter 2008). Dredging of the Caucus Shoal, located in 6–8 m (20–26 ft) of water off the eastern end of Perdido Key, along with other shoals associated with Pensacola Pass, has reduced the volume of sediment stored there (Browder and Dean 2000).

Overwash and Island Migration

Overwash is an important process in building island elevation, expanding marsh platforms, and creating and maintaining early succession habitat. The term “washover” refers to the resulting sedimentary deposit created by the overwash process. When storm surges produce waves that overtop the island berm and erode the dune ridge, or that flow through low areas of the dune ridge, sediment is moved from the seaward side landward, and deposited in small washover fans in the interior of the barrier island (fig. 20). By moving sediment on top of and across a barrier island, these processes build island elevation and width, although overwash surging through dune ridges will erode and undermine the base of the dunes (Leatherman 1988). On islands without fixed features such as forested berms or houses, broad washover ramps may form; the ramps gradually diminish toward back-barrier and estuarine habitats (Houser et al. 2015c). The transported sediment across a barrier island maintains narrow marshes that would disappear without this sediment input (Walters et al. 2014). Overwash events also push sediment into low-lying interior areas that do not receive sand during less intense storms or via aeolian processes (Lucas and Carter 2013). Strong frontal winds can also cause small overwash events that deposit sediment in fans behind the berm and in the swale (Chris Houser, University of West Florida, professor, personal communication, cited in National Park Service 2007).

When a major storm erodes the shoreface sand, flattens island topography, and buries vegetation across the island, a low and wide island area results (Houser et al. 2015c). The topographic changes caused by overwash controls the locations of post-storm habitats and revegetation (Riggs and Ames 2007). The resiliency of a barrier island depends on the ability of the dune to recover in height and extent following overwash events.

The extent of overwash depends on the duration of the storm and on the elevation of the storm surge relative to the dune elevation (Moore et al. 2015). The extent of overwash penetration and dune morphology alongshore correlates to nearshore bathymetry, according to a study of offshore Santa Rosa Island (table 4) (Houser et al. 2008a).

The rate at which an island migrates landward through overwash processes is controlled by multiple factors, including the rate of relative sea level rise (Walters et al. 2014). As relative sea level rises, the island will migrate landward on top of the sound side tidal flats. Islands with wide shallow flats are less vulnerable to rising sea level because they can maintain their offshore position without receiving as much new sand from the shoreface or from alongshore transport. When relative sea level rise rates become too high and the input of fine-grained sediments becomes too low, more of the island can transition to become tidal flats (Fagherazzi et al. 2006; Mariotti et al. 2010). Other factors that affect the rate at which an island migrates landward through overwash processes include the following: underlying geology (Riggs et al. 1995) and stratigraphy (Belknap and Kraft 1985; Masetti et al. 2008; Moore et al. 2010), sediment grain size (Storms et al. 2002; Masetti et al. 2008), substrate slope (Storms et al. 2002; Wolinsky and Murray 2009; Moore et al. 2010), and substrate erodibility (Moore et al. 2010).

Sand transport from Gulf of Mexico beaches to the Mississippi Sound shoreline by overwash is common across low-lying portions of the Mississippi barrier islands (Byrnes et al. 2012). However, long-term transgressive landward migration of barriers by "rollover" mechanism is not evidenced because sediment overwashed to back-barrier shores is soon eroded. On Santa Rosa Island, hurricane-driven overwash does occur, but the presence of a shell and gravel lag from the Fort Pickens Road reduces the amount of sediment that can be mobilized (Chris Houser, University of West Florida, assistant professor, personal communication, cited in National Park Service 2007).

Notably, some of the areas that were mapped as Active Overwash Zones (**ovrwsh_zn_a**) (see posters, in pocket) have since become vegetated and now function as a different type of unit, such as an Inactive Overwash Zone, Marsh, or an Active Dune Complex, and would be classified differently in newer mapping efforts (Mark Ford, Southeast Regional Office, ecologist, email communication, 31 August 2017). The "Mapping Issues and Data Needs" section of the "Geologic Map Data" chapter discusses the dynamic nature of barrier islands and other issues associated with geomorphic mapping in these environments.

Inlets

An inlet (locally called a "pass") through a barrier island is created when storm-driven surges flow across an island and excavate a channel from either the seaward side (toward the Gulf of Mexico) or the landward side (adjacent to the Mississippi or Santa Rosa Sounds) of the island (fig. 21) (FitzGerald and Hayes 1980). The inlet widens by erosion and collapse of the adjacent bank and deepens as tidal flow scours the channel (Wamsley et al. 2010).

Tidal currents through an inlet construct a flood-tidal delta on the landward side of a barrier island and an ebb-tidal delta on the seaward side. These tidal deltas are created where sediment is deposited as the swiftly moving tide dissipates into larger water bodies (fig. 21A) (Riggs et al. 2009).

Tidal delta shoals are important components of both the coastal sediment budget and long-term evolution of barrier islands. Ebb-tidal deltas store sand and episodically release it to nearby beaches and coastal systems. Waves and currents rework sand of the ebb-tidal delta into shoals, which migrate alongshore and merge with the beach downdrift of the inlet (Mallinson et al. 2008).

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

If the inlet tidal flow is strong enough to flush sediments faster than they are introduced, the inlet is maintained (Wamsley et al. 2010). Along chains of narrow barrier islands with few tidal inlets, such as the park's islands, some breaches may deepen and widen. An example of this is Camille Cut, a chronic breach between East and West Ship Islands, which was last opened by Hurricane Camille in 1969 and was significantly widened by

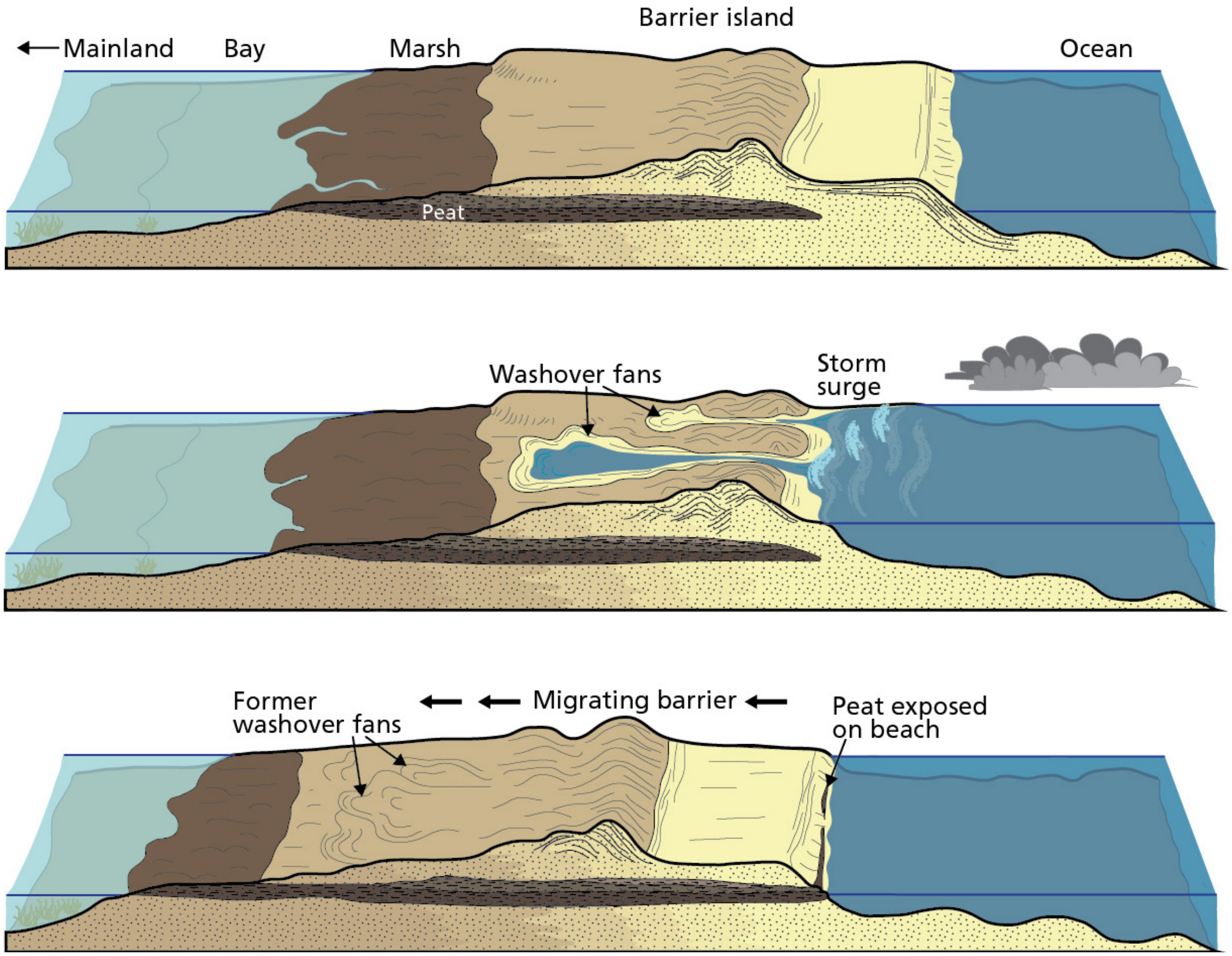

Figure 20. Graphic of washover fan development.
Where waves carry sand across the beach, sediment is deposited as small washover fans in the island interior. Large storm events can drive meters of water across the island (in a process known as "overwash"), resulting in large washover ramps that bury the back-barrier marsh, as depicted here (such as Santa Rosa Island) or beach (such as the Mississippi barrier islands, which do not have marshes on the sound side). Extensive washover deposits can expand the island's area and build shallow shoals in the bay. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after NPS and University of Maryland Center for Environmental Science.

Table 4. Contrasting metrics of areas subject to more and less overwash penetration and breaching.

Source: Houser et al. (2008a).

Metric	More overwash penetration and breaching	Less overwash penetration
Size/quantity/type of dunes	Few, small dunes	Large foredunes, back-barrier dunes
Vulnterable sections	Narrow island sections	Widest island sections
Location	West of inner shelf transverse ridges	Crest of transverse ridges, cuspate headlands
Long-term erosion rates	Higher	Lower
Eroded sediment transportation	Transferred to washover terraces	Deposited within the upper shoreface then returns to beach through nearshore bar migration

Hurricane Georges in 1998 and Hurricane Katrina in 2005 (Twichell et al. 2011).

Lasting only a few days, many inlets are temporary features produced by elevated storm water levels (Dolan and Lins 1986). Ephemeral inlets can open and close on a time scale of months to years (Mallinson et al. 2010). If the inlet closes, the shallow shoals of flood-tidal deltas (sound side) remain as a foundation for future island migration (fig. 21B).

Coastal erosion narrows the island more rapidly in areas underlain by fine flood tidal–delta sediments, while slower erosion occurs where coarse sands are associated with the inlet throat channel (fig. 21C). As overwash covers the back-barrier side of the island, the ephemeral inlet channels are filled with sand. The ocean beach retreats, and earlier buried sediments including marsh peat often crop out on the beach and upper shoreface during storms. As storm surge flows over the narrow portions of a barrier island, the exposed marsh peat surface resists erosion while the adjacent sand–filled tidal channels and narrow portions of the island are more easily eroded, producing new inlet channels (fig. 21D) (Mallinson et al. 2008; Riggs et al. 2009).

Wetlands

Wetlands are present at the park in the form of tidal flats, salt marsh at Davis Bayou, and freshwater interior wetlands on all islands including Sand Island. Interior wetlands and ponds have several water sources: groundwater, precipitation, inflow from bays, and overwash.

Tidal flats and tidal marshes consist of mud and a resistant mat composed of roots of salt-tolerant plants. The Davis Bayou area has an extensive tidal marsh.

Marshes deposit organic peat, which is cohesive and therefore resistant to erosion (Leatherman 1988). Tidal salt marsh accretion rates depend on fine-grained sediment input, which primarily occurs when sediment-laden water floods the marsh (Kirwan et al. 2011; Mudd 2011; Gunnell et al. 2013), and on increases in the growth rate and subsequent organic deposition of marsh vegetation (e.g., *Spartina alterniflora*) in response to high tide levels (Cahoon and Reed 1996; Morris et al. 2002; Mudd et al. 2010; Kirwan et al. 2011). Ellis et al. (2018) presented data for Dauphin Island that provide a basis for assessing organic and inorganic sediment accumulation rates and temporal changes in accumulation rates over multiple decades at multiple locations across that island. Eleven push cores, which varied in distance from the shoreline, were collected from a variety of marsh types, including high marshes, low salt marshes, and salt flats. Accretion helps to offset reduced elevation resulting from subsidence and sea level rise. The elevation of the marsh platform relative to sea level influences the amount of time that plants are inundated and, therefore, the types of marsh plants that can grow in a particular location (French 1993).

Seagrass

Seagrass or submerged aquatic vegetation (SAV) stabilizes bottom sediment, improves water clarity, and slows waves and currents (Kenney 2006). Seagrasses also provide important foraging and nursery habitat for many species in estuaries. Under federal regulations, SAV beds are considered special aquatic sites (40 CFR 230 Section 404 (b)(1), Guidelines—Protection of Wetlands and Other Waters of the United States).

Seagrass beds in the Gulf of Mexico represent more than 50% of the total seagrass coverage in the United States (Green and Short 2003). In 2011, the park supported 1,009 ha (2,492 ac) of seagrass, with 800 ha (1,976 ac) in the Florida portion of the park (i.e., Big Lagoon, Perdido Key, waters on the north side of Fort Pickens, the area north of Santa Rosa Island, and waters near Naval Live Oaks) and 209 ha (516 ac) in the Mississippi portion of the park (behind Ship, Horn, and Petit Bois Islands) (Cantor 2013).

Seagrasses occur in isolated patches usually less than several hundred acres in size. The locations of seagrass beds within park estuarine waters are controlled by water depth, salinity, type of substrate, and protection from wind and waves (Pham et al. 2014). In the Mississippi Sound, seagrasses grow in shallow waters less than 1 m (4 ft) deep (Moncreiff et al. 1998; Moncreiff 2007a), but in the clearer waters of Santa Rosa Sound, they are found in depths of up to 4 m (12 ft) (NPS 2014).

Seagrass beds grow along the northern shores of the barrier islands where there are sandy bottoms, shell fragments, and calm waters (NPS 2014). Seagrass is also found along Naval Live Oaks and there is potential seagrass habitat along the southern shoreline. Cat Island supports seagrasses on both the north and south shores, which are protected from the southeast summer winds by the north–south-oriented sand spit at the east end of the island (Pham et al. 2014).

Groundwater

A sand-and-gravel aquifer underlies most of northwest Florida, extending from central Walton County northwest into Alabama and south to the Gulf of Mexico (Cooper et al. 2005). This aquifer is composed of late Miocene to early Pliocene sand intervals of variable thickness, which are encased in a

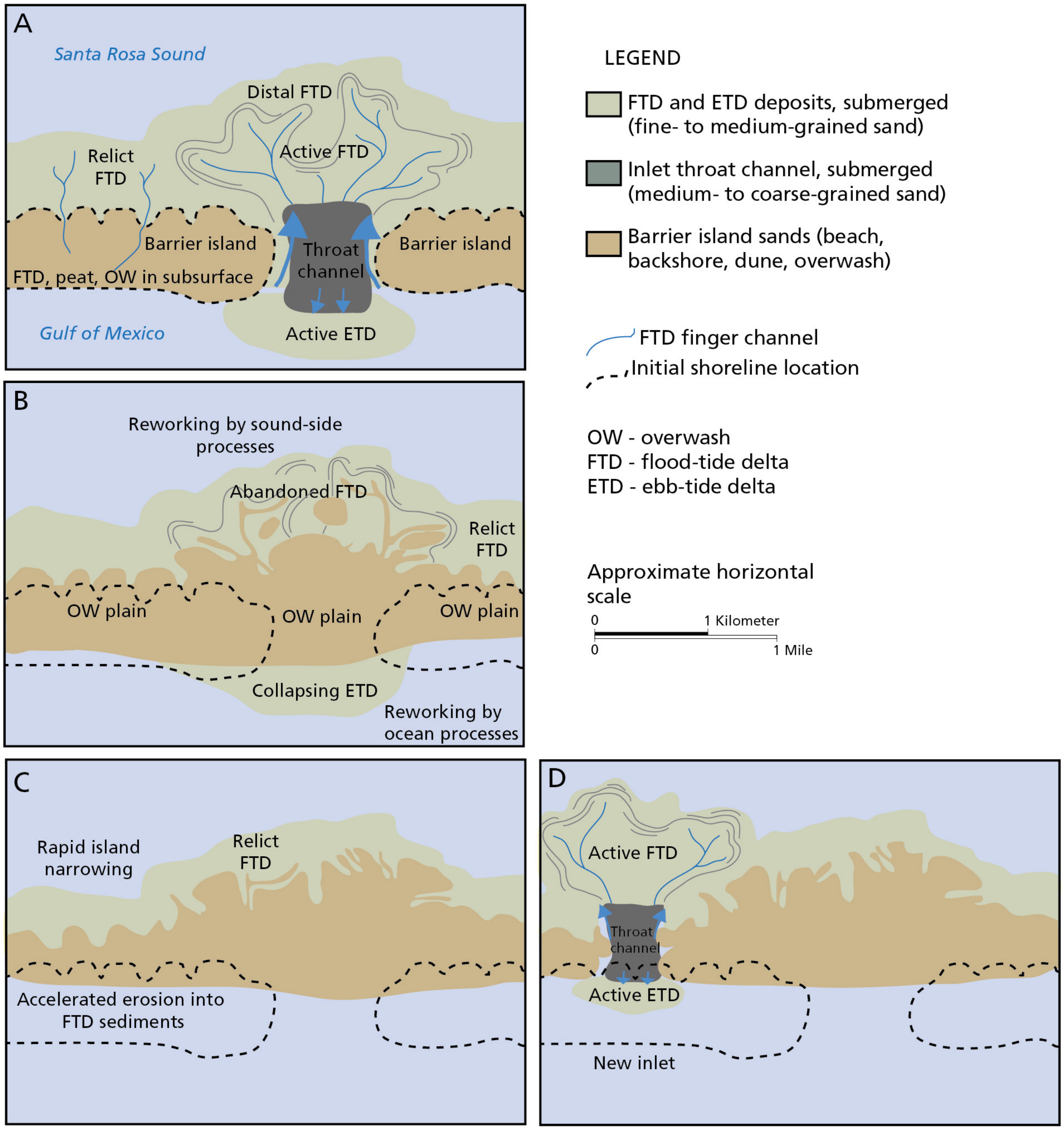

Figure 21. Graphic illustrating inlet formation.
Inlet formation and shoreline recession are important components of barrier island evolution. (A) Active flood and ebb-tidal deltas form in association with an inlet. (B) As the inlet closes, the ebb-tidal delta collapses, causing temporary and localized shoreline accretion, while adjacent areas continue to erode. (C) Continued coastal erosion narrows the island more rapidly in areas underlain by fine flood-tidal delta sediments, while slower erosion occurs where coarse sands are associated with the inlet throat channel. (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 flood-tidal delta sediment, continuing the evolutionary succession. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Mallinson et al. (2008, figure 3).

predominantly muddy sequence that is several hundred feet thick. The aquifer is the primary source of drinking water in Escambia and Santa Rosa Counties (Katz and Choquette 1991) and is of increasing importance in Walton and Okaloosa Counties because of rising water demands in Florida (Guvansen 2000). The thin Pliocene Citronelle Formation and Late Pleistocene deposits, primarily the Prairie Formation, contain thinner and less significant sand and gravel aquifers (NPS 2007). The Citronelle and Prairie Formations are discussed in the "Geologic History" chapter.

In Mississippi at the Davis Bayou area of the park, freshwater aquifers occur irregularly at depths ranging from 370 to 900 m (1,200 to 3,000 ft) below the surface in late Miocene to early Pliocene sandy deposits (NPS 1978). Below these depths, warmer saline water is present (Christmas 1973; Otvos 1985a, 1997). The freshwater aquifer beneath the Mississippi barrier islands occurs in Miocene deposits at depths of about 180 to 240 m (590 to 800 ft) (NPS 1978).

Climate change may influence groundwater by driving saltwater intrusion, higher water tables, and changes in soil moisture. Groundwater dynamics in surficial aquifers are affected directly by rising sea levels and indirectly by the morphological changes driven by sea level rise. An increase in sea level changes the groundwater discharge to surface water (e.g., ponds and wetlands) and aquifer salinity, and can reduce the volume of the freshwater lens that overlies the freshwater–saltwater interface. Models show that a sea level rise of 20 cm (0.7 in) would lead to substantial changes in the depth of the water table and the extent and depth of saltwater intrusion, both of which strongly influence the establishment, distribution, and succession of barrier island vegetation and habitat, particularly in the marsh and shrub thicket zones (Masterson et al. 2014). The increased water-table height in areas with a shallow depth to the water resulted in groundwater inundation of the land surface and a thinning of the underlying freshwater lens. Groundwater response was shown to have a strong interdependence with island morphology (Masterson et al. 2014).

The "Coastal Vulnerability and Sea Level Rise" section of the "Geologic Resource Management Issues" chapter provides more information about climate change drivers and impacts.

Estuarine Sediments

Recent mineral sediments in the Mississippi Sound originated in the Appalachian Mountains (Velardo 2005, as cited in USACE 2016a) and were discharged by the Mississippi and Mobile Rivers, and the smaller river systems located between these two major systems. Additional sediment is organic and locally derived from marsh decomposition. Tidal flows through the passes also carry sediment from (and to) the Gulf of Mexico.

As a result, central portions of the Mississippi Sound are primarily silt and clay; in the Pascagoula area, medium-grained sands are more prevalent. Coarse-grained sands occur near the barrier islands, whereas fine-grained muds accumulate in dredged channels (Upshaw et al. 1966, as cited in USACE 2016a). A mix of mud and sand is found between eastern Horn Island and Pascagoula, and between Biloxi Bay and Dog Keys Pass (Otvos 1973b, as cited in USACE 2016a).

Nearshore Substrate and Benthic Habitat

Lavoie et al. (2013) collected data of benthic substrate types along 1,191 km (740 mi) of seafloor within the park boundary surrounding East and West Ship, Horn, and Petit Bois Islands and provided a high-quality initial assessment of habitats (fig. 22). Results showed that generally the islands are surrounded by coarse-to-medium grained sand including in Camille Cut between the East and West Ship Islands. The sand is finer with increasing distance offshore toward the Gulf of Mexico, with small patches of mud present. Toward the Mississippi Sound, sediment becomes muddy. The passes between islands are primarily medium-to-coarse grained sand, but the dredged shipping channels are fine-grained mud and silt. Large sandy bed forms are on the south (Gulf of Mexico) side of each island, with the largest present to the south of Petit Bois and Horn Islands.

Paleontological Resources

The paleontological resources (fossils) of Gulf Islands National Seashore were summarized by Kenworthy et al. (2007) and are listed in table 5 of this report. These resources are predominantly buried offshore and rarely wash onto shore, although one mineralized fossil that appears to be a mollusk shell of unknown age was found in association with an archeological site and is now held at the NPS Southeast Archeology Center (NPS 2007).

The park's fossils are mostly known from drill cores. Microfossils and archeological materials recovered from drill cores in the Mississippi–Alabama barrier islands and the Mississippi Sound provide well-constrained chronological data of middle to late Holocene coastal development (Otvos and Giardino 2004), which is described in the "Geologic History" chapter. A well on Fairpoint Peninsula, west of the Naval Live Oaks area, contained Late Pleistocene mollusks at a depth of about 8 m (25 ft). In addition, rare Holocene and Pleistocene molds and casts formed by secondary limonite and humate replacement of nearshore and estuarine molluscan shells and foraminifera (calcium carbonate shells of tiny single-celled organisms; a type of microfossil) occur in situ and reworked in the Mississippi islands and mainland area (Otvos 1982b, 1997; NPS 2007). Pliocene to Holocene fossils from fluvial, estuarine, and marine environments including diverse foraminifera, ostracods, mollusks, dinoflagellates, and pollen occur beneath Horn Island. Beneath Santa Rosa Island, east of the Fort Pickens area, cores yielded microfossils and fossil mollusks from Miocene through Holocene sediments. The subsurface fossils found at the park offer scientific, educational, and interpretive opportunities related to barrier island formation and the evolution of the Gulf of Mexico.

Management of paleontological resources is discussed in the "Geologic Resources Management Issues" chapter. The NPS Fossils and Paleontology website provides more information about NPS fossils.

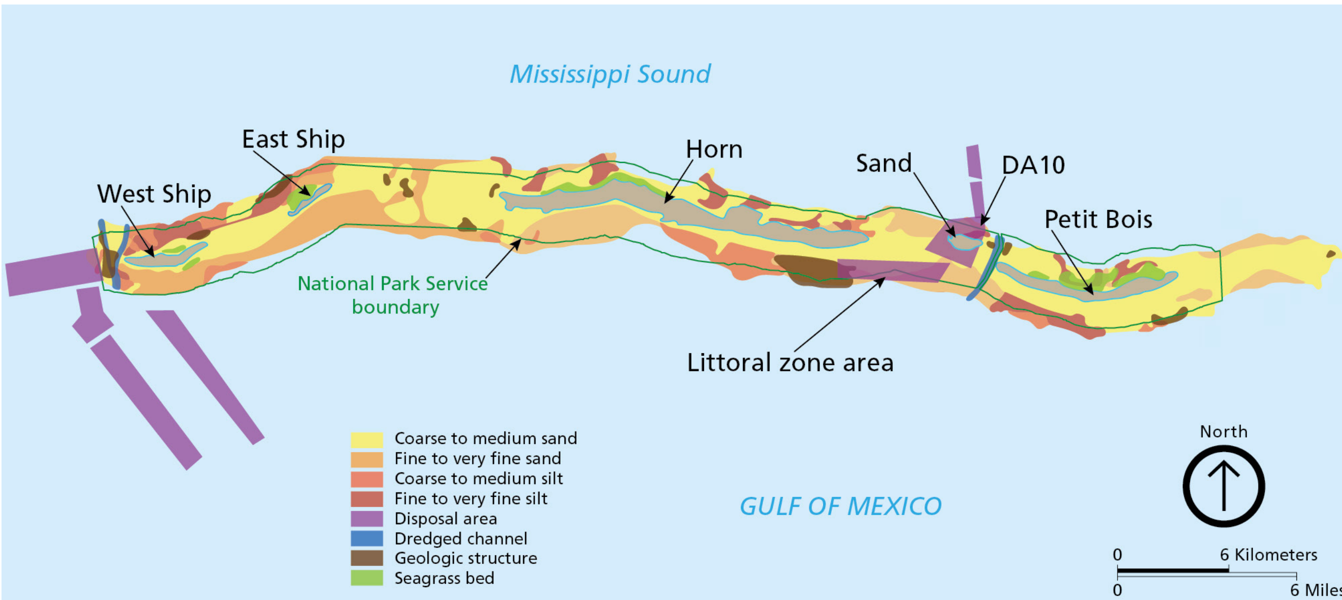

Figure 22. Map of benthic substrate classification of the Mississippi barrier islands.
Sand and silt surround the islands of West Ship, East Ship, Horn, Sand, and Petit Bois (shown as gray on the map). Seagrass beds (green polygons) are present on the sound side of the islands. The NPS boundary is delineated as a green outline. The areas mapped as geologic structures may be sand waves. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Lavoie et al. (2013, figure 5) and USACE (2016a).

Table 5. Paleontological resources at Gulf Islands National Seashore.

Documented by NPS (2007, table 3), using data from Brown et al. (1944), Walton (1960), Marsh (1966), Otvos (1981a, 1982a, 1988), and Gohn et al. (1996). Microfossils occur under all Mississippi barrier islands in both Holocene and Pleistocene units (Ervin Otvos, University of Southern Mississippi, professor emeritus, GRI review comments, 15 September 2017).

Location	Epoch	Fossils
Horn Island	Holocene	Microfossils, echinoid spines, fragmented mollusks, and molluscan molds
Horn Island	Late Pleistocene	Foraminifera and other microfossils, ostracods, mollusks, dinoflagellates, and pollen
Santa Rosa Island	Late Pleistocene	Foraminifera and mollusks
Davis Bayou	Pleistocene	Foraminifera, mollusks, and ostracods

Geologic Resource Management Issues

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

The park's general management plan (NPS 2014), the 2006 GRI scoping meeting (see NPS 2007), and the 16 May 2016 GRI conference call identified the following geologic resource management issues:

- Coastal Resources Management and Planning
- Coastal Erosion
- Coastal Vulnerability and Sea Level Rise
- Hurricane Impacts and Human Responses
- Dredging of Inlets
- Coastal Engineering and Beach Nourishment
- Impacts to Wetlands
- Visitor Use Impacts
- Visitor Safety
- Decline of Seagrass Beds
- Water Quality
- Abandoned Mineral Lands
- Energy Development
- Paleontological Resource Inventory and Protection
- Sediment Budget Data Needs

In addition, the park's foundation document (NPS 2016a) identified the following planning needs: climate change adaptation plan, marine resources management plan, fisheries management plan, wilderness stewardship/backcountry management plan, disaster recovery and impact mitigation plan, resource stewardship strategy, motorized vessel use plan, Fort Pickens Road transition plan, and visitor use management plan. Addressing these needs will benefit from the incorporation of information about the park's geologic resources.

Coastal Resource Management and Planning

The USGS, as part of the National Assessment for Coastal Change Hazards Project (see https://www.usgs.gov/centers/spcmsc/science/national-assessment-storm-induced-coastal-change-hazards), conducts baseline and storm response photography missions to document and understand the changes in vulnerability of the nation's coasts to extreme storms (Morgan 2009). On 1 September 2014 (Morgan 2015) and again on 18–19 September 2015 (Morgan 2016), the USGS conducted an oblique aerial photographic survey from Navarre Beach, Florida, to Breton Island, Louisiana, aboard a Maule MT57 aircraft at an altitude of about 150 m (500 ft) and approximately 370 m (1,200 ft) offshore. These missions were flown to collect baseline data for assessing incremental changes that have taken place since previous surveys. The data can be used in the assessment of future coastal change.

The NPS has developed a variety of databases and guidance for managing coastal resources and planning for the impacts of climate change. To develop additional monitoring protocols related to climate change, the Gulf Coast Network and park staff can refer to the NPS Northeast Coastal and Barrier Network strategy (Stevens et al. 2010).

The NPS *Coastal Adaptation Strategies Handbook* (Beavers et al. 2016a) provides climate change adaptation guidance to park managers in the 118 parks that have been identified by their regional offices as potentially vulnerable to sea level change. Focus topics include NPS policies relevant to climate change, guidance on evaluating appropriate adaptation actions, and adaptation opportunities for planning, incident response, cultural resources, natural resources, facilities and assets, and infrastructure. The handbook also provides guidance on developing communication and education materials about climate change impacts, and it details case studies of the many ways that park managers are implementing adaptation strategies for threatened resources. The associated report, Coastal Adaptation Strategies: Case Studies (Schupp et al. 2015), includes two examples from Gulf Islands National Seashore.

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; and *NPS Reference Manual #39-2: Beach Nourishment Guidance* (Dallas et al. 2012) for planning and managing nourishment projects.

The NPS *Cultural Resources Climate Change Strategy* (Rockman et al. 2016) connects climate science with historic preservation planning. It identifies and describes seven climate change adaptation options for cultural resources and cultural landscapes: (1) no active intervention, (2) offset stress, (3) improve resilience, (4) manage change, (5) relocate or facilitate movement, (6) document and prepare for loss, and (7) interpret the change.

A Geoscientist-In-the- Parks (GIP) project by Toscano (2004) assessed the coastal vulnerability of the park's cultural and archeological resources and recommended actions for their protection and preservation.

Coastal zone management in Mississippi is led by the Mississippi Department of Marine Resources. Permits are required for any dredging or filling activities, and fill material must be nontoxic and either stabilized or of sufficient size to not be displaced during typical storm tides (Dallas et al. 2012).

The Florida Department of Environmental Protection serves as the lead agency in the state for the Florida Coastal Management Program. A joint coastal permit is required to conduct any coastal construction activities in the state. Florida has extensive eligibility criteria for coastal construction permits, including requirements related to marine turtle protection, design, siting, and sediment compatibility. Florida law requires that all sandy sediment excavated from the coastal system is deposited on the adjacent beach or in the nearshore. Monitoring programs also are required for any construction that is determined to have an adverse impact (Dallas et al. 2012).

The park's enabling legislation (P.L. 91-660; P.L. 95-625) states that beach erosion control and hurricane protection activities shall be planned jointly between the USACE and the Department of the Interior, and that the USACE continues to have authority for navigation and related matters. Additional legislation, executive orders, and NPS policies related to coastal management at the park are listed in Appendix B.

The NPS Gulf Coast Network recently published protocol implementation plans (PIPs) for monitoring shoreline position (Bracewell 2017a) and coastal topography (Bracewell 2017b). Network staff members will monitor shoreline position and coastal topography every other year, beginning in May 2018. In Mississippi, both the Mississippi Sound and Gulf of Mexico shorelines will be surveyed at Horn and Petit Bois Islands. In Florida, the Gulf of Mexico and Pensacola Pass shorelines will be mapped at Fort Pickens and Perdido Key. Topography will be measured along 10 transects on Horn Island, six on Petit Bois Island, and eight along Pensacola Pass (Jeff Bracewell, NPS Gulf Coast Network, email communication, 13 September 2017). It is very important to monitor dune line and shoreline simultaneously (Chris Houser, geology professor, Texas A&M University, 2016 GRI kickoff meeting).

Coastal Resources Datasets

Multiple efforts to develop data and models are producing useful information in the form of datasets for coastal parks. These efforts include sea level rise projections, coastal engineering inventories, asset vulnerability assessments, and long-term monitoring:

The NPS Geologic Resources Division (GRD) and Climate Change Response Program (CCRP) developed sea level rise and storm surge data that park managers can use for planning purposes over multiple time horizons. Those data are available in Caffrey et al. (2018; which was published while this report was in final formatting and review) and via an online viewer. For Gulf Islands National Seashore, Caffrey and Beavers (2015) projected the combined elevations of storms surge and sea level for planning horizons of 2030, 2050, and 2100. The "Coastal Vulnerability and Sea Level Rise" and "Hurricane Impacts and Human Response" sections provide more information.

An NPS study (Peek et al. 2015) characterized park assets (e.g., historic structures, visitor facilities, and buildings) based on their overall exposure to a long–term sea level rise of 1 meter and associated storm vulnerability. Of the 436 park assets, 81% were categorized as having high exposure to sea level rise impacts. Mainland assets had limited exposure.

The NPS Gulf Coast Network collects multiple datasets at the park, including shoreline position through remote (lidar) surveys every few years (Hatt et al. 2016) and ground surveys in some portions of the park. Network staff members are developing shoreline monitoring protocols for other areas (Jeff Bracewell, Gulf Islands National Seashore, data manager, personal communication, July 2015). The network funded a natural resource condition assessment (Hatt et al. 2016) that summarized trends and conditions in park resources including geomorphic resources.

To develop additional monitoring protocols for coastal resources, park managers can work with the network staff as well as consult suggested protocols such as those outlined in the chapter about coastal features and processes (Bush and Young 2009) in *Geological Monitoring* (Young and Norby 2009). That chapter describes methods and vital signs (measurable parameters of the overall condition of natural resources) 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. To develop climate change monitoring protocols, the NPS Northeast Coastal and Barrier Network strategy (Stevens et al. 2010) can appropriately serve as a template for planning along Gulf of Mexico coastlines.

The website of the NPS Water Resources Division, Ocean and Coastal Resources Branch, has additional information about servicewide programs and the resources and management programs at ocean, coastal, and Great Lakes parks. Shoreline and water acreage statistics are available at the NPS Ocean and Coastal Parks website. Detailed information is available in Curdts (2011).

General Management Plan

Many of the planning issues and concerns raised in the park's general management plan (NPS 2014) have geologic considerations that are discussed in this report; these include preserving coastal ecosystems, storm recovery and sustainability, oil and gas development, Deepwater Horizon oil spill, and climate change. The general management plan identified desired conditions and associated management strategies for the following geology-relevant resources: terrestrial and marine ecosystem management, geologic processes and resources, soils, water resources, wetlands, floodplains, and climate change.

The plan directs the park to be managed as an outdoor classroom for exploring regional natural and human history while providing recreational opportunities. It also suggests the active pursuit of collaboration and cooperation between a consortium of academia, visiting scientists, conservation organizations, and other agencies to enhance resource management, stewardship, and understanding of the northern Gulf of Mexico environment. The plan sets out the intention to establish a marine management program to inventory and monitor the overall marine environment, including submerged cultural resources.

The plan states that restoration efforts will focus on reestablishing natural resource conditions that have been altered or impacted by human activity; however, natural resource manipulations will continue in areas surrounding coastal fortifications to ensure protection from threats to their stability and integrity that are posed by continuing shoreline changes.

Coastal Erosion

Barrier islands recede when erosion and subsidence exceed the sediment supply. Variations in wave energy, sediment availability, sea level change, and human activities influence the balance between erosion and deposition (Dolan and Godfrey 1972). A study of the park's barrier islands found that the park units on Perdido Key and Santa Rosa Island are experiencing shoreline retreat, and the Mississippi barrier islands are undergoing increasing loss of land area (Morton 2007). On Santa Rosa Island, wider portions of the island have lower erosion and more accretion compared to narrow portions, according to a study of shoreline change between 1858 and 2004 (Hapke and Christiano 2007).

From 1848 to 1986, long-term change rates of island area showed a loss of 2.5, 1.6, 1.7, and 2.0 ha (6.2, 4.0, 4.2, and 4.9 ac) per year for Cat, Ship, Horn, and Petit Bois Islands, respectively (Byrnes et al. 2013). Portions of the Gulf Island beaches that face southeast have higher erosion rates than those that face southwest because long-period waves approach from the southeast (Kish and Donoghue 2013).

The Mississippi islands have decreased in surface area and rotated. The islands and adjacent platform shoals shifted westward in the direction of the net littoral drift. Updrift erosion and downdrift deposition are taking place. The vegetated cores of the island interiors remain fixed (Morton 2007). Along the Mississippi islands, the increasing rate of land loss since the mid-1800s is a result of the deepening of dredged channels across the outer bars of the three tidal inlets, and the most recent land loss accelerations are a result of increased storm activity since 1995 (Morton 2007). The erosion of the Mississippi barrier islands is rapid, demonstrated by an average long-term rate of about 3.1 m (10.2 ft) per year lost along 80% of the shoreline (Morton et al. 2004). The short-term average rate of 60% of the shoreline is even higher, at 5.8 m (19.0 ft) lost per year. Shoreline retreat and land loss in the Mississippi barrier islands have been steadily accelerating over the past 160 years (Otvos and Carter 2008). On the sound side of Horn Island, erosion is evidenced by tree trunks exposed in the surf zone (fig. 23).

Cat Island is losing land area along all shorelines via subsidence of the Mississippi River Delta and reduced sand supply to the island (Otvos and Carter 2013). The sand spit at the southern end is vulnerable to storm and normal wave conditions; it has a net shoreline change rate of a loss of 3 to 6 m (10 to 20 ft) per year. Long-term shoreline changes along the northern end of the island are slower and more stable, with rates of as much as 0.6 m (2 ft) lost per year (Byrnes et al. 2012).

East and West Ship Islands are the most vulnerable of the Mississippi barrier islands because they are the downdrift terminus of the sand source. Island breaching (Camille Cut) and low sand supply from Dog Keys Pass have caused the central portion of the island to be narrow, low, and vulnerable to breaching during tropical cyclones (Byrnes et al. 2012, 2013). In comparison to the other Mississippi barrier islands that

Figure 23. Photograph of Horn Island.
On the sound side of Horn Island (Mississippi) tree stumps in the surf zone are evidence of ongoing erosion. NPS photograph by Courtney Schupp taken 21 July 2015.

have been subjected to storm overwash, only the Ship Islands have been breached multiple times (Byrnes et al. 2013). Additionally, the offshore bathymetry focuses wave energy onto the islands, enhancing storm-driven erosion (Morton 2007). Along the Ship Islands, mean long-term shoreline change is 3.4 m (11.2 ft) per year, ranging from a gain of 3.02 m (9.91 ft) to a loss of 6.29 m (21.6 ft) per year (Morton et al. 2004). The higher long-term erosion rates on East Ship Island (5.2–5.7 m [17.0–18.7 ft] per year) may in part be a result of the presence of an old channel that runs beneath the middle of the island and is exposed on the adjacent inner shelf, in contrast to West Ship Island, which has a large sand shoal offshore (Twichell et al. 2013).

Along Perdido Key, accretion is taking place along the western half and erosion is taking place along the eastern half, except for the area immediately adjacent to Pensacola Pass where accretion is high because of beach nourishment. The placed sediment is quickly eroded, however, resulting from a local reversal in sediment transport direction caused by the ebb-tidal delta. Erosion along the rest of the eastern portion of the island appears to be driven primarily by storms, inlet dynamics, and the presence of inlet-associated shoals. The average long-term (1920–2013) shoreline change rate along 20 km (12 mi) of Perdido Key, including areas outside of the park, is low, a loss of 0.17 m (0.56 ft) per year (Sankar 2015).

Additional information on renourishment volumes is provided in the “Coastal Engineering and Beach Nourishment” section.

Along Santa Rosa Island, back-barrier erosion along Santa Rosa Sound is caused by northerly wind-driven waves generated by cold fronts, which can be significant where fetch is large (Stone et al. 2004; Houser et al. 2007). Erosion along the south (Gulf of Mexico) side of Santa Rosa Island is driven by strong wave action, especially during tropical storms and hurricanes.

The highest storm-driven erosion along Santa Rosa Island occurs in the narrow sections that are inundated early in a storm and are characterized by a high concentration of shell lag and moisture following the storm. The narrow sections of the island will have stronger gradients in surge elevation, leading to the development of breaches. The small dunes that tend to redevelop in these areas lead to little loss of sediment to the shoreface during a storm, and most sediment deposited along the back-barrier is in washover fans (Houser et al. 2008a). These deposits are eroded by frontal winds (Stone et al. 2004) and are transported alongshore toward the cuspate headlands (Houser et al. 2007).

Work on understanding storm-driven erosion continues at the park. Bambach (2013) documented the varying degrees of erosion between 1973 and 2013 of foredunes at 20 locations on Santa Rosa Island. Findings included response to Hurricanes Opal (1995), Ivan (2004), and Dennis (2005).

The rate of ocean shoreline retreat is directly related to the height and extent of the dune line alongshore Santa Rosa Island. The dune variability over a scale of hundreds of meters determines where overwash occurs, which in turns controls longshore sediment transport gradient, migration, and shoreline retreat rate. As a result, a long linear dune line protects the island better than beach nourishment does (Houser et al. 2007).

Both the long-term and storm-driven shoreline change rates are more variable within the Fort Pickens area than within the Santa Rosa area of the park. The shoreline was relatively stable in the Santa Rosa area; the long term (1858–2004) shoreline change rate of a loss of 0.1 m (0.3 ft) per year was within the range of uncertainty (Hapke and Christiano 2007). At Fort Pickens, the western 1.5 km (0.93 mi) of the island is accreting, but the long-term shoreline change rate in the rest of the area is eroding at 0.7 m (2 ft) per year. Portions that had high, long-term change rates, as much as 1.3 m (4.3 ft) lost per year, went on to experience high rates of erosion, overwash, and road damage during the 2004 hurricane season (Hapke and Christiano 2007). An online viewer to examine long-term and short-term shoreline change rates is available from the USGS Coastal Change Hazards Portal.

A GIS compilation of vector datasets for shoreline change in the park is available through the USGS (Morton et al. 2004). All files necessary to run shoreline change analysis are provided. The digital shoreline analysis system (DSAS)—computer software that computes rate-of-change statistics from multiple historic shoreline positions residing in GIS—was used for the analysis of these data (Thieler et al. 2017). DSAS is also useful for computing rates of change for just about any other boundary change problem that incorporates a clearly identified feature position at discrete times. The DSAS software is freely available at the USGS Digital Shoreline Analysis System website.

Severe storms can cause dramatic coastal erosion that is much higher than the long-term rates. During the 140-year period before the hurricanes of 2004 and 2005, average shoreline change rates (loss) in the Fort Pickens and the Santa Rosa areas were 0.7 m (2 ft) per year and 0.1 m (0.3 ft) per year, respectively. In the two-year period that included five hurricanes from September 2004 to September 2005, shoreline change rates in these areas averaged losses of 70 m (230 ft) per year (Hapke and Christiano 2007).

Coastal erosion and storm events threaten historical and archeological resources, including archeological sites (middens) that may contain shells, pottery sherds, artifacts, and sensitive resources that represent at least five levels of occupation or cultural periods (Toscano 2004). In turn, subsequent looting following bluff erosion threatens significant archeological sites (NPS 2007).

Coastal Vulnerability and Sea Level Rise

Eustatic refers to worldwide changes in sea level (fig. 24). On a global scale, sea level varies with changes in the volumes of ocean basins and ocean water, which are caused by expansion from 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, pertains to the combination of global rise with regional and local factors, such as sediment compaction and changes in ocean circulation patterns and wind patterns (Williams 2013).

Historical Sea Level Rise

Sea level has fluctuated over geologic time and over the past millennia (figs. 25 and 26). The Gulf of Mexico and global records are similar, though the timing of the sea-level events in the Gulf of Mexico lags slightly behind the global timing (Balsillie and Donoghue 2011). These differences are discussed in the "Geologic History" chapter.

During the Pleistocene Epoch (2.6 million–11,700 years ago), global sea level was approximately 120 m (410 ft) below present (Fairbanks 1989). Beginning about 18,000 years ago and continuing until 8,000–6,000 years ago, glacial melting caused rapid sea level rise. About 15,000 years ago, a major meltwater event took place, and meltwater entered the northern Gulf of Mexico via the Mississippi River (Balsillie and Donoghue 2011). Approximately 12,800–11,400 years ago, the Younger Dryas cooling event included temporary advance of the ice sheet and a slowing or reversal in the rate of sea level rise (Balsillie and Donoghue 2011). A second pulse of meltwater occurred approximately 10,000 years ago (Fairbanks 1989). Within the last 6,000 years, five sea-

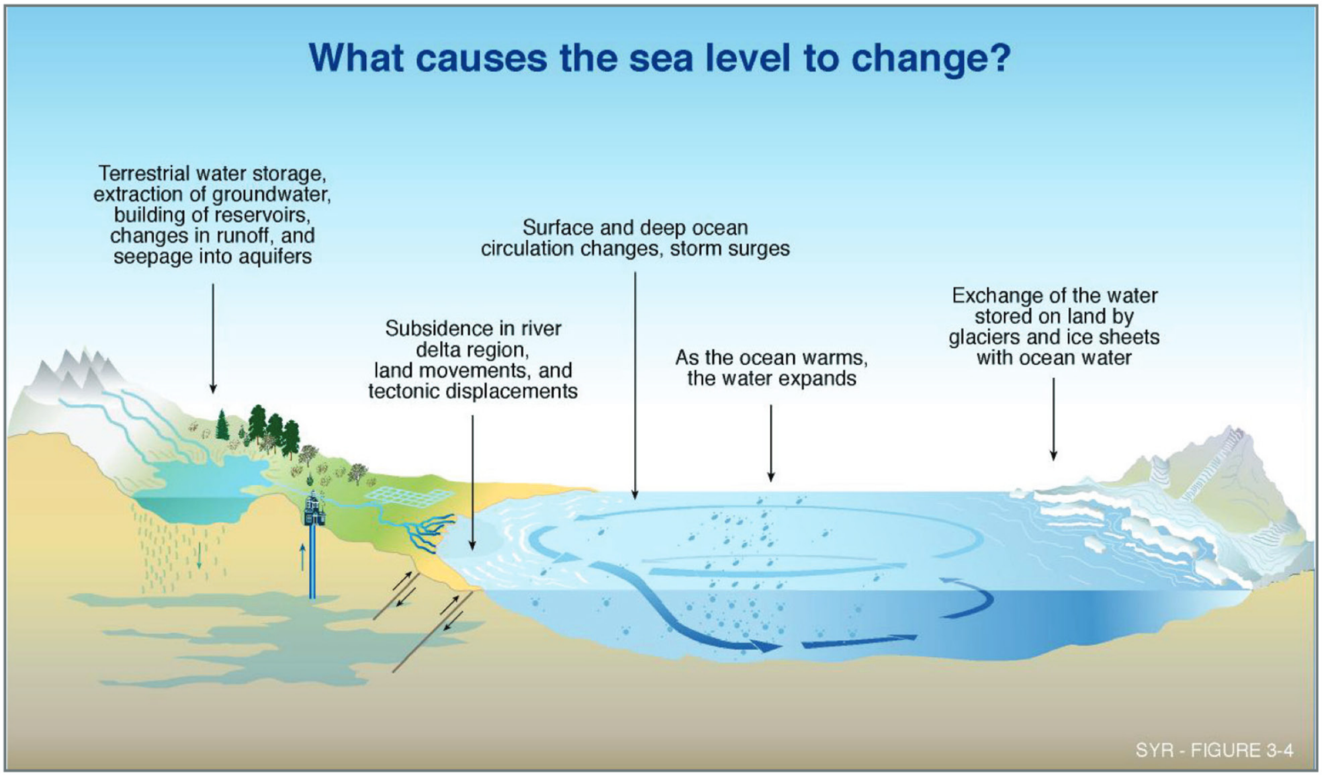

Figure 24. Graphic illustrating causes of sea level change.
Global eustatic sea level rise is caused by global climate warming that results in glacial melt and thermal expansion of surface waters, in combination with relative sea level change, which is caused by regional and local effects of geologic, oceanographic, and atmospheric conditions, such as vertical land movements, that vary spatially and temporally. Graphic from Williams (2013, figure 1).

level highstands in the Gulf of Mexico and worldwide took place; each caused a few meters of change. All these highstands were less than modern sea level (Balsillie and Donoghue 2011).

Geomorphic evidence from the slowly inundated Cat Island strand plain indicates that local tectonic subsidence substantially added to the relative sea level rise rate in the St. Bernard lobe of the Mississippi River Delta during the Holocene Epoch (Otvos and Giardino 2004; Otvos and Carter 2008).

Twentieth century global sea levels rose at a rate of approximately 1.7 mm (0.067 in) per year, with acceleration occurring over the latter part of the century (Church and White 2006). Since 1970, the primary driver of increasing global sea level rise has been the release of anthropogenic greenhouse gases (Slangan et al. 2016). Satellite altimetry data show that present-day global relative sea levels are increasing at approximately 3.3 mm (0.13 in) per year (Cazenave et al. 2014; Fasullo et al. 2016).

Historic sea level trends have been calculated for three NOAA tide gauges near the park. Relative sea level rise rates increase westward toward the area of crustal loading and high rates of subsidence associated with deposition of the Mississippi Delta (Holdahl and Morrison 1974, as cited in Buster and Morton 2011). At Pensacola, Florida (NOAA Station 8729840), mean sea level trend was 2.31 mm (0.09 in) per year from 1923 to 2016, or 0.23 m (0.76 ft) in 100 years (NOAA 2016). This gaging station is at a geologically stable open-ocean location, and so should be a good indicator of the historical eustatic sea level rise (Buster and Morton 2011). At Dauphin Island, Alabama (NOAA Station 8735180), mean sea level trend was 3.5 mm (0.024 in) per year from 1966 to 2016, or 0.35 m (1.1 ft) in 100 years. The higher rate recorded at this station is probably caused by slow subsidence in the offshore region (Buster and Morton 2011). At Bay Waveland, Mississippi (NOAA Station 8747437), relative sea level rise was 4.37 mm (0.172 in) per year from 1978 to 2016, or 0.44 m (1.4 ft) in 100 years (Buster and Morton 2011). Table 6 summaries these trends.

Future Sea Level Rise

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 (Church et al. 2013). Many recent assessments have proposed a projected global average sea level rise of 1 meter by 2100 as a reasonable value to be used for planning purposes (Williams 2013). Some estimates include the possibility that sea level may rise as much as 2 meters by 2100 along the mid-Atlantic coast, based on the future instability of the Antarctic ice sheet (Rahmstorf 2007; Parris et al. 2012). Models that also consider accelerated melting of glaciers and the Greenland and West Antarctic ice sheets, along with the relationship between sea level and temperature, predict that sea level may rise by 0.9 to 1.2 m (3 to 3.9 ft) by the end of this century (Karl et al. 2009; Schellnhuber et al. 2012) with variable regional and temporal influences on local rates of sea level rise depending on geophysical and oceanographic factors (Williams 2013).

Refer to Caffrey et al. (2018) for sea level rise projections specific to NPS areas, including Gulf Islands National Seashore.

Coastal Vulnerability to Sea Level Rise

The USGS calculated a coastal vulnerability index (CVI) for the shoreface areas of the Gulf Coast (Pendleton et al. 2004). Of the approximately 150 km (90 mi) of mapped shoreline evaluated in the park, 24% was classified as being very highly vulnerable to future sea level rise, 18% as highly vulnerable, and 21% as having low vulnerability (fig. 27). For the park, the principle variables determining vulnerability were regional coastal slope and shoreline change. In contrast, wave height, tidal range, and geomorphology produced little to no variability.

One area east of Fort Pickens that was identified as being highly vulnerable has no dune and has an extremely narrow back-barrier marsh in comparison to neighboring areas. Erosion on the sound side of Santa Rosa Island and recent hurricane impacts have made this area vulnerable to a major breach in the future, which would effectively isolate the Fort Pickens area from the rest of the island. During Hurricane Dennis in 2004, a breach occurred just east of the informally named “Three Ponds Area” necessitating realignment of the Fort Pickens Road.

Most of the Mississippi barrier islands were categorized as highly vulnerable except West Ship Island. However, the CVI results preceded Hurricane Katrina, which caused serious erosion along eastern West Ship Island, East Ship Island, and the eastern ends of Horn and Petit Bois Islands (Otvos and Carter 2008).

A recently developed coastal change hazards viewer is available from the US Geological Survey and includes coastal vulnerability.

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 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), coastal and nearshore oceanographic processes (i.e., waves, currents, and circulation patterns) (Williams 2013), sediment supply and transport (Williams 2013), and human actions that alter sediment movement (e.g., jetties) (Williams 2013).

Sea level change and storm surge are expected to affect the park in the following ways: loss of land and critical habitat as a result of rising sea levels, increased erosion and/or accretion across the coastline by storms coupled with shorelines adjusting to new mean sea levels, rising groundwater and possible saltwater intrusion as a result of rising sea levels, increased risk of high-intensity storm events, and potential loss of nearby freshwater ecosystems as sea levels rise (Caffrey and Beavers 2015).

In the face of frequent storms, islands tend to be bi-stable, that is, they are either extremely vulnerable or fairly stable in terms of storm recovery. On islands where dune building is driven by vegetation trapping sand, islands tend to be well-developed with high ecosystem diversity, and tend to migrate slowly, if at all. Such islands have minimal vulnerability to storms. In contrast, some islands are vulnerable even to mild storms. Those islands have low elevation, with a lack of dunes, frequent overwash, rapid migration, and low ecosystem diversity. Sea level rise may lead to their disintegration (Moore et al. 2015).

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 (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).

The following are indicators of threshold conditions: increased rate of landward migration of a barrier island, decreased barrier width and elevation of a barrier island and sand dunes, increased frequency of storm overwash, increased frequency of barrier island

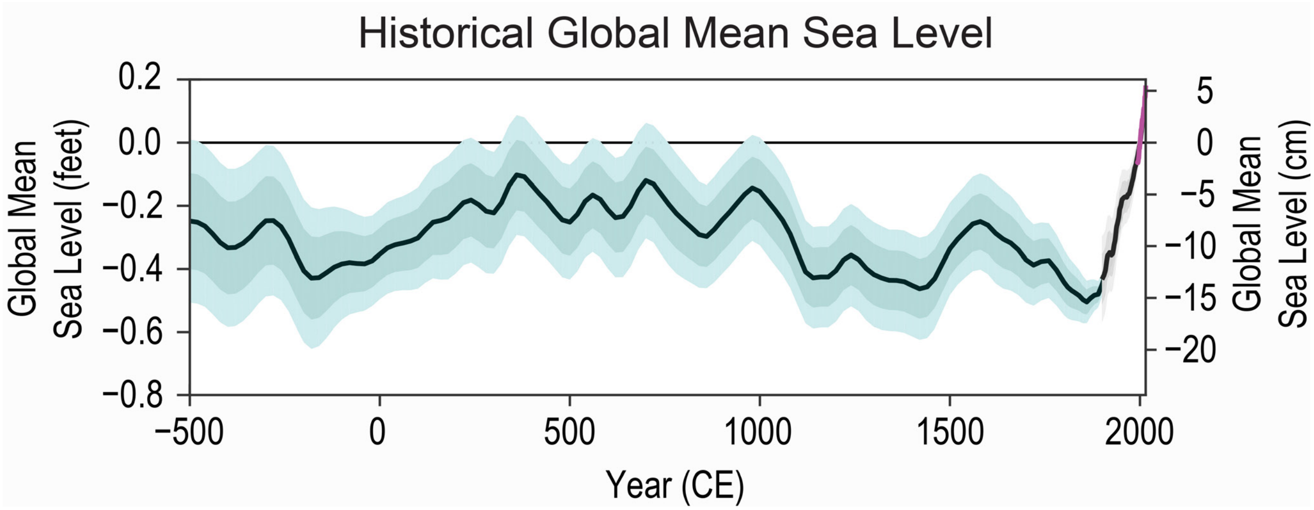

Figure 25. Graph of global mean sea level for the past 2,500 years.
Sea level has fluctuated over geologic time and over the past millennia. The record for the Gulf of Mexico is similar to the global record, though the timing of changes in the Gulf lags slightly behind global timing. Graphic from Sweet et al. (2017, figure 12.2).

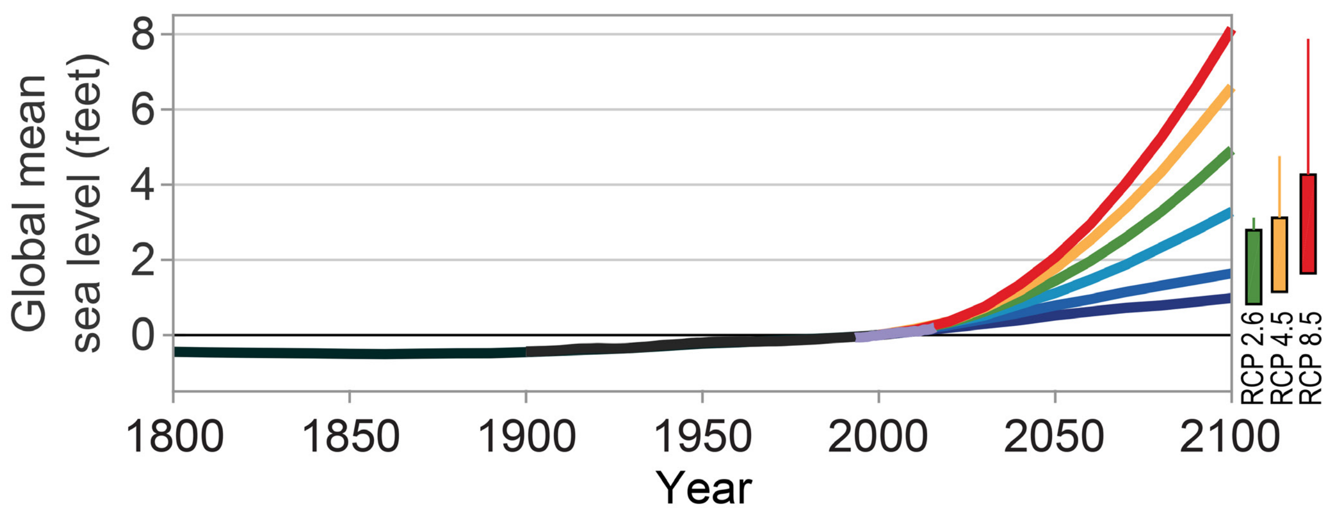

Figure 26. Graph showing measured and projected sea level change.
The graph shows the measured global mean sea level (MSL) from 1800 to 2015 and the projected "very likely" ranges through 2100. The black and magenta lines show global MSL based on recent geologic, tide gauge, and satellite altimeter reconstructions. The six colored lines represent various modeled emissions scenarios and melting of Antarctic ice. Green, yellow, and red boxes indicate the central 90% probability ranges of representative concentration pathways (RCP) of greenhouse gases based on IPCC scenarios. Graphic from Sweet et al. (2017, figure 12.4).

Table 6. Historical and projected sea levels for Gulf Islands National Seashore.

Source: Caffrey and Beavers (2015). Based on SLOSH MOM model Pensacola Bay v4. Projections for 2050 were calculated using IPCC data (Church et al. 2013). Projections for 2100 are the ensemble mean based on IPCC data used for figure 13.20 in Church et al. (2013).

Metric	2015	2050	2100
Sea level trend 1923–2014	+0.02 cm (+0.09 in) per year	N/A	N/A
Low emissions scenario (RCP 4.5) Projected sea level	N/A	+0.23 m (+0.75 ft)	+0.55 m (+1.82 ft)
Intermediate emissions scenario (RCP 6.0) Projected sea level	N/A	+0.24 m (+0.80 ft)	+0.57 m (+1.87 ft)
High emissions scenario (RCP 8.5) Projected sea level	N/A	+0.24 m (+0.79 ft)	+0.71 m (+2.32 ft)

breaching and inlet formation and widening, and barrier island segmentation (Gutierrez et al. 2007).

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). As described in the "Geologic Features and Processes" section, the presence of marsh decreases island migration rate as sea level rises (Moore et al. 2010).

Expected climate change impacts to the Gulf region include warmer sea surface temperatures, hotter summer temperatures, fewer winter freezes, higher sea level, higher storm surges, and altered rainfall patterns. Prolonged drought conditions, storm surges, and rising sea levels may reduce availability of freshwater resources, alter river and wetland hydrology, increase erosion, and induce changes in the distribution of coastal plant and animals species (Florida Oceans and Coastal Council 2010; Loehman and Anderson 2010; Runkle et al. 2017). Additionally, when sea level rises faster than marshes can grow, plants may drown and sediments may become too salty for some marsh plants to thrive (Reed et al. 2008).

The selected alternative/record of decision (NPS 2015) for the park's general management plan (NPS 2014) will enhance the park's resilience to climate change impacts by pursuing funding for multiple strategies including burying overhead powerlines, reducing the need for new development through facility rebuilding/reuse and use of mobile interpretive vans, rebuilding Fort Pickens Road only if feasible, enhancing use of alternative transportation (e.g., ferries) and solar technology, and addressing long-term sustainability strategies and viability of future investments.

Hurricane Impacts and Human Responses

The past four decades have had an unusually high concentration of storms affecting the park. The Gulfport, Mississippi, area experienced 21 tropical storms and 10 hurricanes (categories 1–5) from 1901 to 2000 (Muller and Stone 2001). Forty-eight hurricanes came ashore on the Florida Panhandle between 1885 and 1985 (Wolfe et al. 1988). Deltares (2013) provided a list of hurricanes and tropical storms in the Gulf of Mexico (1917–2001). Morton (2007) provided descriptions of the impacts of individual hurricanes on the Mississippi barrier islands. Table 7 of this report provides descriptions of significant hurricanes affecting the park.

Hurricanes and other major storms are important drivers of geomorphologic change along the park, because winds, waves, and storm surges move sand across and off the islands. Table 8 provides a version of the Saffir-Simpson hurricane wind scale, which describes a range of hurricane impacts. Maximum storm surge usually occurs to the right of landfall under the eyewall and decreases with distance away from the center of the storm. Under present conditions, storm surge is predicted to reach 4 m (12 ft) if a Category 4 storm strikes at mean tide (Caffrey and Beavers 2015).

Island response to storms is controlled primarily by antecedent topography and geomorphic characteristics (e.g., island width, elevations, and bathymetry) (Morton 2010). For example, a fairly shallow nearshore area can lead to elevated storm surge (Sankar 2015). Wave and currents associated with storms remove sediments from the lower beach and intertidal areas, converting portions of the island to shallow subtidal shoal belts on the barrier platform (Otvos 1985a). Storm parameters such as path and wind speeds also change the impacts of storms. For example, higher winds build higher waves, which cause more damage; also, hurricanes that pass west of an area are likely to cause more damage than the same storm tracking east of an area. The frequency of storms also affects beach and dune response: without a post-storm recovery period, dunes become increasingly

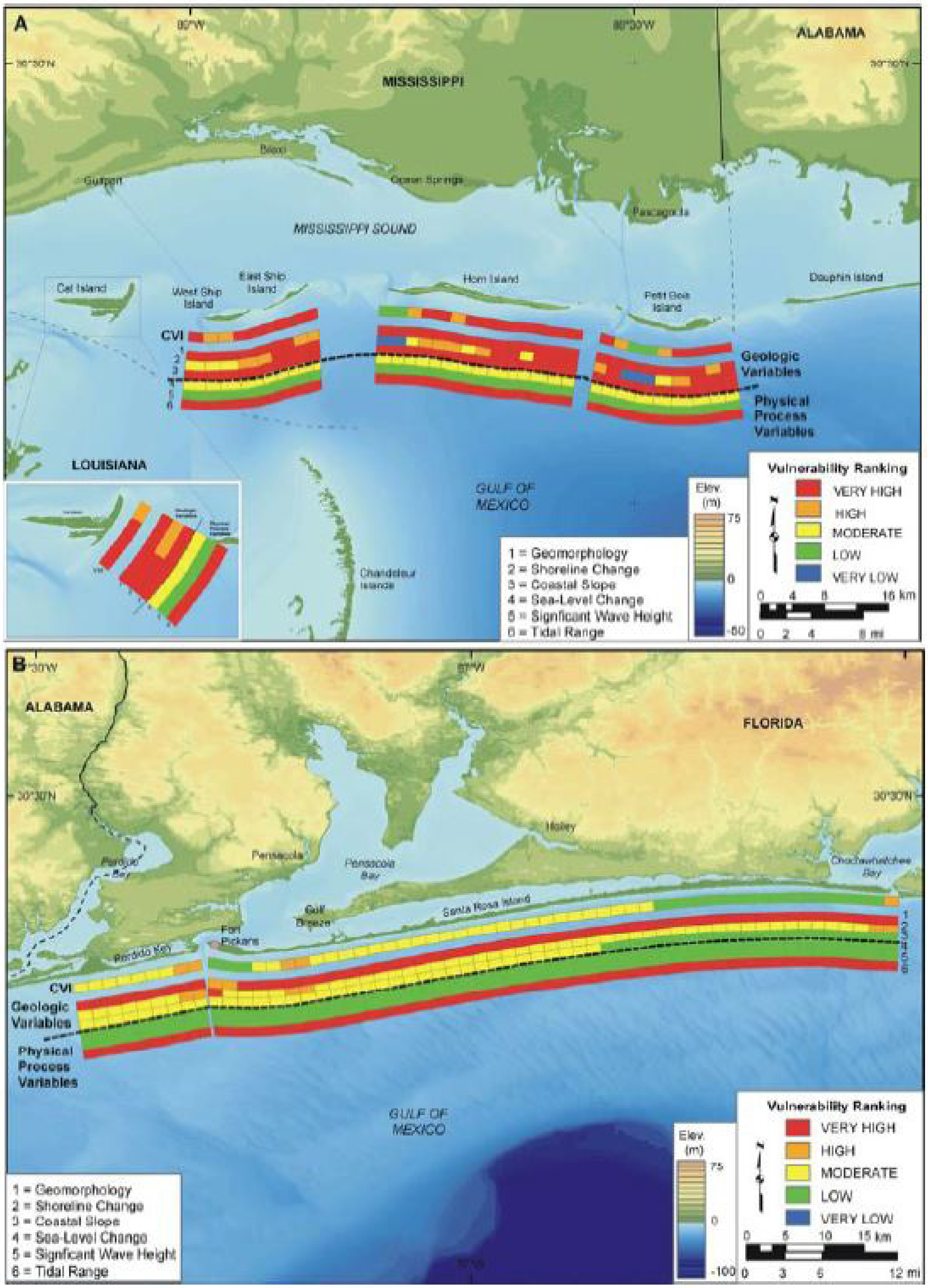

Figure 27. Coastal vulnerability index map for Gulf Islands National Seashore.
The graphic shows the relative coastal vulnerability of park islands to sea level rise. (A) The very high vulnerability shoreline is generally along the eastern Mississippi islands. (B) In Florida, Perdido Key and western Santa Rosa Island have moderate vulnerability and eastern Santa Rosa Island has low vulnerability. The innermost color bar is the relative coastal vulnerability index (CVI) calculated from six geologic and physical process variables. High vulnerability shoreline is concentrated around areas with a shoreline change rate between ± 1 meter. Graphic from Pendleton et al. (2004, figure 9).

Table 7. Major recent hurricanes affecting Gulf Islands National Seashore.

Sources: Browder and Dean (1999), Beavers and Selleck (2005), Houser et al. (2007), NPS (2007), Claudino-Sales et al. (2010), NPS (2014), Sankar (2015), and Anderson et al. (2016a).

Hurricane	Date	Metrics (at time of landfall near park)	Affected area	Impacts
Frederic	9/12/1979	Category 3 Winds 233 kph (145 mph) Storm surge 3.7–4.6 m (12–15 ft) on Gulf Coast beaches	MS, FL	In MS, overwash extended several hundred meters inland and reached the island centers and the sound shores, locally destroying tall foredunes. In FL, foredune retreat and 18 m (60 ft) of beach erosion along Perdido Key.
Erin	8/3/1995	Category 2 Winds 161 kph (100 mph) Storm surge 2 m (7 ft) at Navarre Beach, 1.2 m (4 ft) at Pensacola Beach	FL	Damaged Fort Pickens Road and J. Earle Bowden Way. Dune erosion. Caused 990,000 m^3 (129,000 yd^3) of erosion along a 12-km (8-mi) stretch of renourished beach on Perdido Key, with most of the sand being transported into the pass, and beach retreat of 18 m (60 ft). Nearly complete removal of foredunes along Perdido Key.
Opal	10/4/1995	Category 3 Maximum sustained winds 185 kph (115 mph) Maximum significant wave height 8.3 m (27 ft) off of Perdido Key Storm surge up to 5 m (15 ft) at Navarre Beach and 3–4 m (10–13 ft) at Pensacola	FL	Damaged Fort Pickens Road and J. Earle Bowden Way. Dune erosion. Caused 990,000 m^3 (129,000 yd^3) of erosion along a 12-km (8-mi) stretch of renourished beach on Perdido Key, with most of the sand being transported into the pass, and beach retreat of 18 m (60 ft). Nearly complete removal of foredunes along Perdido Key.
Georges	9/28/1998	Category 2 Winds 161 kph (100 mph) Storm surge 2–3 m (5–10 ft) at Pensacola	MS, FL	Damaged Fort Pickens Road and J. Earle Bowden Way. Beach erosion and washover deposition.
Ivan	9/16/2004	Category 3 Winds up to 209 kph (130 mph) Sustained winds of 40 m (130 ft) per second Storm surge 0.9–1.4 m (3–4.5 ft) at Perdido Key	MS, FL	Overwash, breaching, erosion of dunes and beaches. Covered Santa Rosa Island wetlands with washover sand. Net loss of sediment to the offshore region. Substantial damage to Fort Pickens Road, J. Earle Bowden Way, contemporary and historic structures, a campground, utilities, and landscapes. Perdido Key: Washover deposits extended over 140 m (450 ft) inland. Destruction of the berm, frontal dune, and substantial portions of secondary dunes. Foredune elevation decreased from approximately 4 m (12 ft) prior to the storm to 2 m (5 ft) after the storm. Shoreline retreat of 6 m (20 ft). In MS, overwash extended several hundred meters inland and reached the island centers and the sound shores, locally destroying tall foredunes.
Tropical Storm Arlene	6/11/2005	Winds 97 kph (60 mph) Storm surge 0.4 m (1.3 ft) Storm tide (surge + tide) 1.2 m (3.9 ft)	FL	Damaged Fort Pickens Road and J. Earle Bowden Way. Beach erosion and breaching.

Table 7 (continued). Major recent hurricanes affecting Gulf Islands National Seashore.

Hurricane	Date	Metrics (at time of landfall near park)	Affected area	Impacts
Dennis	7/10/2005	Category 3 Winds 195 kph (121 mph) Storm surge 2 m (7 ft) at Navarre Beach and 1.2–1.8 m (3.9–5.9 ft) at Pensacola	FL	Damaged Fort Pickens Road and J. Earle Bowden Way. Substantial beach and dune erosion. Perdido Key shoreline retreated 15 m (50 ft) and foredune complex was converted to washover platform.
Katrina	9/28/2005	Category 3 Winds 193 kph (120 mph) Storm surge 9 m (30 ft) Flow depth of the storm surge was at least 6 m (20 ft) on Cat Island, 7 m (23 ft) on West Ship Island, 8 m (25 ft) on East Ship Island, and 4 m (13 ft) on Horn Island. At Pensacola storm surge was 3–6 m (10–20 ft)	MS, FL	Caused pre-storm dunes and ridges on Petit Bois Island to migrate landward. Large pieces of shipwrecks carried far inland. Destroyed all NPS facilities on West Ship and Horn Islands except Fort Massachusetts. Severely damaged Davis Bayou unit (MS) and facilities in Florida. Damaged Fort Pickens Road and J. Earle Bowden Way.
Gustav	9/1/2008	Storm tides 2 m (7 ft) at Pascagoula Wind gusts 30 m (100 ft) per second	FL, MS	Perdido Key dune lowering. East Ship Island: algal flat expansion, foredune blowout, conversion of vegetated habitat to bare sand, and land area expansion and overwash created intertidal zone extending from island core down length of the northeast spit. Sand Island: spit reworking and land growth on island's southeast flank.
Ike	2008	No data	FL	Perdido Key dune lowering
Tropical Storm Fay	2008	Storm surge 1.5 m (4.9 ft)	FL	No data
Tropical Storm Ida	2009	Storm surge 1.3 m (4.2 ft)	FL	Perdido Key dune lowering
Tropical Storm Claudette	2009	Storm surge 1.2 m (3.9 ft).	FL	No data
Tropical Storm Lee	9/4/2011	Winds 72 kph (45 mph)	MS	Heavy rainfall and flooding. Ship Island: Damaged pier and eroded beach along southern side.
Tropical Storm Debby	7/2012	Waves 2.1 m (6.9 ft) Elevated water level of 0.15 m (0.49 ft) above normal tide level	FL	Erosion along Perdido Key.
Isaac	8/29/2012	Storm tides 2 m (7 ft) at Pascagoula Wind gusts 32 m (105 ft) per second	MS	East Ship Island: Growth of southeast spit, 23 ha (57 ac) added. Sand Island: southwest flank erosion, 11 ha (4.5 ac) lost.
Nate	10/7/17	Category 1	FL	Damage to Fort Pickens Road through the Fort Pickens area and Highway 399 through the Santa Rosa area. Road closures for nearly 2 months.

susceptible to large-scale modification, resulting in increased vulnerability of the coast (Sankar 2015).

When bathymetry is modified by major storms, nearshore wave conditions change. Bathymetric and shoreline changes driven by cyclones and ongoing erosion have caused northeastward rotation of eastern West Ship Island and Petit Bois Island and to a lesser extent, Horn Island. Because those islands have an east–northeast to west–southwest shoreline orientation, in contrast to the east–west trend of barrier islands to their east, they are more susceptible to hurricane waves, which approach from the south–southeast and south–southwest. As a result, land loss has been higher on the eastern end of the vulnerable islands (Otvos and Carter 2008).

Overwash during several major hurricanes (e.g., Ivan, Frederic, and Katrina) extended several hundred meters inland and reached the Mississippi island centers and the sound shores, locally destroying tall foredunes (Otvos and Carter 2008). The tallest dunes in the interior of West Ship Island and elevated parts of Horn Island provided barriers to overwash (Ervin Otvos, University of Southern Mississippi, professor emeritus, written communication, 4 February 2007, as cited in NPS 2007).

Barrier island response to extreme storms depends on both the magnitude of the storm and the pre-storm morphology (Houser et al. 2007). For example, the morphological response of Santa Rosa Island to Hurricane Ivan was found to vary with the height of the foredune relative to the elevation of the storm surge. Where overwash was restricted by closely spaced dunes, offshore sediment erosion increased (Houser et al. 2007). Dune survival depends on barrier island width, dune height, and storm duration and frequency (Claudino-Sales et al. 2008).

Hurricane Katrina

In 2005, Hurricane Katrina caused significant damage and changes along the Gulf of Mexico coast when it passed west of the Mississippi barrier islands (Flocks et al. 2011b). Although it was only a Category 3 storm when it hit the coast, it had very high water levels because of the wave setup generated prior to landfall when it was a Category 5 storm (Fritz et al. 2008). Another factor was the storm's large size—a radius of 50 km (30 mi) and a 140 km (90 mi) swath of hurricane force winds (Fritz et al. 2007).

Storm surge reached heights of 6.9 m (23 ft) on Cat Island, 9.2 m (30 ft) on West Ship Island, 8.2 m (27 ft) on East Ship Island, 5.7 m (19 ft) on Horn Island, and 4.9 m (16 ft) on Petit Bois Island, as indicated by bark stripped off trees, mud lines, and rafted debris (Fritz et al. 2008).

East Ship Island lost all its pine trees during the storm (fig. 28), and Horn Island lost 80% of its slash pine (*Pinus elliotti*) (Otvos and Carter 2008; Lucas and Carter 2013) because of the combined effects of wind damage, salt spray, and saltwater immersion (chloride toxicity), followed by a severe, months' long, post-Katrina drought that prevented soil flushing. Cat Island's lower pine mortality may be attributed to the protective effects of topography and bathymetry (Otvos and Carter 2013).

The storm widened the widths of all the channels between Cat and Dauphin Islands by a total of 37% (Fritz et al. 2007). The eastern ends of all three Mississippi barrier islands were eroded and reoriented to the southeast wave direction (Houser 2011). Most of the sediment eroded from the beachface and dune systems was stored in nearshore bars (Houser 2011). Washover deposits on the islands extended 150 to 200 m (500 to 650 ft) inland in thicknesses of 20 to 80 cm (8 to 30 in) (Dalal 2006).

Along the Mississippi barrier islands, the hurricane's morphological impact was related to the average pre-storm elevation. The Ship Islands lost a significant amount of land from both ends because of lower pre-storm elevation (Houser 2011). Inter-ridge swales directed storm waters to the East Ship Island interior, further reducing its area (Otvos and Carter 2008). In contrast, the western ends of Petit Bois and Horn Islands gained volume, and their shorelines accreted via sediment transport from the east.

On Petit Bois Island, the high surge and elevated wave energy caused the pre-storm dunes and ridges to migrate landward in a similar manner to nearshore bars in the inner surf zone. Also, no significant change in elevation or bathymetry took place. This behavior is attributed to the extreme surge levels, which would have covered the island, and an exponential increase in significant wave height, thus prohibiting the island from progressing through the impact regimes proposed by Sallenger (2000). The landward migration of the dune sections was related to the pre- and post-storm dune height and connectivity (Houser and Greenwood 2007). The spit terrace on the eastern end of Petit Bois Island lost 1.5 m (4.9 ft) of elevation and migrated 315 m (1,033 ft) toward the Mississippi Sound.

On Horn Island, hurricane waves removed the upper 1–2 m (3–7 ft) of the relict dunes even in the island interiors (Otvos and Carter 2008). The eastern 3-km- (2-mi-) long sand spit eroded away, and on the western end, a 700-m- (2,300-ft-) wide breach separated the tip of the island, causing an overall loss of 20 ha (50 ac) (Otvos and Carter 2008). Washover sand was deposited as much as 430 m (1,410 ft) inland; more washover fans were deposited toward the western end of the island than on the eastern end (Morton 2010).

Park infrastructure was also damaged. On West Ship Island, Hurricane Katrina removed all structures except for Fort Massachusetts. On Horn Island and in Davis Bayou, multiple structures were damaged (Jolene Williams, Gulf Islands National Seashore, environmental protection specialist, GRI review comments, 3 September 2017).

The combined hurricane seasons of 2004 (Hurricane Ivan) and 2005 (Hurricanes Dennis and Katrina) transformed Santa Rosa Island. Washover terraces displaced the discontinuous foredune backed by hummocky back-barrier dunes and maritime forest. In the gaps between dunes, overwash corridors formed, extending all the way across the island to Santa Rosa Sound (Houser et al. 2015b).

Geomorphologic impacts of Hurricane Katrina are captured in the GRI GIS data because source maps

Table 8. The Saffir-Simpson Hurricane Wind Scale.

Source: National Hurricane Center. 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 Caused by Hurricane Winds
1	74–95 mph 64–82 knots (kt) 119–153 kph	**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.

Figure 28. Photograph of East Ship Island.
Hurricane Katrina killed many trees on East Ship Island. Photograph is taken from the Mississippi Sound looking southward across the island. NPS photograph by Courtney Schupp taken 22 July 2015.

were developed using aerial orthophotographs taken approximately two years after the storm.

Impacts of Hurricanes on Park Infrastructure

Recent hurricanes have caused repeat damage to park infrastructure such as roads, campgrounds, and buildings in both the Mississippi and Florida portions of the park. Table 7 summarizes these impacts.

A study of road damage on Santa Rosa Island (Houser et al. 2007) found that the road sections that had little to no damage were located close to the shoreline in areas with higher elevation, such as along large foredunes or high and wide upper foreshore berms. These areas tended to be in wider sections of the island (the cuspate forelands) with a dissipative (gently sloped) offshore profile. Road sections with major damage were generally along the back of the barrier and in narrow sections of the island where the offshore profile was reflective (steep). These areas were also characterized by a low-island elevation (poorly developed foredunes or small berm) and no secondary dunes. Areas where the road received extensive damage will continue to be the areas of concern for infrastructure maintenance (NPS 2007).

Impact of Climate Change on Hurricanes

Hurricane wind speed is predicted to increase, along with rainfall intensity and storm surge height and strength (Carter et al. 2014). Future storm surge and wave runup will be superimposed on rising mean sea level, which increases the impact of storm events (Tebaldi et al. 2012; Goldstein and Moore 2016).

Storm Recovery

The development of dunes in narrow sections of barrier islands is limited by the low supply of nearshore sediment (Houser et al. 2015b). Also, narrow sections of barrier islands are more likely to be significantly eroded by overwash during storms, according to studies along Perdido Key and Santa Rosa Island (Houser et al. 2015b; Sankar 2015).

Studies along Santa Rosa Island found that post-storm recovery of the beachface and dune system correlates with island width, height of the pre-storm dunes, overwash penetration, offshore bathymetry (the locations of transverse ridges on the inner shelf) (Houser and Hamilton 2009), and the landward migration of nearshore bars (Houser et al. 2015b). Natural dune recovery was also directly related to the timing, strength, and frequency of storms, according to a study along Perdido Key. For example, the impacts of Hurricane Dennis in 2005 were magnified by the preceding passage of Hurricane Ivan in 2004. The dune lowering caused by Hurricane Ivan made the island more susceptible to enhanced erosion during the storms that followed, particularly in the low and narrow portions of Perdido Key, where foredunes were completely flattened and sand was redistributed as washover sheets (Sankar 2015). The speed at which a dune recovers from storm impacts will shape the future vulnerability of the island to storm events and to sea level rise (Houser et al. 2015b).

Where adequate sand volumes are available from updrift islands and platforms, transported sand will repair breaches across the central and downdrift portions of islands (Otvos and Carter 2008). Shoals and bars regenerate and merge into subtidal bars, emerging berms, or adjacent islands. For example, after Hurricane Georges in 1998, nearshore bars fed the reemergence and growth of a long sand shoal connecting East and West Ship Islands (Otvos and Carter 2008).

Dredging of Inlets

Inlet dynamics are a critical component of natural barrier island processes and sediment transport. The “Inlets” section in the “Geologic Features and Processes” chapter provides more information about inlets at the park. Anthropogenic modifications, such as dredging and jetty stabilization, disrupt an inlet’s ability to respond to storms, bypass sediment between islands, exchange sediment between flood- and ebb-tidal deltas, migrate, and 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, mitigate erosion, and maintain navigation channels, but these modifications have commonly altered the behavior of coasts considerably (Williams 2013).

The park’s foundation document (NPS 2016a) identified alteration of the sand transport system via dredging as one of the park’s most pressing issues because of potential adverse impacts on the barrier islands, including effects on natural physical processes. The foundation document also recognized increased public interest in dredging a pass through Santa Rosa Island east of Navarre Beach (fig. 1), which would affect the park by changing alongshore sediment transport and estuarine circulation patterns.

Dredging occurs in three inlets (locally called “passes”) near the park: Pensacola Pass (Florida), Ship Island Pass (Mississippi), and Horn Island Pass (Mississippi) (fig. 1). Other passes in the vicinity include East Past (Florida) and Dog Keys and Petit Bois Passes (Mississippi). The “Coastal Engineering and Beach Nourishment” section of this chapter, figure 22, and table 9 provide details about beach nourishment projects affecting the park.

East of the Mississippi barrier islands, dredge spoil disposal from the deep Mobile Pass shipping channel, which crosses an extensive ebb-tidal delta, may be diminishing or even terminating westward littoral drift, thereby contributing to long-term island erosion downdrift along the Mississippi–Alabama island chain (NPS 2007).

Pensacola Pass

The Pensacola Channel was authorized in 1878 and excavated in 1883 as an 8-m- (25-ft-) deep entrance channel. Migration of Santa Rosa Island is causing the throat of the pass to migrate westward (Browder and Dean 1999).

The sedimentation rate of the channel is approximately 229,000 m3 (300,000 yd3) per year (Florida Department of Environmental Protection 2000). From 1880 to 1960, the channel was dredged annually. The dredged material was placed in an offshore disposal site (Florida Department of Environmental Protection 2015). The channel was deepened in 1959 to 11 m (37 ft), and

Table 9. Statistics of beach nourishment events affecting Gulf Islands National Seashore.

(1) Anderson et al. 2016a; (2) Browder and Dean 1999; (3)Florida Department of Environmental Protection 2015; (4) Ford 2013; (5)Marsh 2016; (6)NPS 2011; (7) Otay and Dean 1993; (8) Pensacola News Journal 2016; (9) USACE 2013; (10) USACE 2016a; (11) Western Carolina University 2016; (12) Jolene Williams, Gulf Islands National Seashore, environmental protection specialist, GRI review comments, 5 September 2017; (13) Jolene Williams, Gulf Islands National Seashore, environmental protection specialist, MsCIP meeting notes, 28 September 2017; (14) Jolene Williams, Gulf Islands National Seashore, environmental protection specialist, written communication, 27 December 2017

Placement Location	Year(s)	Length (m)	Length (ft)	Volume (m^3)	Volume (yd^3)	Source (see above)
Cat Island	2017	5,800	19,000	1.9 million	2.5 million	13
Sand Island/DA-10	1917–2010	Varied	Varied	5.3 million	6.9 million	10
	2009–2010	Unknown	Unknown	Unknown	400,000	1, 14
	2012	Unknown	Unknown	841,000	1.1 million	4
Fort Massachusetts	1974	Unknown	Unknown	382,277	500,000	11
	1980	Unknown	Unknown	76,000	100,000	11
	1984	Unknown	Unknown	160,000	210,000	11
	1991	206	676	44,000	58,000	11
	1996	Unknown	Unknown	42,000	55,000	11
	2002	Unknown	Unknown	Unknown	Unknown	5
	2012	3,155	10,350	432,000	565,000	11
Camille Cut	2017–2018	5,630	18,480	In process as of December 2017	In process as of December 2017	14
Perdido Key beach	1980	7,481	24,544	4.0 million	5.3 million	11
	1985	1,585	5,200	1.9 million	2.4 million	11
	1989–1990	7,481	24,544	4.1 million	5.4 million	7, 11
Perdido Key nearshore (6 m [20 ft] water depth)	1989–1991	7,500	24,600	3.0 million	3.9 million	2
	2011–2012	2,865	9,400	400,000	520,000	3, 6
	2016	2,865	9,400	Unknown	Unknown	12
Santa Rosa Island	1961	Unknown	Unknown	57,600	75,300	11
Pensacola Beach	2003	13,036	42,768	3.2 million	4.2 million	11
	2006	8047	26,400	2.2 million	2.9 million	3
	2016	13,036	42,768	1.3 million	1.7 million	11
Navarre Beach	2006	6,600	21,700	2.3 million	3.0 million	9
	2010	490	1,600	9,100	12,000	9
	2016	6,600	21,700	990,000	1.3 million	8, 9

the dredged material was placed on Santa Rosa Island (Florida Department of Environmental Protection 2000). Dredged material was also placed in Perdido Key for beach nourishment purposes several times over the last few decades (Florida Department of Environmental Protection 2015).

Significant shoreline changes near Pensacola Pass resulted from the large dredging and nourishment project conducted between 1989 and 1991, when the pass was deepened to 15 m (48 ft) deep and 240 m (800 ft) wide to accommodate a naval aircraft carrier (Browder and Dean 1999). The project created two major perturbations in the system: (1) a substantially over-dredged channel and (2) a large quantity of dredged sand, which was placed along the beach and in the nearshore. The project also reduced the volume of the ebb shoals surrounding the inlet and created an overall loss of sediment from the littoral system.

In total, approximately 35 million m3 (46 million yd3) of material was removed from the channel between 1883 and 1991, and only 14 million m3 (19 million yd3) of that volume was placed on or near the adjacent shoreline. Maintenance dredging has accelerated erosion rates along Perdido Key and Santa Rosa Island (Browder and Dean 1999).

Ship Island Pass / Gulfport Channel

Ship Island Pass separates Cat Island and West Ship Island (fig. 1) by about 8 km (5 mi) of open water that overlies a shallow sand bottom. A natural channel, more than 9 m (30 ft) deep, is located along the western edge of West Ship Island. The channel has been moving westward because of longshore transport of sediment (USACE 2015).

The Gulfport Channel (in Ship Island Pass) was established by the River and Harbors Act of 1899. In 1993, the pass was relocated 580 m (1,900 ft) to the west to allow West Ship Island to continue migrating westward for 50 years (NPS 2007). The old channel was never backfilled (Chaney 1999) and is now used as an impoundment to prevent the new channel from filling (NPS 2007). It also continued to be used as a source for beach nourishment, and therefore continued to impede westward migration (Toscano 2004).

Sediment dredged during channel maintenance is deposited in open water sites along the length of the navigation channel. Sandy sediment that is dredged from a small area near the barrier islands is placed in an open water site southeast of Cat Island (USACE 2015). Byrnes et al. (2013) provides a detailed accounting of dredged volumes and placement locations for Ship Island Pass, 1899–2009.

Horn Island Pass / Pascagoula Channel

Horn Island Pass, at the west end of Petit Bois Island, separates Horn and Petit Bois Islands (fig. 1) and is about 6 km (4 mi) wide. A portion of the pass is dredged to a maximum depth of more than 12 m (40 ft) to provide access for the Pascagoula Port shipping channel (NPS 2007) but most of the pass is less than 3 m (10 ft) deep. Byrnes et al. (2013) provides a detailed accounting of dredged volumes and placement locations for Horn Island Pass, 1899–2009.

East Pass

East Pass marks the eastern end of Santa Rosa Island, near the Okaloosa area of the park (fig. 1). It connects Choctawhatchee Bay to the Gulf of Mexico. It was formed when the island breached during storms in 1928 and 1929 (Morang 1992). Between 1928 and 1968, the inlet's throat was stable but the channel migrated over a developing ebb-tidal delta. The inlet was stabilized with rubble-mound jetties in 1967–1969. In 1977, a 90-m-(300-ft-) long spur jetty was built to divert the flow of water farther toward the center of the channel. This has caused deep scour holes to form at the toe of the spur (Morang 1992).

East Pass and Old Pass Lagoon (also known as Destin Harbor) are maintained navigation channels that are periodically dredged.

East Pass is now migrating eastward (Kish and Donoghue 2013) for three reasons: (1) because waves approach from the southwest; (2) because ebb currents are directed toward the eastern side of the inlet as a consequence of the shape of the flood-tidal shoal and channel within the bay; and (3) as a result of freshwater inputs, the ebb current, which flows along the east side of the pass, has a higher velocity and a longer duration than the flood current, which flows along the western side of the pass (Santa Rosa Island) (Morang 1992).

Dog Keys Pass

Dog Keys Pass lies between East Ship and Horn Islands (fig. 1) and has a maximum depth of 10 m (32 ft) but is less than 3 m (10 ft) deep for most of its 9 km (6 mi) width. It is the widest pass in the system and the only one in the Mississippi barrier chain that acts as a net sediment sink, leading to a sand deficit along the downdrift East Ship Island (Byrnes et al. 2012).

Petit Bois Pass

Petit Bois Pass separates Petit Bois and Dauphin Islands (fig. 1) and has a maximum depth of 7 m (22 ft) but is 1.5 to 3 m (5 to 10 ft) deep for most of its 9 km (6 mi) width. It does not have a maintained deep shipping channel.

Coastal Engineering and Beach Nourishment

NPS *Management Policies 2006* (Sections 4.1 and 4.8 and related subsections) 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. Appendix B of this report provides additional information on relevant legislation and policies.

The park's enabling legislation (Public Laws 91-660 and 95-625) specifies that beach erosion control, hurricane protection, and spoil sediment deposition must be planned jointly between the USACE and Department of the Interior. These two agencies continue to build partnerships that enable effective beach control and hurricane protection as well as collaborate on placing dredged sand back into the active transport system.

Seawalls and other structures that attempt to inhibit wave impacts are expensive and do not prevent sediment loss in front of the structures. Instead, they commonly accelerate erosion locally 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 (McDowell Peek et al. 2016). Laws, regulations, and policies that apply coastal structures in parks are listed in Appendix B of this report.

Alternative erosion control structures such as sandbags are sometimes used 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. The beach in front of the sandbags is lost to wave energy, and erosion on adjacent beaches increases (McDowell Peek et al. 2016).

Beach nourishment, another temporary solution, requires the availability of compatible sediment within a reasonable transport distance. This can be an attractive option because it quickly increases beach width, reduces wave energy near infrastructure, offers protection from moderate water rise, and can promote tourism. However, the solution is temporary because beach nourishment does not reduce or eliminate erosive processes. Moreover, it can encourage increased human development in high-risk areas. Also, finding sufficiently large quantities of sand compatible with the eroding beach can be difficult (McDowell Peek et al. 2016). 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, and dredging can have physical and biological impacts on the dredge site (Byrnes et al. 2004; Hayes and Nairn 2004). Removal of sediment from within the regional sediment system, such as from inlet passes and shoals, has impacted the Gulf barrier islands (Browder and Dean 1999; Toscano 2004; Finkl 2012).

Studies have found that many human mitigation efforts, such as beach nourishment, result in little reduction in barrier island migration rates and result in barrier island vulnerability to collapse (Moore et al. 2007). Human activities that reduce deposition by overwash may increase island migration rates (Moore et al. 2015).

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

Fort Massachusetts Stabilization and Renourishment

Historic Fort Massachusetts (fig. 12 and front cover) on West Ship Island has been threatened by coastal erosion for over a century. In 1917, the USACE constructed a seawall and groin on Ship Island in an attempt to protect the fort. During the mid-1960s, local citizens on a "Save the Fort" committee further constructed a circular rock jetty around the fort as a makeshift breakwater (NPS 2007).

Periodic beach nourishment began in March 1974 with the placement of sand dredged from Ship Island Pass; table 9 summarizes beach nourishment statistics. Erosion of the new beach rapidly took place, with the loss of more than 1 m (3 ft) per month during the winter storms of 1974–1975 (Henry 1978). The circular rock jetty was re-exposed in 1975, and by August 1977 the beach had retreated to within 15 m (50 ft) of the fort. Subsequent renourishment efforts rapidly eroded because of sound side processes and winter storms (Chaney 1993; Stone et al. 1998), allowing water to surround the fort (Toscano 2004).

A 1995 study found that old piles of rock and concrete at the location of the old Ship Island Lighthouse and just west of the Fort Massachusetts pier were restricting east-to-west sand movement along the north shore, exacerbating erosion around the fort (Oivanki 1995).

More recently, the Fort Massachusetts beach was renourished in 1996 and 2002 using sediment from the old Ship Island Pass (which had been closed in 1993 to allow westward island migration), thus maintaining a sand sink that is preventing island migration (Toscano 2004). As part of Mississippi Coastal Improvement Program, it was renourished again in 2012, the old piles and concrete were removed, and rows of grasses were planted to stabilize the adjacent dunes.

Perdido Key Stabilization and Renourishment

Due to the deepening of Pensacola Pass, erosion along Perdido Key accelerated between 1984 and 1996. The beach was renourished with material that was dredged from the pass several times between 1980 and 2016. Table 9 provides details. To mitigate human-caused disruption to sediment transport, the NPS allowed the renourishment; placement is intended to help preserve natural processes such as overwash and island migration (NPS 2007).

Two small jetties, part of the historic Fort McRee, are located on the Perdido Key side of Pensacola Pass, but are believed to have minimal effect because of their relatively small size and location, well back in the inlet throat (Dean et al. 2006).

Pensacola Beach Renourishment

Pensacola Beach was nourished three times between 2003 and 2016. Table 9 provides details. The 2003 renourishment used sand from a borrow site located about 5.6 km (3.5 mi) offshore to expand the beach width to 58 m (191 ft). Approximately 19% of the sediment used in the 2006 nourishment event was recovered storm washover material (e.g., cleared from roads) (Florida Department of Environmental Protection 2015).

Navarre Beach Renourishment

In 2006, Navarre Beach was renourished with sediment dredged from East Pass, and a vegetated dune was constructed, replacing an emergency protective berm that had been funded by the Federal Emergency Management Agency. Table 9 provides details. Sediment was sourced from a borrow area located about 6 km (4 mi) offshore. In 2010, an upland borrow site was used to add sediment to the western end, adjacent to the park. Additional nourishment was completed in spring 2016 (Florida Department of Environmental Protection 2015; Pensacola News Journal 2016).

Mississippi Coastal Improvements Program

In 2009, the Mississippi Coastal Improvements Program (MsCIP) was developed by the USACE Mobile District in conjunction with other federal and state agencies to help reduce future storm damage along the Mississippi Gulf Coast. The program has a barrier island restoration component with four objectives: (1) maintain the estuarine ecosystem and resources of the Mississippi Sound, (2) preserve the natural and cultural resources of the Mississippi barrier islands, (3) restore the barrier islands structure to reduce storm damage impacts on the mainland coast of Mississippi, and (4) enhance the long-term littoral drift system for the Mississippi barrier islands (Read 2015; USACE 2016b).

To restore a portion of the Mississippi barrier islands, sand will be placed at and adjacent to Camille Cut in an effort to connect East and West Ship Islands and to augment sediment to the updrift system along East Ship Island. Restoration of Camille Cut began in December 2017. Over a period of two-and-a-half years, 10.3 million m^3 (13.5 million yd^3) of sand will be placed in the 5.6 km (3.5 mi) wide Camille Cut and planted with dune vegetation (NPS 2016b). An additional 4.2 million m3 (5.5 million yd^3) of sand will be placed along the southern shoreline of East Ship Island. Sand will be excavated from five borrow sites outside, or partially outside, waters of the state of Mississippi. No sand will be dredged from Sand Island (DA-10) or within the boundaries of the park (NPS 2016b). Turbidity barriers to protect the seagrass beds were placed on the north sides of East and West Ship Islands before infilling of Camille Cut began. Modelling suggested that by restoring Ship Island, storm surge height at the mainland beach will be reduced by as much as 1.25 m (4.10 ft) (USACE 2016a).

Additional sand has been placed on the northern shore of West Ship Island around Fort Massachusetts. Restoration of the eastern beach fronting Cat Island, including beach nourishment and dune planting, was completed in November 2017. Table 9 provides details. The MsCIP plan also modifies dredging practices for Horn Island Pass to enhance the natural sediment transport to Horn Island. In the future, maintenance dredging will place the material on the south and west portions of the existing Sand Island (DA-10) and the northern portion of the disposal site south east of Horn Island, all within park boundaries (NPS 2016b). The USACE places approximately 300,000 m^3 (400,000 yd^3) at Sand Island/DA-10 every 18 months when performing maintenance dredging in the Pascagoula Channel (Jolene Williams, Gulf Islands National Seashore, environmental protection specialist, email communication, 27 December 2017).

Dog Keys Pass and Little Dog Keys Pass have been sand sinks throughout the historical record, resulting in limited sand movement from Horn Island to East Ship Island and associated coastal erosion along East Ship Island. Restoration of Ship Island is intended to augment the natural littoral transport system and to create subaerial and subaqueous habitat within the barrier island system. This sediment addition, in combination with hydrologic changes resulting from the closure of Camille Cut, could increase sedimentation in Ship Island Pass, particularly during hurricane events. Closure of Camille Cut is expected to change estuarine circulation patterns.

The MsCIP Monitoring and Adaptive Management Program will be implemented before, during, and after project construction, allowing assessment of restoration progress and adjustments to the project as part of an adaptive management strategy (USACE 2016b). The strategy will be informed by collection of wave measurements seaward and landward of Camille Cut; surveys of the hydrologic circulations patterns through Ship Island Pass, Little Dog Keys Pass, and Dog Keys Pass; lidar topography; aerial photography; land and water habitat classifications; nearshore bathymetric surveys; sand tracer study; beach shear strength and compaction testing; pre- and post-construction surveys of Horn Island dredge placement, navigational channel, and extensions; and a contingency plan for storm-related bathymetry and/or lidar surveys (USACE 2016b). More information about the project is available at the US Army Corps of Engineers Program and Project Management page.

Impacts to Wetlands

In at least two park areas, natural flow and drainage are blocked by walkways and wetland drainage modifications (e.g., damming and diking). The park's general management plan (NPS 2014) outlines wetland restoration strategies to include the following:

- Davis Bayou unit: Replacement of impermeable pavement with permeable surfaces would increase infiltration and reduce sheet flow into adjacent wetlands.
- Cat Island: A comprehensive wetland restoration effort would be made to restore natural processes via wetland restoration, including possible removal of dikes (earthen berms) that block the natural flow of water.

Coastal wetlands are highly vulnerable to climate change, not only in response to sea level rise. Macroclimate (e.g., temperature and precipitation regimes) greatly influences coastal wetland ecosystem structure and function. A study by Gabler et al. (2017) projected that transformative ecological changes are probable throughout the Gulf region this century, even under conservative climate scenarios.

Visitor Use Impacts

Providing access to nearly 5 million visitors annually results in a variety of impacts to park resources. Impacts include social trails—improvised access points between dunes that are created by visitors despite the presence of established boardwalks. The proliferation of social trails increases dune erosion. Moreover, sand sliding and similar activities adversely affect the dunes on the barrier islands and a relict dune on the north side of Naval Live Oaks (NPS 2016a). Fragile relict dunes in the park are closed to visitor use, including hiking over them, except on designated boardwalks and access points (Gulf Islands National Seashore 2016). Camping on Horn Island has led to dune blowouts (fig. 29) or flattening of interior dune fields (Gary Hopkins, Gulf Islands National Seashore, biologist, personal communication, 21 July 2015).

Ferry Infrastructure and Use

In the Mississippi portion of the park, a commercial ferry service transports visitors to and from Gulfport Harbor to a pier near Fort Massachusetts on the sound side of West Ship Island (fig. 30). The area around the pier is shallow and may need to be dredged for ferry access in the near future (Jolene Williams, Gulf Islands National Seashore, environmental protection specialist, GRI review comments, 3 September 2017).

Park managers worked with local governments (the City of Pensacola and Escambia County) in Florida to establish a public ferry system. The passenger ferry service will connect the Fort Pickens area with Pensacola Beach and downtown Pensacola, providing an alternative means of accessing the park and maintaining island access when the road is closed following storm damage or other conditions. If in the future the road is not rebuilt, the ferry service could provide the only public access to Fort Pickens (Brown 2015). Construction on the infrastructure began in late 2016, and the ferry is expected to begin service in May 2019.

Boating and Personal Watercraft Use

Private and NPS boats are used to access all the shorelines of the Mississippi barrier islands, except in areas with designated closures. Public launches are available at the Okaloosa, Perdido Key, and Davis Bayou areas of the park. Personal watercraft can be used in any area that motorized boats are allowed. Boats and personal watercraft are not allowed in the Perdido Key lagoons (NPS 2014).

Increased and expanded NPS and private boat use would disrupt natural shoaling processes, including at Cat Island, which is surrounded by submerged sands that form shallow shoals. Increased boat activity and associated wave action also would increase coastal erosion. Additional dredging would be required to accommodate increased boating demand (NPS 2014).

Figure 29. Photograph of blowouts.
Recreational use such as camping has caused dune blowouts in the interior of Horn Island (Mississippi). NPS photograph by Courtney Schupp taken on 21 July 2015.

Figure 30. Photograph of Turtle Runner passenger ferry.
The ferry, shown here with the sound side of Fort Pickens visible in the background, will provide an alternative means of accessing the park and maintaining access to the western end of Santa Rosa Island when Fort Pickens Road is closed following future storm damage or for other reasons. If in the future the road is not rebuilt following damage, the ferry service could provide the only public access to Fort Pickens. NPS photograph.

Seagrass beds, which provide important habitat and stabilize sediment, are also impacted by boats and personal watercraft. Boat propellers cause physical destruction of the seagrass beds, increase sediment resuspension, and potentially increase the susceptibility of seagrass beds to damage from hurricanes. When vessels run aground, vessel operators sometimes free the vessel using the motor's power, which creates large "blow holes" in the vegetation and substrate. Propeller scars also occur where boaters use the propeller to dredge new channels or maintain existing, unmarked channels, also referred to as "wheel ditches." Sediment excavated by boat propellers from blow holes and wheel ditches can form berms adjacent to the holes. Berms may bury seagrass beds, causing vegetation mortality (Duarte et al. 1997; Whitfield et al. 2002). Analysis of aerial photographs taken in 2011 revealed 21.8 km (13.6 mi) of propeller scars through seagrass beds within the park's Florida boundary (Cantor 2012).

Personal watercraft can also impact submerged aquatic vegetation through direct impacts including engine intake and through indirect impacts such as increasing water turbidity and sediment suspension, which reduces light availability and therefore impacts growth (NPS 2014).

Fort Pickens Road

The 11-km- (7-mi-) long Fort Pickens Road provides vehicular access to the western end of Santa Rosa Island, including historic Fort Pickens, a visitor center, and a campground. The road affects dune formation, dune migration, and storm impact on island topography. In 2004, as surge waters from Hurricane Ivan rushed across the roadway, the sand on the north shoulder was destabilized and washed away, creating a 3-km- (2-mi-) long swale that retained water. In 2005, Hurricane Dennis moved considerable amounts of sand across the island, partially filling the swale so that it no longer holds water but is still slightly lower than the surrounding area and stays moist. The swale also captures blowing sand, inhibiting it from reaching and subsequently building the secondary dunes (Houser et al. 2008b).

The road has been damaged repeatedly during storms, leading to extended closures while awaiting repairs. A few inches of water can destroy a road by scouring material from beneath the landward (sound side) edge, causing collapse or even rafting of large sections (Houser 2009), and by causing the top layers of asphalt to peel off when submerged (fig. 31). The asphalt debris ranges in size from large piles to small grains mixed in with sand. Also, the road had to be closed several times because of overwash, which covered the road with sand in early 2016.

Park managers have developed several adaptation strategies for maintaining a paved road through Fort Pickens. In 2009, the road was rebuilt at a lower elevation to allow water to wash over rather than undercut the road. In late 2016 and early 2017, the damaged road was repaved, and 2.4 km (1.5 mi) of that project was moved north (toward Santa Rosa Sound) behind the dune line (Jolene Williams, Gulf Islands National Seashore, environmental protection specialist, GRI review comments, 3 September 2017).

A study by Houser (2009) identified connections between storm–related road damage and island geomorphology. Road damage is not related to the distance between the beach and the road, but to whether a line of dunes is situated between the beach and the road. Where dunes are present, the road is covered with sand but not damaged. Island width and elevation also influence road response. Minimal damage takes place where roads are located near the shoreline on island sections that are wider and higher. In contrast, major damage takes place where a road lies in the back-barrier area, on narrow and lower elevation sections of the island, or landward of a steep offshore profile. Furthermore, where dunes were absent, sheet flow destroys roads. Because island geomorphology controls road damage, areas that experienced damage in the past will continue to be areas of concern regardless of how the road is designed and placed (Houser 2009).

Park managers are concerned about the impact that the asphalt debris may be having on island habitats, particularly turtle nesting grounds (NPS 2007). In January 2016, park managers initiated a five-year project to remove asphalt fragments and road base materials from about 490 ha (1,200 ac) in the Perdido Key, Fort Pickens, and Santa Rosa areas. The priority was removal of abandoned, broken, and partially buried parking lots and road sections in a 0.8 ha (2 ac) area at Opal Beach before shorebird nesting season began in March 2016. By December 2017, approximately 600 m^3 (800 yd^3) of fragments had been removed from more than 46 ha (115 ac). Work is restricted to the fall and winter to avoid interfering with nesting shorebirds and sea turtles (Gabriel 2017).

The park's general management plan (NPS 2014) states that should a destructive storm alter the west end of Santa Rosa Island such that it is no longer feasible to maintain Fort Pickens Road, the campground may be converted to a tent-only facility accessible by the planned ferry service (Brown 2015). At that time, tent cabins (or similar facilities) operated by a concessioner may provide visitors an opportunity to stay overnight at the Fort Pickens campground. Planning and compliance

Figure 31. Photograph of Fort Pickens Road.
The Fort Pickens Road on Santa Rosa Island has been repeatedly damaged by storms. Flood waters can scour material from beneath the road, causing the road to collapse and break apart. Flood waters also may cause the top layers of asphalt to peel off. Asphalt debris ranges in size from large chunks to black grains mixed into white sands. NPS photograph (date unknown).

for this change would take place in the future, at the time of the actions.

J. Earle Bowden Way (US 399)

The 13-km- (8-mi-) long J. Earle Bowden Way provides vehicular access to beaches and day use facilities at Opal Beach and serves as a commuter route between the towns of Pensacola Beach and Navarre Beach and as a secondary emergency evacuation route from Santa Rosa Island. The road is frequently overwashed during storms, for example, requiring about 12 km (8 mi) of repairs following destruction of large portions by Hurricane Ivan in 2004 and subsequent major wind storms (Tropical Storm Arlene and Hurricanes Cindy and Dennis) in 2005.

Visitor Safety

Nearshore water depth interacts with waves and currents to develop rip currents (fig. 32), which are common along the park's shorelines in Mississippi and Florida and pose a safety concern for visitors. Waves break more strongly in some locations than in others, a pattern seen most often along beaches with nearshore bars separated by channels. A rip current forms as the narrow, fast-moving section of water travels in an offshore direction, usually through a break between the nearshore shore-parallel bar (National Weather Service 2004; fig. 32). Their powerful flow moves offshore and can carry swimmers from the shallow water through the gap in the nearshore bars and into deep water. The locations of rip currents change when the nearshore bathymetry changes and when alongshore current directions and strengths change.

The western tip of West Ship Island is known for having strong rip currents, including near old Ship Island Pass. Along Santa Rosa Island, persistent locations of rip currents are controlled by the nearshore ridge and swale bathymetry (Houser et al. 2011; Barrett and Houser 2012). Most beach users occupy sites directly seaward of their primary access point, such as a parking lot, and enter the water very near to where they have settled on the beach (Houser et al. 2015a). During a summer 2010 survey, less than 20% of beach users were able to identify the rip channels and currents, despite most of them believing that they would be able to identify one (Caldwell et al. 2013). Therefore, it is important for park managers to consider the safety aspects of visitor infrastructure, such as parking lots and bathhouses at Fort Pickens, by locating facilities away from hazard areas and by identifying safe swim spots, for example with "Swim between the flags" signs, in addition to providing information that increases swimmers' understanding of rip currents (Houser et al. 2015a).

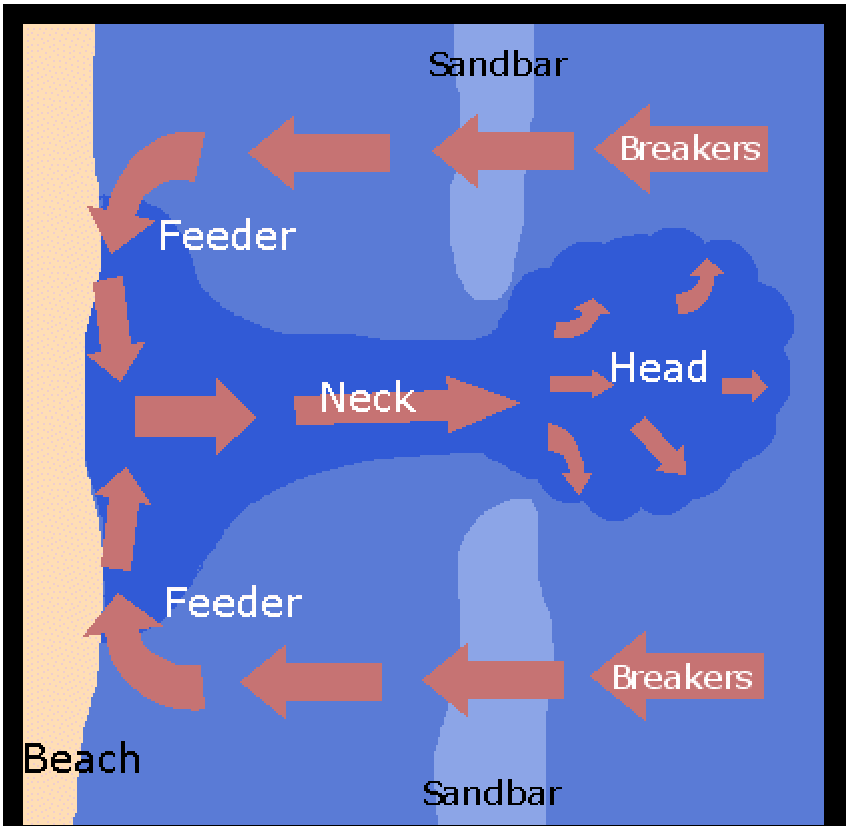

Figure 32. Graphic of rip currents.
Rip currents are strong offshore-directed flows that move through low spots or breaks between nearshore bars. They present a safety hazard for swimmers. National Weather Service Riptide Current graphic.

Decline of Seagrass Beds

Seagrass coverage is declining around the park (Florida Department of Environmental Protection 2001; Handley et al. 2003), likely as a result of increased turbidity and reduced water quality from human activities, including dredging and filling that takes place in harbors and the Intracoastal Waterway; boat traffic; shoreline modification; residential, commercial, and industrial development; hurricane-related effects; loss of barrier–island land area; and decreased salinity resulting from Mississippi River diversions during flood periods (Kenney 2006; Moncreiff 2007a, 2007b; Pham et al. 2014). Seagrass decline along Petit Bois Island may be partially related to the island's rapid westward migration (Morton 2007; Otvos and Carter 2008) and land loss from 1940 to 2007 (Carter et al. 2011). The extent of seagrass coverage has varied over the last decade, with no apparent negative impact of Hurricanes Camille and Katrina (Carter et al. 2011).

The park's general management plan (NPS 2014) identifies designated seagrass bed zones that will be managed to prevent resource damage to seagrass beds from vessel groundings, anchoring, and propeller scarring. Depending on the degree of impacts observed and recorded through NPS monitoring efforts, restrictions may be placed on visitor use in these areas. To prevent any new moderate and severe propeller scars in park seagrass beds, the park's general management plan identified the following management strategies, which will be fully addressed in the marine resources management plan:

- Increase visitor education about seagrass habitat and safe boating practices in seagrass bed zones.
- Improve marking of shallows and other aids to navigation.
- Improve posting of regulations.
- In coordination with the Florida Fish and Wildlife Conservation Commission, additional measures may include more idle or slow-speed zones, mandatory education and/or permits, temporary access limitations (e.g., regulations for sizes of boats), and/or localized area closures.

Water Quality

Land use in contributing watersheds influences the groundwater, biology, chemistry, and ecology of the park. In Mississippi, the distance between the mainland

and the barrier islands reduces water-quality impacts from mainland urban storm water and agricultural runoff, recreational boating, commercial shipping, and the 20 marinas along Mississippi Sound in Jackson and Harrison Counties in which the barrier islands are located.

In Florida, increased urbanization surrounding the park has impacted water quality; factors include pollutant loading in storm water runoff, changes in groundwater recharge rates, oil and gas emissions from watercraft, atmospheric deposition of heavy metals, and sewage effluent disposal. Also, degraded water quality has resulted in the loss of submerged aquatic vegetation (NPS 2014).

All waters within the park's Florida boundaries were designated as "Outstanding Florida Waters" by the Florida Department of Environmental Protection in 1979. This designation forbids issuance of new permits for direct or indirect pollutant discharges that would degrade ambient water quality of the designated waters. Permit requests for new dredging or filling in such designated waters must undergo an intensive review to determine if these activities are clearly in the public interest (e.g., conservation of fish and wildlife, navigation, fishing, recreation, and marine productivity, prevention of erosion and shoaling) (NPS 2014).

Climate-driven changes in precipitation patterns may affect runoff rates, oxygen and other nutrient content, and hydrology (NPS 2014). Increases in extreme precipitation and drought are projected (Runkle et al. 2017).

The Gulf Coast Network is working with the University of West Florida to develop groundwater monitoring protocols to understand where groundwater is being discharged and how this will affect park resources through development-related contamination, saltwater intrusion, and changes in salinity that will affect oyster and scallop habitat (NPS 2007; Cass Bromley, Gulf Islands National Seashore, Resource Management Division chief, conference call, 16 May 2016). A related study by Greg Carter of the University of Southern Mississippi has been using piezometers to monitor groundwater of the Mississippi barrier islands following Hurricane Katrina (Jolene Williams, Gulf Islands National Seashore, environmental protection specialist, GRI review comments, 3 September 2017). Resistivity and temperature-change studies may enable identification of groundwater discharge sources; that data could be gathered at the same time as geologic mapping surveys (seismic and side-scan sonar survey) (NPS 2007).

Abandoned Mineral Lands

Abandoned mineral lands (AML) are lands, waters, and surrounding watersheds that contain facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation, including oil and gas features and operations. The NPS acts under various authorities (see Appendix B) to mitigate, reclaim, or restore AML features in order to reduce hazards and impacts to resources. Resource management of AML features requires an accurate inventory and reporting. The NPS Geologic Resources Division maintains a servicewide AML database, and can assist park managers in recording AML features. An accurate inventory identifies human safety hazards and contamination issues, and facilitates closure, reclamation, and restoration of AML features. An accurate inventory also may identify opportunities for interpretation of AML features as cultural resources. Burghardt et al. (2014) and the NPS AML website provide more information.

The "Old Quarry Trail," also known as the "Old Borrow Pit Trail," is an abandoned borrow pit that was used in building Highway 90. This feature, which is in Naval Live Oaks, is not currently a restoration priority for park managers. If restoration of this area becomes a priority in the future, park managers can contact the NPS Geologic Resources Division for technical assistance. To facilitate future assistance, a record of this site is needed, and park managers should consider documenting this site in the NPS AML database, which currently does not include any listings for the park.

Energy Development

The NPS Geologic Resources Division is available to provide park staff with policy and technical assistance regarding energy issues, including renewable energy development, oil and gas leasing, and oil spills and response (discussed below). The NPS Energy and Minerals Management website, provides additional information.

Renewable Energy Development

The NPS uses a combined technical and policy approach to manage and protect park resources and values as renewable energy resources are identified and developed near NPS areas. Park resources and values that may be impacted by renewable energy development include water quantity and quality, air quality, wildlife, dark night skies, natural soundscapes, cultural resources, scenic views, soils, geologic and hydrologic processes, and visitor experience.

Oil and Gas Leasing

Historically, exploration for natural gas took place near Horn and Cat Islands (Jolene Williams, Gulf Islands National Seashore, environmental protection specialist, GRI review comments, 3 September 2017). The scoping summary (NPS 2007) noted widespread oil and gas development to the north of the park in onshore salt basins, and offshore to the south and west in the Gulf of Mexico. According to Burghardt et al (2014) and the NPS AML database, however, no known oil and gas wells have been drilled within the park, and federal mineral leasing is not allowed within its boundaries. Nevertheless, the State of Mississippi (including lessees, contractors, and permittees) has the right to explore for and develop oil and gas resources beneath the park through directional drilling from locations outside the park boundary. This could result in increased well drilling and siting of facilities immediately adjacent to the park boundary, and of seismic operations inside the park boundary. Offshore drilling on federal oil and gas leases could occur in federal waters outside the park but within the park's viewshed (NPS 2007). The Secretary of the Interior may permit additional rights-of-way or easements (Public Law 91-660). Oil and gas development activities would include but are not limited to seismic surveying, oil and gas extraction, drilling, and other mineral production operations (NPS 2016a).

The NPS opposes such activities near the park because of a variety of possible and known threats to park resources and values and natural processes (NPS 2014). Oil and gas drilling and production can cause ground subsidence. Hydrocarbon withdrawals have been linked to activation of faults that may have accelerated subsidence, resulting in land masses sinking below sea level (Morton and Purcell 2001). Production-caused subsidence may also exacerbate the already high rate of island erosion (NPS 2014). Hydrocarbons and other toxic and contaminating substances can spill from the drilling/production rigs, vessels, and pipelines. The types of oil and gas drilling platforms that may be developed near the park have a history of discharges that impact barrier island and mainland wetlands. Boats used for seismic surveys can disturb seagrass beds (NPS 2014).

The NPS has procedural and legal concerns related to park boundary delineation, jurisdictional concerns, and NPS obligations under the Organic Act and the Wilderness Act. NPS Nonfederal Oil and Gas Rights Regulations (36 C.F.R. Part 9 Subpart B) give the NPS the authority to regulate both the seismic activities and the directional drilling operations associated with state leases within the park boundaries. Outside the boundary, the NPS would encourage oil and gas operators to adopt mitigation measures that protect park resources and values (NPS 2007). GIS mapping of submerged oil and gas pipelines would aid park managers in responding to minerals leasing targeted for the waters around the Mississippi islands (NPS 2016a).

Oil Spills and Response

On 20 April 2010, the Deepwater Horizon oil drilling rig exploded and sank. By 15 July 2010, when the first successful cap was finally installed, the associated Macondo well had leaked approximately 4 million barrels into the waters of the Gulf of Mexico (Graham et al. 2011). The presence of oil in park waters and on park beaches prompted a comprehensive response by the NPS, US Coast Guard, NOAA, and US Fish and Wildlife Service, and many state, local, and community organizations.

Oil stranded along the beachface was treated or cleaned to a depth of 15 cm (6 in), predominantly using handheld equipment and some mechanized equipment such as beach sifters to remove oil from the sand. A more intensive cleaning, down to 45 cm (18 in) below the surface, took place on designated recreational beaches: 8.8 km (5.5 mi) in Florida and 0.4 km (0.25 mi) on West Ship Island in Mississippi.

As of November 2012, more than 2.1 million kg (2,400 tons) of oiled debris had been removed from the park: 500,000 kg (600 tons) in Florida and 1.5 million kg (1,700 tons) in Mississippi. Spill response officially ended in July 2014, but the NPS may reevaluate and adjust treatment measures if a future storm causes additional stranding or resurfacing of oil. The NPS collected data for the natural resource damage assessment and performed a variety of cleanup and recovery efforts to protect natural and cultural resources, including removal of tar balls before bird nesting season and cleanup for recreational fishing and boating (NPS 2014). Current information about the National Park Service and Department of the Interior response to the spill and its effects are available online.

The Oil Pollution Act of 1990 authorizes certain federal agencies, states, and Indian tribes, collectively known as the Natural Resource Trustees, to evaluate the impacts of oil spills on natural resources. The trustees are responsible for pre-assessment data collection, injury assessment, and restoration planning. This process identifies restoration activities, rehabilitation, or the need for replacement of natural resources. The responsible parties will be required to fully compensate the public for the damage to natural resources.

Paleontological Resource Inventory and Protection

All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act. As of April 2019, Department of the Interior regulations associated with the act were being finalized. Appendix B summarizes this act and other laws, regulations, and policies related to geologic resources in NPS areas. Park policy allows the collection of unoccupied modern (not fossil) seashells for personal use, except within archeological sites. Nothing else should be collected or removed from the park without a permit (Gulf Islands National Seashore 2016).

Active paleontological surveys and protection efforts are not a current park management priority. If park managers choose to conduct a paleontological survey in the future, a variety of NPS publications and resources provide guidance, including Brunner et al. (2009), which addresses unauthorized fossil collecting, and Santucci et al. (2009), which provides guidance for monitoring in situ paleontological resources. If a future paleontological survey yields significant findings, park managers should consider the following actions:

- Develop resource management plans including inventory and monitoring to identify human and natural threats to these resources.
- Incorporate findings or suggestions into the park's general management plan.
- Train park staff (including interpreters and law enforcement) in resource protection, as the fossil-trade black market has become quite lucrative for sellers and commonly results in illegal collecting from federal lands.
- Track down collections taken from the area residing in outside repositories for inventory purposes.
- Utilize fossils in interpretive programs.

Sediment Budget Data Needs

Understanding the park's sediment budget is a high priority for park managers. Some of the following questions and data needs may be addressed by the MsCIP Monitoring and Adaptive Management Program (described earlier in this chapter). Relevant research would address the following:

- Guidance on whether beach nourishment is appropriate in certain park areas and if so, in which areas.
- Regional sediment budget to determine whether the system, in addition to individual islands, is losing sand (NPS 2007).
- How park areas will be affected by dredging and renourishment activities at adjacent beaches (Cass Bromley, Gulf Islands National Seashore, Resource Management Division chief, conference call, 16 May 2016; NPS 2016a).
- A study of the natural movement of Petit Bois Island to replicate natural processes by placing dredged material west of the Pascagoula Channel, where the sand would naturally have migrated in the absence of the shipping channel (NPS 2016a).
- Sand transport studies along Santa Rosa Island to address the potential adverse effects of a proposal to cut a channel through the island at the west end of Navarre Beach. This action would affect the downdrift Santa Rosa, Fort Pickens, and Perdido Key areas of the park (NPS 2016a).
- Geomorphic monitoring, particularly of the Mississippi islands' vulnerability to sea level rise (Hatt et al. 2016).
- Identification of erosional hot spots subject to high rates of erosion and breaching to inform redevelopment of infrastructure downdrift along the Mississippi–Alabama island chain (Cass Bromley, Gulf Islands National Seashore, Resource Management Division chief, personal communication, 23 July 2015).

Geologic History

This chapter describes the chronology of geologic events that formed the present landscape of Gulf Islands National Seashore. Table 10 is a generalized geologic time scale that highlights these events. Table 11 is a stratigraphic "column" of surface and subsurface units in the park area. Figure 33 is an index map for the cross sections/figures used to illustrate the geologic histories of the islands. Refer to Appendix C for URLs.

As sea level fluctuated over millions of years, the geologic units described in this chapter controlled the locations and types of sediments deposited along what is now the northern Gulf Coast. The resulting geologic framework influences landform vulnerability to modern-day coastal processes, including the location and persistence of erosional hot spots and breaching (Flocks et al. 2011b) and the continuous reshaping of the modern landforms and reworking of Quaternary sediments (deposited in the past 2.6 million years).

Geologic units formed before the Miocene Epoch (more than 5.3 million years ago) occur deep in the subsurface of the park (more than 300 m [980 ft] below the surface). At present, Miocene and older rocks are not involved in processes that are active along the park's coastline.

Oligocene Epoch (33.9 million to 23.0 million years ago)

Oligocene rocks (table 11) occur deep below the land surface. They represent important regional aquifers but are not involved in modern coastal processes in the park area.

The Chickasawhay Limestone is found beneath Pensacola Beach on Santa Rosa Island, east of the Fort Pickens area. This dolomitic limestone is gray and porous (Marsh 1966). Extending inland from the park toward the Florida mainland, the limestone is part of the Floridian aquifer and supplies water to several wells in the park.

The Tampa Member of the Arcadia Formation, which was deposited during the late Oligocene Epoch, is also present beneath Pensacola Beach (Marsh 1966). The hard limestone is light-gray and includes several clay beds.

Miocene Epoch (23.0 million to 5.3 million years ago)

Global cooling between 16 million and 12 million years ago led to major sea level decline and regression (seaward advance of the shoreline as the sea retreats) between 14.5 million and 14.1 million years ago (Otvos 1994). This change in sea level occurred because water expands when warm and contracts when cold, and water trapped in glaciers is stored on land, reducing the volume of water in the oceans. In Mississippi, the lower Miocene Catahoula Formation is overlain by the middle Miocene Hattiesburg Formation and the upper Miocene Pascagoula Formation (Dockery 2008). These deposits are part of paralic (nonmarine "by the sea"), fresh-to-brackish water sequences, deposited inshore, at or near sea level under the influence of combined fluvial, estuarine, and marine environments (Otvos 1994, 1997). These sediments are characterized by sand beds formed as lenses in laterally extensive silt and clay beds. In Florida (fig. 34), a thick upper Miocene and lower Pliocene sediment sequence of alluvial (river-deposited), brackish (estuarine), and marine sands formed at the present site of Santa Rosa Island (Otvos 1985a, 1988).

Pliocene Epoch (5.3 million to 2.6 million years ago)

Climate during the early Pliocene Epoch was warm and sea level was above present-day. Then, about 5.3 million to 4.8 million years ago, temperatures cooled, polar and glacial ice volumes increased, and sea level declined by 60 to 70 m (200 to 230 ft) because of glaciation (Otvos 2001). Later, about 4.8 million years ago and again 3.2 million years ago, the global climate was very warm (Krantz 1991; Kennett and Hodell 1995; Crowley 1996). Transgressions (major rises in ocean levels leading to a reduction in exposed land surface) took place between 4.6 million and 4.5 million years ago and again 4.2 million years ago (Lawless et al. 1997).

During the early and middle Pliocene Epoch (5.3 million to 3.6 million years ago), rivers deposited sediments across the shelf between Mississippi and northwest Florida. The resulting Pensacola Clay occurs east of Fort Pickens at Pensacola Beach (Marsh 1966). This hard, sandy clay contains fossil remains of carbonized plant fragments, abundant mollusks, and foraminifera (Marsh 1966).

The thin, muddy Perdido Key Formation near the Alabama–Florida state line (Otvos 1988, 1994) is represented by a fossil-rich nearshore marine lens found within a thick fossil-free sediment interval. This unit lies 15 to 30 m (45 to 90 ft) beneath Perdido Key in northwest Florida and adjacent Alabama. Relatively

Table 10. Geologic time scale.

The divisions of the geologic time scale are organized with the oldest at the bottom and youngest at the top. Major life history and tectonic events occurring in Florida and Mississippi are included. Bold lines indicate major boundaries between eras. "mya" = millions of years ago. Colors are standard colors approved by the USGS to indicate different time periods on geologic maps. Use Dates follow the International Commission on Stratigraphy international chronostratigraphic chart.

Period	Epoch	Date	Gulf Island Events
Quaternary	Holocene–Miocene	23 mya–present	**Florida–Mississippi region events** Fluvial processes, erosion of Peidmont and Appalachian Mountains, sediment deposition in Coastal Plain
Quaternary	Holocene	2005	Hurricane Katrina submerged Mississippi barrier islands and caused mainland flooding and erosion.
Quaternary	Holocene	1969	Hurricane Camille divided Ship Island with Camille Cut and converted eastern Petit Bois Island into a shoal.
Quaternary	Holocene	1916	Unnamed hurricane converted eastern Petit Bois Island to a shoal platform and divided Isle of Caprice.
Quaternary	Holocene	1,800 years ago	St. Bernard lobe of the Mississippi River Delta was abandoned. Beach ridges formed on Ship Island.
Quaternary	Holocene	3,800–1,800 years ago	St. Bernard lobe began expanding, ending westward growth of Ship Island and surrounding western end of chain with marshlands.
Quaternary	Holocene	4,000–3,500 years ago	Santa Rosa Island emerged from an elongated shoal.
Quaternary	Holocene	5,000 years ago	Mississippi barrier islands formed from shoals. Sea level was 2–3 m (6–10 ft) lower than present.
Quaternary	Holocene	5,700 years ago	Sea level was 7 m (23 ft) lower than present.
Quaternary	Pleistocene	12,900–11,700 years ago	Younger Dryas cooling event. Pinnacle reef growth.
Quaternary	Pleistocene	18,000 years ago	Beginning of last sea level lowstand, 120 m (394 ft) below its present position.
Quaternary	Pleistocene	25,000–21,000	Last glacial maximum; global glaciation. Sea level 120–130 m (394–425 ft) lower than present.
Quaternary	Pleistocene	71,000–11,700 years ago	Wisconsinan glaciation; sea level 20–130 m (65–425 ft) below present.
Quaternary	Pleistocene	130,000–80,000	Sangamonian interglacial stage; last interglacial warm period; most of Earth's glaciers melted. Sea level approximately 3–6 m (10–20 ft) higher than present.
Quaternary	Pleistocene	2 mya	Late Pliocene cooling caused major regression and sea level decline. Atlantic sea level dropped more than 50 m (164 ft) (estimates are unavailable from the Gulf of Mexico). Alluvial deposition declined.
Neogene	Pliocene	3.5–2.7 mya	Upper Pliocene transgressive cycle in northeastern Gulf of Mexico. The broad belt of paralic (alluvial, estuarine, and nearshore marine) depositional facies extended 75–90 km (47–56 mi) and up to 75 m (246 ft) surface elevations.
Neogene	Pliocene	3.7 mya	Sea level stopped rising. Global cooling and sea-level decline recurred shortly before the start of the late Pliocene.
Neogene	Pliocene	4.2 mya	Most extensive Pliocene transgression; seaward progradation of the shelf.
Neogene	Pliocene	4.6–4.5 mya	Warm period included at least one major transgression.

Table 10 (continued). Geologic time scale.

Period	Epoch	Date	Gulf Island Events
Neogene	Pliocene	5.2–4.8 mya	Sea level dropped 60–70 m (200–230 ft) during early Pliocene glaciation.
Paleogene	Oligocene–Paleocene	66–23 mya	**Florida–Mississippi region events** Limestone desposited in Coastal Plain, erosion, and weathering continued
Cretaceous	Lower–Upper	145–66 mya	**Florida–Mississippi region events** Ongoing erosion and weathering in Piedmont and Appalachian Mountains, Coastal Plain built outwards
Jurassic	Lower–Upper	201–145 mya	**Florida–Mississippi region events** Rift basins formed; brittle faulting and volcanism
Triassic	Lower–Upper	252–201 mya	**Florida–Mississippi region events** Breakup of Pangaea began; Atlantic Ocean opened

Table 11. General stratigraphic column for Gulf Islands National Seashore.

Notes: The column is based on information in NPS (2007, table 2) and on interpretations by Brown et al. (1944; Davis Bayou), Marsh (1966; Santa Rosa Island), Williams (1969; Mississippi), Otvos (1982a, 1995, 2001, 2004a, 2009), Champlin et al. (1994; Mississippi), and Gohn et al. (1996; Horn Island). In addition, Ervin Otvos (University of Southern Mississippi, professor emeritus) provided comments during the GRI review process (19 October 2016). Colors are standard colors approved by the USGS to indicate different time periods on geologic maps. Use of "lower," "middle," and "upper" conforms to usage in source publications and not to current standards set by the International Commission on Stratigraphy.

Epoch	Timing of Event	Rock/ Sediment Unit	Description
Holocene	3,800–1,800 years ago	Recent marine, beach, and dune sands, and riverine sediments	MS/LA: growth and shoaling of the St. Bernard lobe of the Mississippi Delta ends sand transport to and further growth of Cat Island; delta lobe surrounds and/or buries the western sector of the island chain west of Cat Island in southwest MS and adjacent LA. Perdido Key: lower shoreface shell bed capped by a marine sand sheet.
Holocene	5,400–4,500 years ago	Recent marine, beach, and dune sands	Barrier islands began forming. Strand plains, low supratidal flats, intertidal beach sequence deposited. Under barrier islands: vertical regressive sequence from marine to aeolian deposits.
Holocene	5,400–4,500 years ago	Nearshore marine and brackish inshore sands and muds	Brackish lagoon (Mississippi and Santa Rosa Sounds), bay, salt-brackish marshes, swamps, and river delta. Horn Island: coarsening upward core shows westward migration of island (Unit 3 in fig. 37).
Holocene	Less than about 11,000 years ago	Estuarine, beach, and dune deposits	At 5,000 years ago, sea level rise slows at 2–3 m (6–10 ft) below present. At 5,700 years ago, sea level is 7 m (23 ft) below present. Naval Live Oaks: unconsolidated to poorly consolidated light gray, tan, brown to black, clean to clayey, variably organic-bearing sands and blue green to olive green poorly to moderately consolidated sandy, silty, clays. Fort Barrancas: surface expression of beach ridges and dunes. Perdido Key: About 6,070 years ago, estuarine deposits (11,200 years old) are overlain by open bay deposits and a flooding surface. Horn Island: early shoreline established 9,500 years ago (Unit 3 in fig. 37).
Pleistocene-Holocene	n/a	n/a	Unconformity between Pleistocene units and Holocene units.

Table 11 (continued). General stratigraphic column for Gulf Islands National Seashore.

Epoch	Timing of Event	Rock/ Sediment Unit	Description
Pleistocene	71,000–11,000 years ago Wisconsinan glaciation Marine Isotope Stage (MIS) 2–4	Dunes and sand sheets	FL: dunes and sand sheets form along mainland coast and cover the Gulfport Formation. Source of the sand is the Gulfport Formation. Late in MIS 2, the lowest sea level was 120 m (390 ft) below present.
Pleistocene	132,000–112,000 years ago Sangamonian interglacial MIS 5e	Gulfport Formation	Barrier complex. Shallow nearshore, beach and dune sands. Grades upward. Fossils uncommon. FL: Forms continuous zone north of Santa Rosa Sound. Present in the Pleistocene core below Santa Rosa Island where it is 3–10 m (10–30 ft) thick, well sorted sand. Forms eastern portion of Dauphin Island, AL. MS: Forms discontinuous mainland zone north of Mississippi Sound. Not present beneath MS barrier islands.
Pleistocene	132,000–112,000 years ago Sangamonian interglacial MIS 5e	Biloxi Formation	Present along the entire northern Gulf Coast. Shallow nearshore to estuarine deposits. Nearshore marine sands and estuarine sands-clayey sands. Contains foraminifera fossils. FL: Deposited in open nearshore marine and estuarine-lagoonal brackish environments. Clay and mud units are primarily sandy in FL. Present in the Pleistocene core below Santa Rosa Island. MS: Not present beneath Horn Island. Much muddier in MS and AL than in FL, which is sandier.
Pleistocene	130,000–80,000 years ago Sangamonian interglacial MIS 5e, 5d–a	Prairie Formation	Floodplain alluvial deposits. Fossils uncommon. Muddy and clayey fine sands; moderately silty, fine and very fine sands. At depth, the sediments are yellowish-gray, greenish-gray and gray. Between 125,000 and 122,000 years ago, sea level was 3–6 m (10–20 ft) above present. MS: on mainland coast, bounded by Mississippi Sound and estuarine embayments. Thickness of 4.5 to 12 m (15 to 40 ft). Wedge narrows landward. Interfingers with the Biloxi Formation. FL: Deposited seaward of Sangamonian estuarine and marine unit. Light yellowish-gray, yellowish-brown, silty-sandy and sandy deposits. Lie seaward of Citronelle Formation. May be present under Santa Rosa Island as nonfossiliferous silty-muddy sands.
Pleistocene	216,000–176,000 years ago MIS 7	Montgomery Terrace deposits	Penultimate interglacial fluvial deposits. Present in LA, MS, and AL. Contains fossil plants.
Pleistocene	2.6 million-11,700 years ago	Undifferentiated fluvial deposits	No fossils.
Pleistocene-Pliocene	n/a	n/a	Unconformity caused by uplift, land surface erosion, and stream incision following deposition of the Citronelle Formation.

Table 11 (continued). General stratigraphic column for Gulf Islands National Seashore.

Epoch	Timing of Event	Rock/ Sediment Unit	Description
Pliocene	3.6 million–2.6 million years ago	Citronelle Formation	Predominantly fluvial. Red iron oxide mineral coloration at the surface. Extensive upland surfaces north of Pleistocene coastal strip of Gulfport Formation and overlying Wisconsinan aeolian deposits. Sea level rises 35 ±18 m (115 ±59 ft) between 3.5 million and 3.0 million years ago. FL: Extensive estuarine facies in northwest FL. Underlies upland a few km north of Santa Rosa Island. Light yellowish-brown to reddish-orange silty-to-sandy deposits, and gray gravelly-to-sandy layers. AL: Several sites contain local brackish estuarine facies. Major land flora fossils of a warm temperate period found near Mobile, AL. MS: May lie 18 to 23 m (60 to 76 ft) below East and West Ship Islands.
Pliocene	5.3 million–3.6 million years ago	Perdido Key Formation	Nearshore fossil-rich marine lens 15–30 m (50–100 ft) beneath Perdido Key in northwest FL at AL border. Overlain by a 5–15-m- (17–50-ft-) thick fossil-free, fine siliciclastic sandy Neogene deposit. Glaciation causes sea level to drop 60–70 m (200–230 ft).
Pliocene	5.3 million–3.6 million years ago	Fluvial and paralic deposits	Fluvial deposits found under Bellefontaine, Jackson County, MS, and elsewhere between MS and northwest FL. MS: Beneath present-day Horn Island, deposits from a migrating creek, intertidal mud flats, and estuarine channel (fig. 36).
Pliocene	5.3 million–3.6 million years ago	Undifferentiated fluvial and paralic deposits	Contains upper Miocene and lower Pliocene deposits. Contains sparse fossils.
Pliocene	5.3 million–3.6 million years ago	Pensacola Clay	FL: present beneath Santa Rosa Island (Pensacola Beach east of the Fort Pickens area).
Miocene	About 10 million–5.3 million years ago	Pascagoula Formation	Present 300–900 m (1,000–3,000 ft) below Horn Island, MS. Fluvial, estuarine, and nearshore marine (undifferentiated) deposits. Green and bluish-green clay, sandy clay, and sand; gray siltstone and sand; locally fossiliferous (bivalves and mollusks).
Miocene	14.8 million–about 10 million years ago	Hattiesburg Formation	Present 300–900 m (1,000–3,000 ft) below Horn Island, MS. Fluvial, estuarine, and nearshore marine (undifferentiated) deposits. Green and bluish-green clay, sandy clay, and sand; gray siltstone and sand; locally fossiliferous (bivalves and mollusks).
Miocene	23 million–14.8 million years ago	Catahoula Formation	MS: fluvial-paralic sequences. Top of formation on sound side of islands is about 1,300 m (4,400 ft) thick at Ship Island or 760 m (2,500 ft) thick at Horn Island. Upper layer is clay, shale, and gravelly sands with black chert.
Oligocene	More than 23 million years ago	Tampa Member of Arcadia Formation	FL: present beneath Santa Rosa Island (Pensacola Beach east of the park). Hard, light gray limestone with several beds of clay.
Oligocene	More than 23 million years ago	Chickasawhay Limestone	Present beneath Santa Rosa Island (Pensacola Beach east of the park). Gray, vesicular, dolomitic limestone.

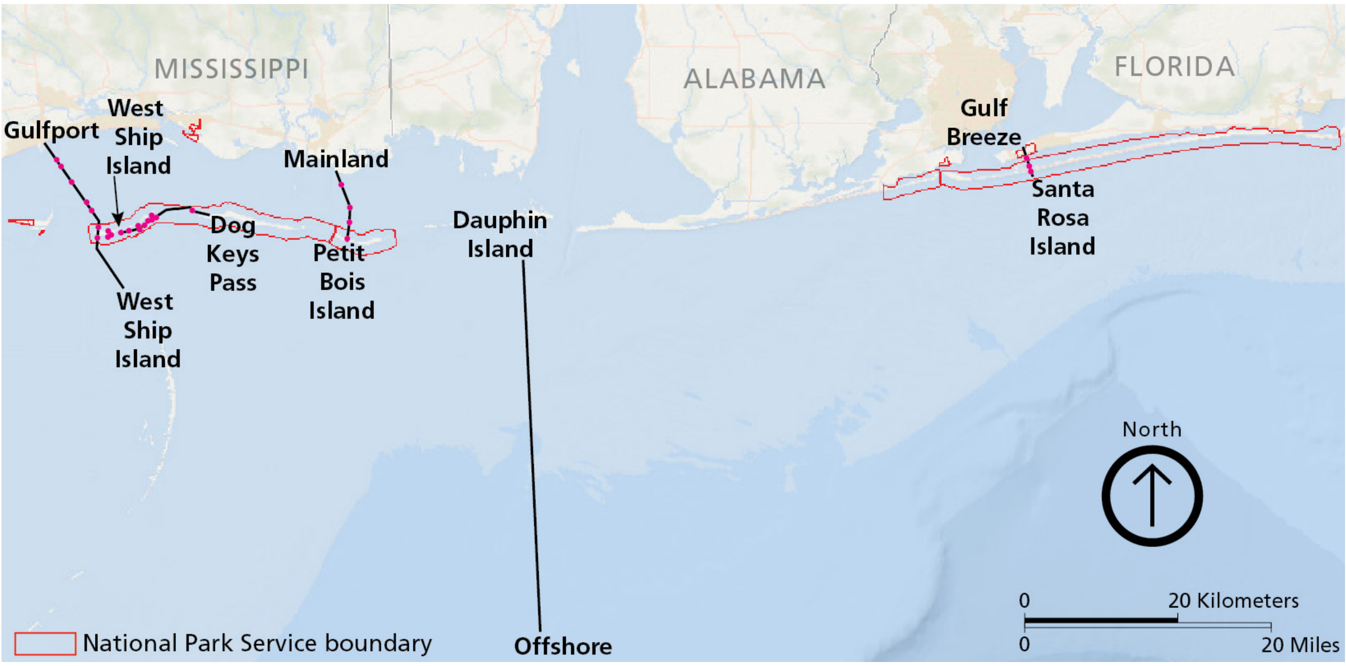

Figure 33. Index map showing locations of geologic cross sections.
Most of the cross-section lines have red dots, which represent core locations. From left to right: Gulfport [Harbor] to [West] Ship Island (fig. 42), West Ship Island (fig. 45), West Ship Island through Dog Keys Pass (fig. 44), mainland to Petit Bois Island (fig. 43), Dauphin Island to offshore Gulf of Mexico (fig. 40), and Gulf Breeze to Santa Rosa Island (fig. 41).

thick (5 to 15 m [16 to 50 ft]), fossil-free, fine sandy deposits overlie the Perdido Key Formation.

Another cooling episode accompanied by sea level decline took place just before the end of the middle Pliocene Epoch. The shoreline repeatedly shifted landward and seaward (Lawless et al. 1997). Sea level rose 35 m (115 ft) in 500,000 years, between 3.5 million and 3 million years ago (Dowsett and Cronin 1990).

The Citronelle Formation (Matson 1916) accumulated under warm-temperate, temperate-to-subtropical conditions during moderately high-to-declining sea levels during the late Pliocene Epoch, between 3.6 million and 2.6 million years ago (Otvos 1998). Consisting of a predominantly fluvial blanket of material, the Citronelle Formation has a thickness of up to 50 m (160 ft). Cross-bedded sandy-gravelly river channel and muddy-sandy floodplain deposits dominate. The Citronelle Formation is the most widespread geologic unit in the coastal plain of the northeastern Gulf of Mexico. Extensive elevated upland surfaces, located north and inland of the narrow Pleistocene coastal strip, are composed of the Citronelle Formation (Otvos 1998). East of Mobile Bay, the formation also displays interlayered fossiliferous estuarine lenses (Otvos 1997, 2005a) and consists of red silty sands, clean milky-white quartz sands with some gray chert gravels that contain silicified ancient fossils, which were reworked from much older source sediments (USGS 2013).

In Mississippi, Champlin et al. (1994) proposed that the Citronelle Formation lies 18 to 23 m (60 to 76 ft) below East and West Ship Islands, but this finding is contradictory to the presence of late Pleistocene and Holocene deposits in drill cores at the same depth (Otvos 1981a). Estuarine deposits in outcrops of the Citronelle Formation east of Mobile Bay locally include estuarine sediments that may contain a variety of molluscan molds (fossil impressions) or an abundance of shallow subtidal *Ophiomorpha* (ghost shrimp burrows, a type of trace fossil). Extensive estuarine Pliocene beds in the coastal plain of northwest Florida correlate to the outcrops in Mississippi (in geologic terms, correlation is the demonstration of the equivalence of two or more geologic phenomenon in different areas). A marine regression (retreat of sea from land areas) and major sea level decline terminated deposition of the Citronelle Formation by the end of the Pliocene Epoch (Otvos 1998).

Quaternary Period (the past 2.6 million years)

Global sea levels, and the presence of corresponding newly formed continental ice sheets, are recorded by changing oxygen isotope ratios preserved in microfossil assemblages within marine sediments. Temperature and sea level fluctuations are well documented by

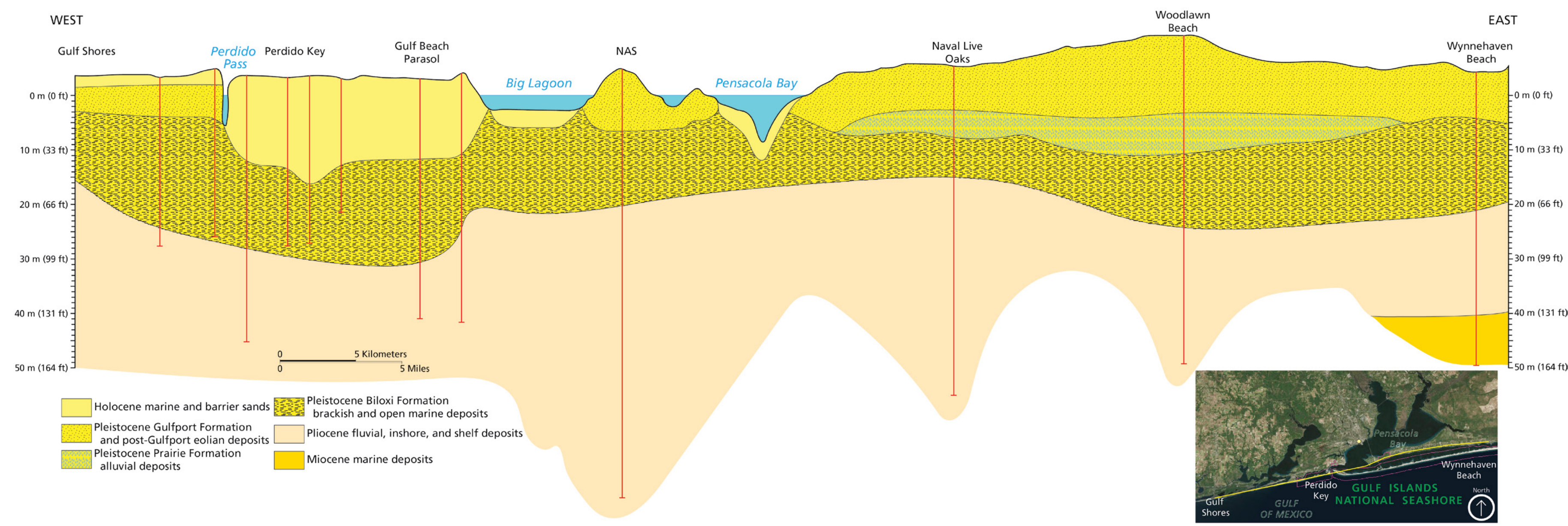

Figure 34. Cross section of the Florida barrier islands, from Gulf Shores to Wynnehaven Beach.
The cross section extends from Gulf Shores, Alabama, eastward through Perdido Key, Pensacola Naval Air Station (NAS), Naval Live Oaks, and along the mainland shoreline of Santa Rosa Sound (Florida). Red lines indicate locations of cores that support the stratigraphic interpretation. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Otvos (1985a, figure 3) and Otvos (1988, figure 3).

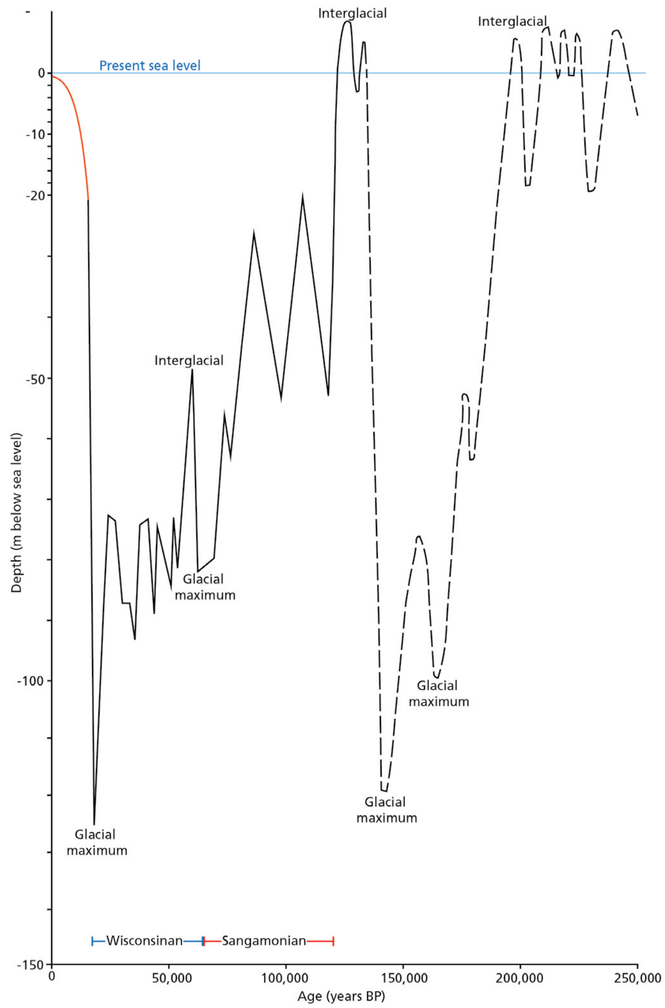

Figure 35. Graph showing sea level during the past 250,000 years.
The red line shows the Holocene sea level curve for the northern Gulf of Mexico as reported by Anderson et al. (2014, figure 13). The black line shows the Late Pleistocene global sea level curve from Otvos (2005c, figure 5). The Sangamonian is the last interglacial stage. The Wisconsinan is the last glacial stage. The last glacial maximum took place about 25,000–21,000 years ago. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

these values. One hundred and four marine isotope stages (MIS) are documented in the Quaternary Period. Changes in global ocean sea level can be correlated to individual marine isotope stages and substages. Local transgressions and regressions have been correlated to these global events in the geologic history of the park (fig. 35).

Pleistocene Epoch (2.6 million years ago to 11,700 years ago)

Following late Pliocene glaciations (Otvos 1998), the early and middle Pleistocene Epoch was relatively cool, with low sea level interrupted by interglacial (warmer) episodes. Temperatures and associated sea levels constantly fluctuated during the Pleistocene Epoch. One of the most remarkable and longest interglacial episodes occurred during MIS 11 (424,000–360,000 years ago) (Otvos 2015). The last interglacial stage, referred to as the "Sangamonian," occurred between about 130,000 and 80,000 years ago, during MIS 5 (Otvos 2015). It was followed by the Wisconsinan glacial stage (MIS 4 through MIS 2) between 71,000 and 11,700 years ago. Continental ice sheets and glaciers reached their maximum extent during MIS 2, approximately 25,000–21,000 years ago; this event, known as the "last glacial maximum" (LGM), occurred during the late Wisconsinan glacial stage (fig. 35).

Pre-Sangamonian Time (2.6 million years ago to about 130,000 years ago)

The entire Pleistocene record that predates the Montgomery Terrace (fig. 37) sediment interval (MIS 7) was lost from the northeastern coastal plain as a result

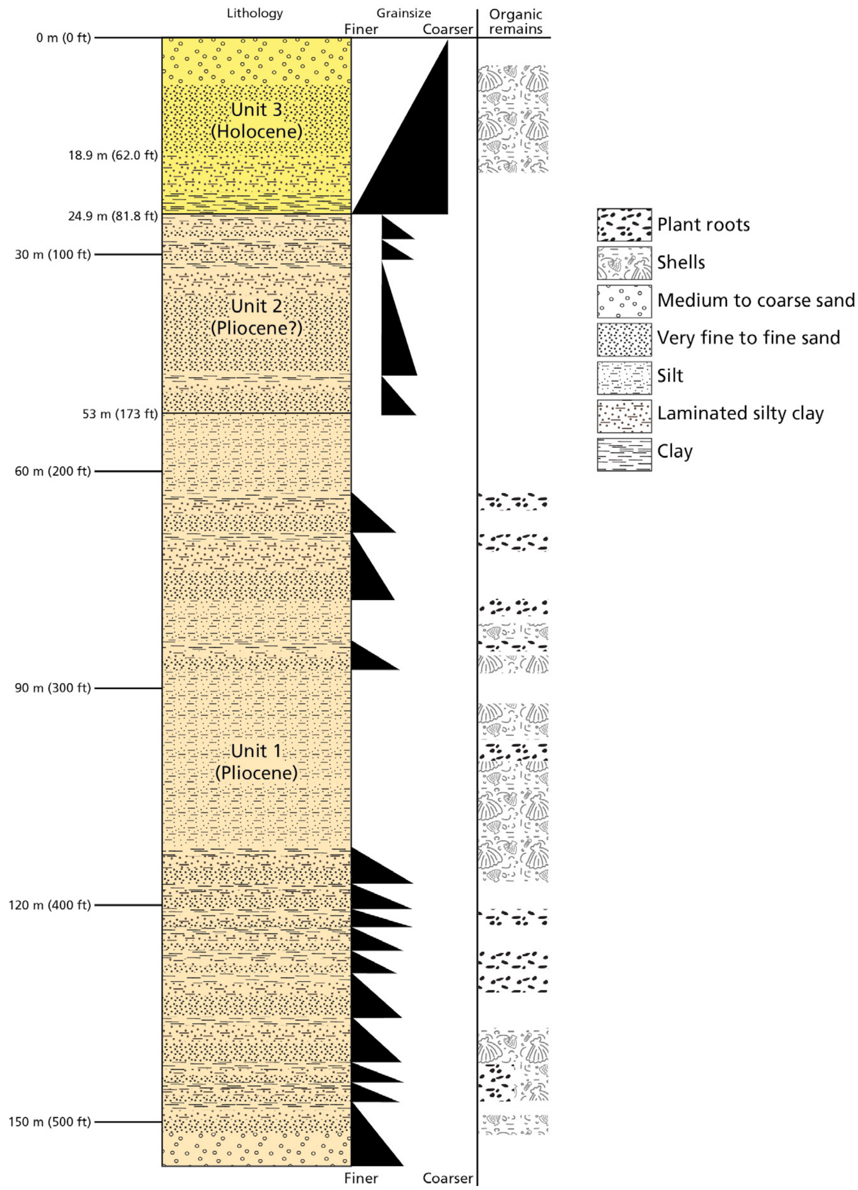

Figure 36. Graphic of drill core from Horn Island.
Unit 1 (Pliocene Epoch) shows cycles of fining-upward sections with shelly fine sand at the base of each sediment cycle, which were deposited in the channel of an intertidal creek, overlain by clay-silt laminations deposited as the creek migrated. Bioturbated clays with Rangia bivalve fossils represent a shallow subtidal estuary, and the rooted, oxidized clayey silts represent supratidal flats. The coarser sand section at the base of Unit 1 probably represents one of the main channels of the estuary. Unit 2 (Pliocene Epoch) consists of cyclic fining-upward sections of noncalcareous sands and clays that were deposited in a river or upper estuarine setting. The fining-upward sand-clay cycles were deposited by migrating streams. Unit 3 (Holocene Epoch) consists of coastal and nearshore-marine sediments. An early Holocene shoreline was established in the vicinity of modern Horn Island approximately 9,500 years ago. The organic marsh and tidal flat deposits at the base of Unit 3 represent a low-energy part of that shoreline complex. As sea level rose and the shoreline flooded, fine-grained sediments were deposited. A coarsening-upward sequence records the late Holocene westward migration of Horn Island to its present position. The sandy upper subunit primarily represents the pre-modern subtidal part of Horn Island, which likely includes inter-barrier, inlet sediments, and shoreface sediments. The sands above modern sea level at the top of Unit 3 may be mostly aeolian and would now be part of map units Active Dune Complex (dn_cplx_a), Stable/Stabilized Dune Complex (dn_cplx_s), Beach Ridge Complex (bch_rdg_cplx), Vegetated Barrier Flats (veg_brr_flt), or Vegetated Barrier Core (veg_brr_cr) of the GRI GIS data (see poster, in pocket). Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Gohn et al (1996, figure 2).

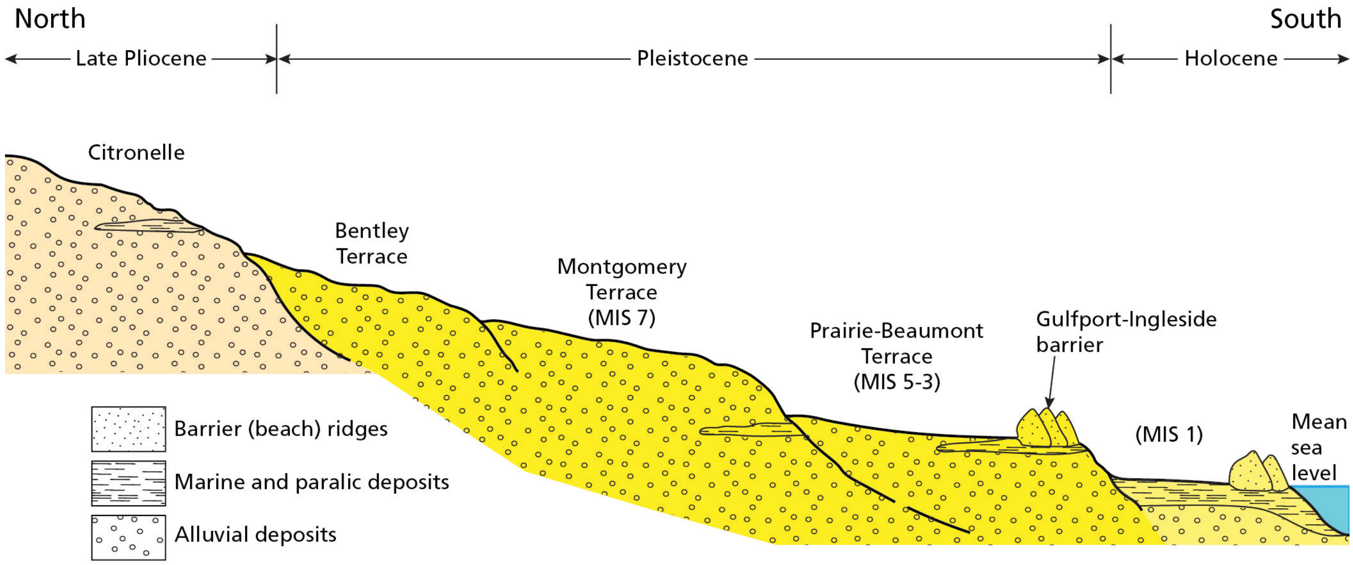

Figure 37. Generalized composite cross section across northern coastal plain terrace units. No scale. This combination of all the major coastal landforms is not found in site-specific shore-normal cross sections, and elevation and width are highly variable between locations. Coastal terrace deposits older than the Montgomery Terrace are present only in northwestern coastal plain and are absent from the northeastern coastal plain. Marine isotope stages (MIS) coincide with times of high and low sea level. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Otvos (2005a, figure 1).

of regional post-Pliocene uplift (upward movement of the earth's surface), land-surface erosion, and river-valley incision during low sea level stages (Otvos 1975, 1981b, 2009). All Pleistocene marine and brackish-paralic coastal sediments that were deposited before the Biloxi Formation (table 11) have been eroded from the Mississippi–northwest Florida coastal plain and nearshore zone (fig. 36). Likewise, no pre-Sangamonian (pre-Gulfport Formation) Pleistocene barrier ridges or other relict shoreline features remain in the northern Gulf of Mexico coastal plain (fig. 34) (Otvos 1975).

The post-Citronelle unconformity (a surface formed by erosional removal of earlier deposits) is overlain by undifferentiated fossil-free fluvial deposits. West of Mobile Bay, Alabama, and extending through Louisiana and into Texas, fluvial sediments of the shore-parallel Montgomery Terrace were deposited between 216,000 and 176,000 years ago (table 11; fig. 37). The terrace developed during an interglacial episode that corresponds to MIS 7. Montgomery Terrace deposits contain an important fossil land flora in Mississippi (Otvos 1997, 2001; Oivanki and Otvos 2005; Ervin Otvos, University of Southern Mississippi, professor emeritus, written communication, 19 October 2016).

Sangamonian Interglacial Stage (130,000 years ago to 80,000 years ago)

The last interglacial stage, known as the Sangamonian, occurred during MIS 5. At the start of the Sangamonian transgression, approximately 130,000 years ago, sea level along the Gulf Coast was 80 m (264 ft) lower than today (fig. 35) (Otvos 2001). As continental ice sheets and mountain glaciers melted, sea level rose again. By the time global sea level exceeded 10 m (30 ft) below present, it was rising at a millennial average rate of 5.6 mm (0.22 in) per year. During the warmest phase of the Sangamonian interglacial stage (between 130,000 and 120,000 years ago), sea level reached at least 6.6 m (22 ft) higher than today (Katsman et al. 2011).

Pleistocene deposits directly overlie Neogene (Miocene and Pliocene; Table 10) units in the shallow subsurface (fig. 34) (Otvos 2009). Although earlier Pleistocene highstand deposits may have been deposited along the Gulf Coast, subsequent erosion removed them. None remain, not even from the extended warm period that occurred from 424,000 to 360,000 years ago during MIS 11 (Otvos 2015). Deposition during the Sangamonian interglacial stage on the mainland coast started with the Prairie Formation (table 11; fig. 34), which contains river channel and floodplain alluvium with few fossils. The Prairie and two other formations were deposited between 130,000 and 80,000 years ago during MIS 5e (warmest) and MIS 5d–a (generally much colder). The Prairie Formation is a sediment wedge (4.5 to 12 m [15 to 39 ft] thick) that tapers out landward. It formed before, during, and after barrier progradation (building seaward) (Otvos 2001). During this highstand of sea level and as sea level began to fall, barrier strand plains prograded toward the Gulf of Mexico from the seaward edge of the coastal plan (Otvos 2001). The Prairie Formation interfingers with laterally adjacent, overlying and underlying beds of the Biloxi Formation (fig. 34).

The muddy estuarine and sandy marine sediments of the fossiliferous Biloxi Formation were laid down mostly during global sea level rise and highstand (table 11). This formation represents transgressive and regressive intervals of nearshore marine and inland brackish paralic sedimentation phases. The Biloxi Formation is overlain by the ancient beach-dune ridges of the Gulfport Formation and farther inland by the Prairie Formation (fig. 34). The Gulfport Formation represents a barrier strand plain (prograded shoreline built seaward by waves and currents) (Otvos 2004a). The barrier trend continues westward to Mobile Bay Pass. On the far side of the pass, the ridges form the core of eastern Dauphin Island, the focal location for the westward littoral transport during the mid- and late Holocene Epoch (Otvos and Giardino 2004). Both the Biloxi and the Gulfport Formations were deposited during the last interglacial stage that coincided with MIS 5e between 132,000 and 112,000 years ago (Otvos 2015).

The Gulfport and Biloxi Formations form a relatively thin (less than 30 m [100 ft]) interglacial sequence (succession of geologic events) along the coast. Including the Sangamonian–early Wisconsinan alluvium of the Prairie Formation, the upper Pleistocene coastal complex rarely exceeds 10 km (6 mi) wide (Otvos 2009). These geologic units are the only Pleistocene deposits that remain on the northeastern Gulf Coast between Mobile Bay, Alabama, and Florida. Post-Pliocene uplift and associated erosion have eliminated all earlier shore features. This marine highstand sequence (succession of geologic events, processes, or rocks) that formed inshore and nearshore is the only stratigraphic reference interval along the Gulf Coast that can be correlated (showing connections between separated areas) with other last interglacial units (marine and paralic MIS 5e deposits) worldwide (Otvos 2015).

Wisconsin Glacial Stage (71,000 years ago to 11,700 years ago)

During the early and middle Wisconsinan glacial stage, sea level stood between 20 and 130 m (65 and 425 ft) below the present level. During the last glacial maximum (about 25,000 to 17,000 year ago, though timing varies widely worldwide), a record extent of ice cover occurred. At its lowest, between 22,000 and 18,000 years ago, sea level stood approximately 120 m (390 ft) below the present sea level (fig. 35) (Fairbanks1989). During full glacial intervals, when the climate was cooler and drier, sea level was very low, and streams incised deeply into the ancient coastal plain. This surface is now the inner and middle continental shelf (Otvos 2001).

In the adjacent Florida and southeastern Alabama mainland areas, including the park headquarters area in Gulf Breeze, Florida, reworked sands of the Gulfport Formation cap coastal ridges, also composed of the Gulfport Formation (table 11; fig. 34) (Otvos 2004a). The Gulfport Formation sands probably also formed the narrow Pleistocene core from which Santa Rosa Island emerged (Otvos 2004a). The northern (bay) bluff in the Naval Live Oaks area is the highest point in the park. This 14-m- (45-ft-) high bluff is composed of Wisconsinan and early Holocene sand dunes, which blanket barrier sands that are composed of the Gulfport Formation (fig. 34) (Otvos 2004a, 2004b, 2005b, 2005c).

During the late Pleistocene and Holocene Epochs, sea level changes controlled major episodes of deposition and erosion on the Mississippi–Alabama inner continental shelf (fig. 38). When sea level was low or falling, rivers cut through the coastal plain and shelf sediments (Flocks et al. 2011a). Remnants of deltas that formed during lowstands left distinct lobes along the shelf break and the previous middle shelf area (fig. 39A) (Otvos 2018; Sydow and Roberts 1994). One large relict delta complex, which extends from the Lagniappe Delta eastward to south of Perdido Key, is 20 m (70 ft) thick (Kindinger 1988; Kindinger et al. 1994; Rodriguez et al. 2008).

The lobes that were deposited during lowstands occur between late Pleistocene–Holocene reefs, known as "pinnacle reefs." The reefs rise an average of 11 m (36 ft) above the seafloor (Ludwick and Walton 1957) in two distinct depth ranges: 74–82 m (243–269 ft) and 105–120 m (344–394 ft) below sea level (fig. 39B) (Gardner et al. 2002; Flocks et al. 2011a). The mounds are composed of cemented calcareous algae that grew upward as sea level rose. The shallower pinnacle reef zone formed during the Younger Dryas (12,900 to 11,700 years ago) (Sager et al. 1992, as cited in Flocks et al. 2011a). The Younger Dryas is distinct cold period that preceded warming within the Holocene Epoch.

Two major river valleys—the Mobile River with its Pascagoula and possibly Pearl River tributary, and the Apalachicola River that crossed the continental shelf—were entrenched (incised) into the continental shelf during Wisconsinan lowstands. Mid-to-inner shelf deltas related to the ancient Mobile–Pascagoula river valley (Kindinger 1988; Kindinger et al. 1994; Flocks et al. 2011a) and several small mid-shelf and larger shelf-

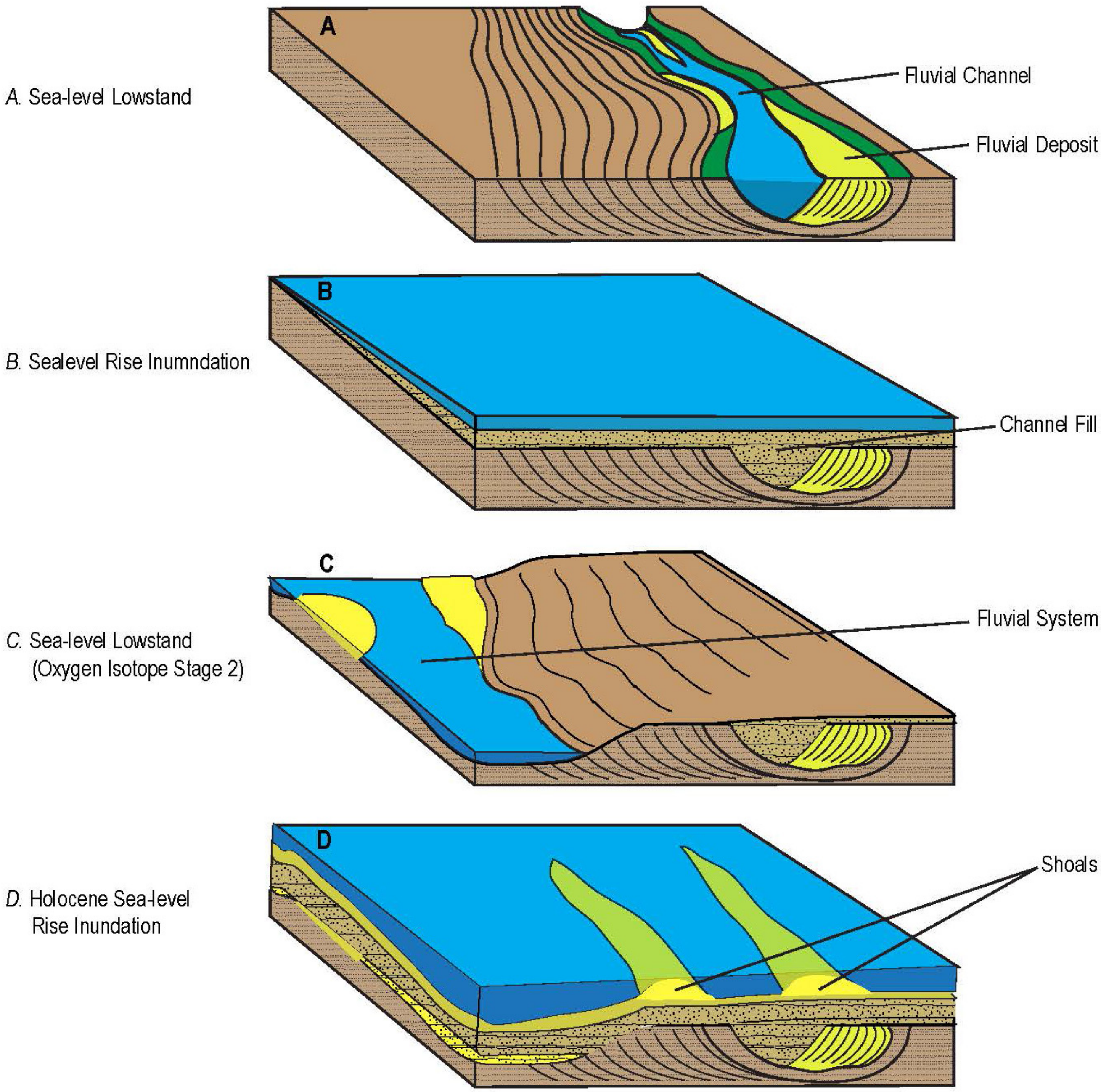

Figure 38. Graphic of Pleistocene and Holocene stratigraphic development offshore of Petit Bois Island. North (landward) is up; the shelf is toward the bottom. Blue depicts water. (A) Fluvial deposits at the outer shelf during a sea level lowstand (prior to the last lowstand). (B) Sea level rise flooded the fluvial channels, filling them with sediment. (C) During the last sea level lowstand (MIS 2) between 22,000 and 18,000 years ago, river channels cut through the older transgressive and fluvial deposits. (D) Holocene sea level rise flooded the area, depositing transgressive sand sheets while wave action reworked earlier deposits into shoals. Figure 43 provides a labeled cross section of offshore stratigraphy. USGS graphic from Flocks et al. (2014, figure 17).

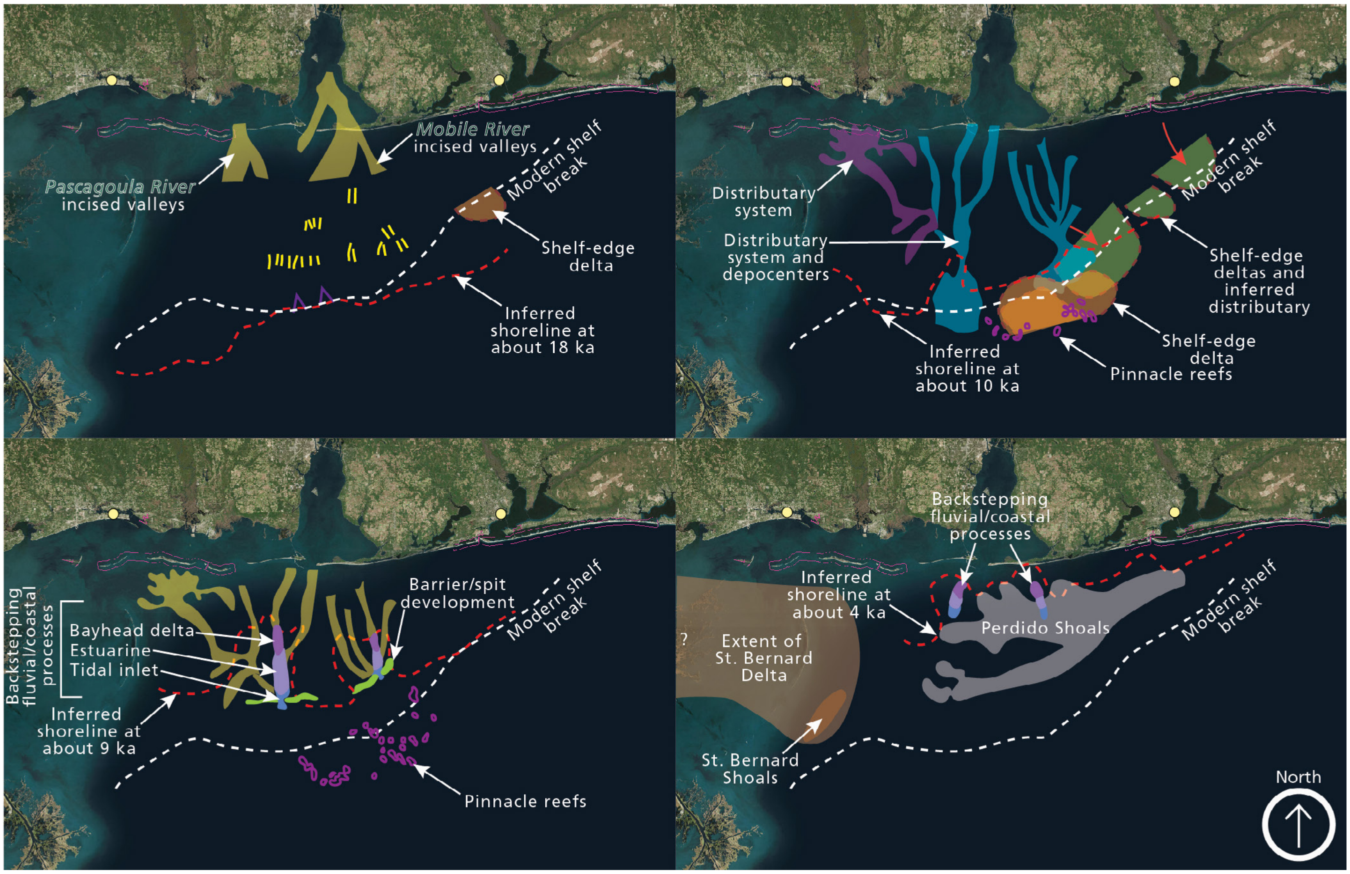

Figure 39. Depositional model for the Mississippi–Alabama shelf since the last glacial maximum. (A) About 18,000 years ago ("ka" on figure), incised valleys migrate landward and some deltas developed along the shelf-edge. (B) Landward-migrating channels deposit sediment in the shelf-edge deltas. (C) Sea level rises rapidly, flooding the shelf and the incised valleys. Estuarine deposits and bayhead deltas form upstream. Tidal-inlet and barrier development seaward of the estuaries provide coarse sediment that is reworked into shoals. Pinnacle reefs drown. (D) Sea level approaches its current level. A sand sheet from reworked fluvial and shoreline deposits buries the estuarine deposits and the incised channels. The St. Bernard lobe of the Mississippi River Delta system develops, depositing fine-grained sediments. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Flocks et al. (2010, figure 9).

margin deltas also existed here at that time (McKeown et al. 2012). Delta shorelines underwent major landward shifts across the mid- and inner shelf.

As sea level rose, the incised river channels began to fill with fluvial and estuarine sediments. A thick sedimentary unit formed over underlying bedrock (Cretaceous carbonates) (Martin 1976; Flocks et al. 2014). The heavy weight of the deltaic sediments caused the underlying ground to subside. Deposits that formed bathymetric highs were reworked by coastal erosional and depositional processes. Variations in the sediment thickness across the shelf caused variations in the rates of shelf subsidence. This process, in turn, may have controlled river orientation and shelf geometry (Bartek et al. 2004).

Holocene Epoch (the past 11,700 years)

Between about 10,000 and 7,000 years ago, global warming caused valley glaciers and polar ice sheets to melt (fig. 35). The rising sea flooded the earlier incised fluvial channels—including the valleys of the Mobile, Pascagoula, and Pearl Rivers—across the continental shelf (Anderson et al. 2016b). Sandy mud and estuarine and marine muds accumulated in the nearshore Gulf of Mexico along the present Mississippi Sound between 8,000 and 7,000 years ago (figs. 39 and 40C) (Twichell et al. 2011). As sea level continued to rise, a thin (less than 4 m [13 ft] thick) blanket of sand, mud, and sandy mud was deposited over the newly flooded middle continental shelf south of the future Mississippi barrier islands (fig. 39D) (Twichell et al. 2011).

By approximately 7,000 to 6,500 years ago, sea level stood only about 6 m (20 ft) below its current level. Gulf

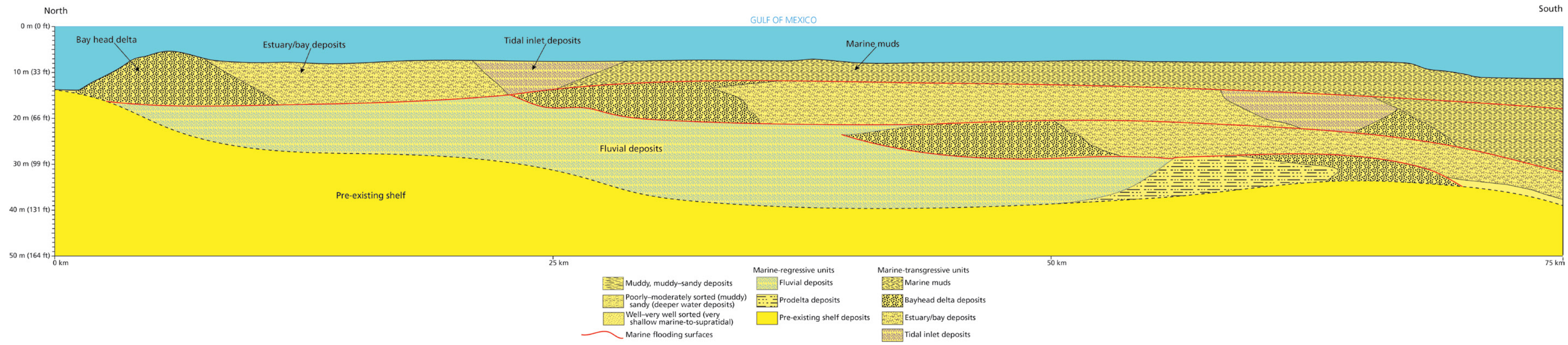

Figure 40. Geologic cross section from Dauphin Island to offshore.
This conceptual geologic cross section is for 8,000 to 2,000 years ago and extends from the Mobile ebb-tidal delta offshore of Dauphin Island. It shows deposition from a marine transgression composed of tidal-inlet, estuarine, and bayhead-delta facies. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Flocks et al. (2010, figure 6C).

waters started to invade the incised stream valleys and fill the wide (10–20 km [30–70 mi]) basin of the future Mississippi Sound. Nearshore Gulf Coast deposits formed under brackish and muddy conditions that were influenced by stream runoff (Otvos 2001). Present-day eastern Dauphin Island was at this time still an 11-km- (7-mi-) long, 12-m- (40-ft-) high ridge remnant of the Gulfport Formation, which consisted of a coastal beach–dune barrier chain on dry land. When sea level rose to 10 m (30 ft) below its current elevation, Dauphin Island was surrounded by the sea and the ridge became an island.

By 5,500 years ago, sea level stood approximately 5.5 to 6.0 m (18 to 20 ft) below its present level (Otvos 1994; Anderson et al. 2014, 2016b). The Gulf of Mexico inundated the present Mississippi Sound area. Massive westward-directed sand volumes were transported from the large Mobile River ebb-tidal delta to the new Dauphin Island (fig. 40).

Approximately 5,500 to 5,100 years ago, when sea level reached between 5.0 and 4.0 m (15 to 12 ft) below the present level (Otvos 2004b; Anderson et al. 2014, 2016b), the rate of sea level rise slowed. A subtidal shoal platform started to aggrade between east Dauphin Island and southeast Louisiana. The shoal platform isolated the Mississippi Sound from the Gulf of Mexico, converting the area from open marine conditions to a lagoon with salinities that decreased landward and vertically upward (Otvos and Giardino 2004). Barrier islands emerged on the platform and evolved through the gradual seaward growth of parallel beach ridges (Otvos and Giardino 2004). A large beach-ridge plain, including Perdido Key, also formed on the mainland coast and expanded toward the Gulf of Mexico from the Alabama and northwest Florida coast.

A scarp-like Pleistocene erosional surface is present along east Dauphin Island (Otvos 1981a; Flocks et al. 2011b). Under the other islands, thick late Holocene muddy marine deposits separate the deeply buried Pleistocene surface from the shoal platform. The mid-Holocene seafloor configuration and position of the Mobile ebb-tidal delta and east Dauphin Island were the key factors that have determined the sites of the Mississippi barriers (Ervin Otvos, University of Southern Mississippi, professor emeritus, written communication, 15 September 2017).

Shoal deposits formed through wave and current action out to the 20 m (70 ft) water depth (Flocks et al. 2011b). The topographic lows formed by incised (and later infilled) valleys (fig. 38) may contain material that is more easily erodible than the surrounding sandy platform. This may focus modern-day storm erosion and island breaching at these locations (Flocks et al. 2011b).

As sea level approached its current position (fig. 39D), the St. Bernard lobe of the Mississippi River Delta complex extended across the mid-shelf from the west, covering the incised stream valleys. East of the delta lobe, Holocene deposits (table 11) include transgressive marine sediments, sand sheets, and shoals. As indicated by the shoals' position relative to river channels (Morton 2007), the shoals were formed from reworked sediments from lower Pleistocene units. Relict shoals remain on the shelf and modern coast (Flocks et al. 2011a). Shoals are also discussed in the "Nearshore Geomorphology and Geologic Framework" section of the "Geologic Setting and Significance" chapter.

Santa Rosa Island

There are two hypotheses for the formation of Santa Rosa Island. One proposes that the island emerged 4,000–3,500 years ago from an elongated shoal (Otvos 1982a, 2005b, 2005c) that formed by sand transported alongshore from the east. As sea level rose, the island likely emerged over and around a Pleistocene core that was a topographic high during the emergence of the island, though at a lower elevation than present-day sea level (Otvos 1985a). Gulfport Formation barrier sand may have formed the assumed narrow Pleistocene core under the middle sector of Santa Rosa Island (Otvos 1982a), the Pleistocene barrier ridge on the western flank of the Mobile Bay entrance, and the core of eastern Dauphin Island, which provided sand for westward littoral transport as sea level rose (Otvos and Giardino 2004).

The second hypothesis proposes a transgressive island history (Houser 2012) supported by work from Hsu (1960), Kwon (1969), Stone et al. (1992, 2004), and Stone and Stapor (1996). As Santa Rosa Island retreated landward, it left a Holocene sand sheet over the Pleistocene surface of the Gulfport Formation and underlying Biloxi Formation (figs. 35 and 42) (Parker et al. 1992; McBride and Byrnes 1995; Otvos and Giardino 2004; Otvos 2005b, 2005c). In this view, the parallel submarine ridges extending from the sand sheet may be remnants of cuspate spits that developed along the back-barrier shoreline from washover sediments. As the island migrated landward over the back-barrier deposits, the cuspate spits survived as topographic highs with a core of back-barrier mud (Houser 2012).

A long line of eroding Pleistocene shore bluffs composed of Sangamonian (interglacial) and Wisconsinan (glacial) dune deposits as far east as the Apalachicola Coast provided the source of sand for Santa Rosa Island and other Holocene coastal landforms (Otvos 1982a, 1997).

Perdido Key and Perdido Shoals

The wide portion of Perdido Key is part of the Holocene mainland ridge plain that extends westward to Mobile Bay and landward by a few kilometers. It evolved by gradual seaward growth of the mainland shoreline before the adjacent Santa Rosa barrier island formed. It became an island when the Intracoastal Waterway canal was dredged, separating it from the mainland.

The closest shoal to Perdido Key is the north Perdido shoal, a 30-km- (20-mi-) long shoal that lies 15–25 km (9–16 mi) offshore in water 20–25 m (70–80 ft) deep (fig. 39D). This and associated shoals represent periods when the rate of sea level rise slowed during the Sangamonian transgression. The shoals may have formed as shoreline ridges during marine stillstands (McBride et al. 2004; Flocks et al. 2011a) or may be remnant shoreface-attached ridges that formed during sea level rise (Parker et al. 1992; Flocks et al. 2011a). Their asymmetrical profile indicates that the ridge sets were reworked. The steeper slopes face landward. Vibracores taken at 10 m (30 ft) water depth off Perdido Key (fig. 34) indicate the presence of a Pleistocene soil horizon that marks an unconformity (surface formed as a result of flooding caused by rising sea level, which removed earlier sediments through erosion). The soil is overlain by estuarine sediments that grade upward into Holocene open bay deposits. A lower-shoreface shell bed, capped by a marine sand layer, completes the sequence (table 11) (McBride et al. 1999).

Mississippi–Alabama Barrier Islands

As indicated, Dauphin Island formed after the rising Gulf of Mexico surrounded a large Pleistocene beach ridge. Sand transmitted from the adjacent large Mobile Bay ebb-tidal delta and westward littoral drift along the new island attached a shallow and narrow sand platform to the west end of the new island. The platform covered muddy-to-sandy nearshore marine deposits. This platform originally extended as far as southeast Louisiana. It descends from sea level to a depth of 6 m (20 ft) below sea level. It is 2 km (1 mi) wide at its widest point (Otvos 1985b, 2005b).

The Mississippi–Alabama barrier chain is underlain by a Miocene to late Pleistocene sedimentary sequence including the Biloxi Formation and what is likely the Prairie Formation, which occur beneath the coastal plain along mainland Mississippi, Alabama, and northwest Florida. Most of the Mississippi islands consist of a series of beach ridges (a strand plain) that

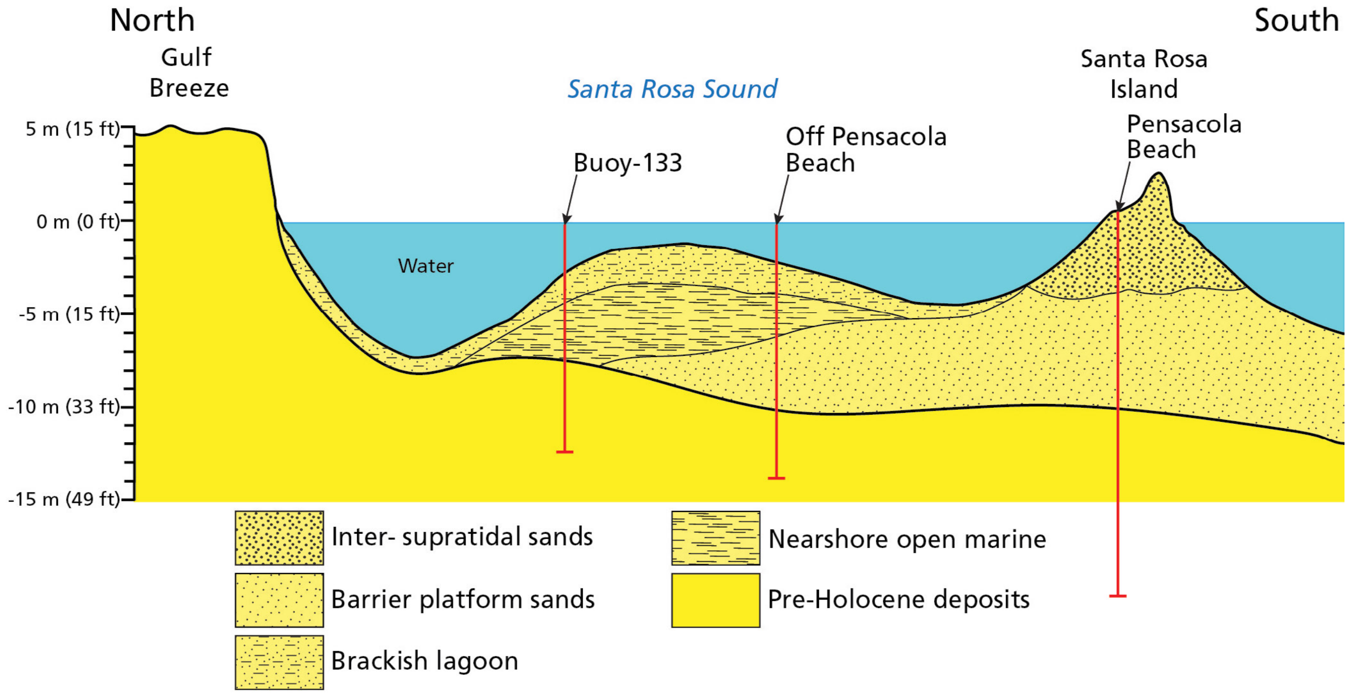

Figure 41. Geologic cross section from Gulf Breeze, Florida, to Santa Rosa Island.
This cross section extends across Santa Rosa Sound through Santa Rosa Island and includes the western prograded island area. Red lines indicate locations of cores that support the stratigraphic interpretation. Red lines indicate locations of cores that support the stratigraphic interpretation. Note the open marine deposits beneath the lagoonal unit. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Otvos (1985b, figure 8).

prograded and are underlain by white sand. Beneath East and West Ship Islands and above the erosional flooding surface (transgressive unconformity) that formed after the St. Bernard lobe of the Mississippi River Delta was built (fig. 42), sediments are 6 to 11 m (20 to 36 ft) thick; they are 4 to 6 m (13 to 20 ft) thick between the islands (in Camille Cut) (Twichell et al. 2013). Beneath Horn and Ship Islands, the sands display sharply contrasting pale-orange and light yellowish-brown pigmentation that resembles dune reddening, which is caused by the oxidation of iron mineral over time, and therefore can indicate the age and environmental conditions of the layers (fig. 43) (Otvos 2001). In the Mississippi Sound, the thickness of Holocene sediments is between 4 and 7 m (13 and 23 ft) (figs. 43 and 44) (Twichell et al. 2013).

The Mississippi barrier island chain aggraded from long shallow shoals over muddy, nearshore marine late Holocene sediments (figs. 44 and 45) (Otvos 1979, 1981a; Otvos and Giardino 2004; Otvos and Carter 2013) approximately 5,700–5,000 years ago when sea level was 2 to 3 m (7 to 10 ft) lower than today and the rate of sea level rise was slowing (Otvos 1979, 1997, 2005a, 2005b, 2005c; Otvos and Giardino 2004).

At one time, the Mississippi–Alabama island chain extended to New Orleans, Louisiana (Otvos and Giardino 2004). Alongshore transport moved the islands westward, carrying sediment from eastern Dauphin Island and the Mobile Pass ebb-tidal delta. Ship Island formed in two stages. Before the island formed, 2–4 m (7–13 ft) of Holocene mud was deposited on the shelf on the transgressive unconformity (fig. 44) (Otvos 1985b). Then, two islands separated by a sandy tidal delta formed seaward of the present islands (fig. 45) (Twichell et al. 2011) about 4,600 years ago (Otvos 1985b). Growth of the island chain isolated what is now the eastern and central Mississippi Sound (Otvos and Carter 2008) approximately 4,500 years ago. Horn Island formed approximately 3,000–4,000 years ago (Otvos 1970) on a Holocene sand platform that is about 12 m (40 ft) thick (fig. 36) (Otvos 1979).

About 4,000 years ago, the St. Bernard lobe of the Mississippi River Delta expanded, resulting in mainland extension, shoaling, and marsh development (fig. 39D). This change reduced waves in the western Mississippi Sound, thereby diminishing littoral sand transport to Ship Island (Otvos 1981a; Otvos and Giardino 2004).

After the St. Bernard lobe was abandoned about 1,800 years ago, the present Ship Islands were reestablished by spit elongation (Otvos and Giardino 2004), forming

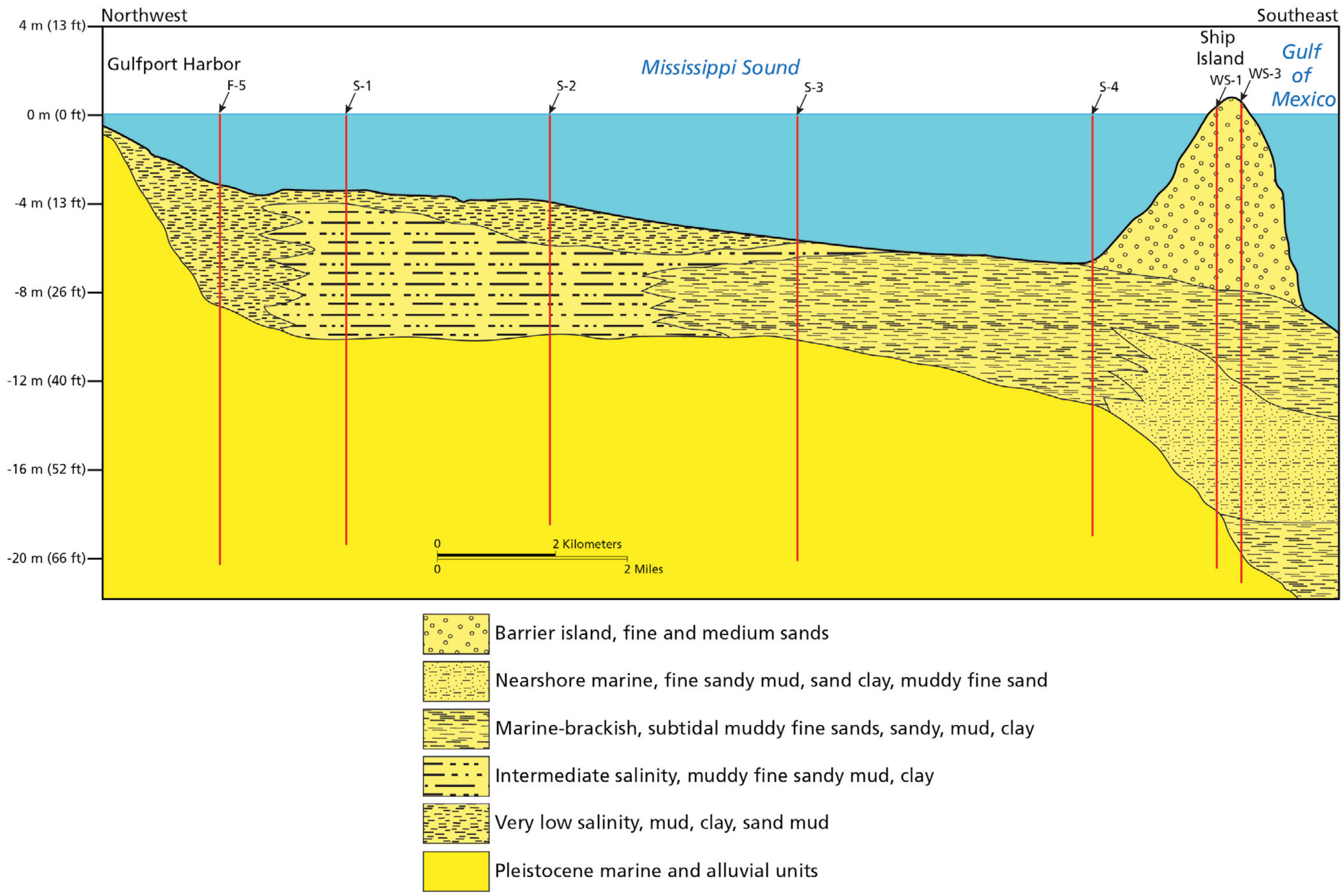

Figure 42. Geologic cross section from Gulfport Harbor, Mississippi, to the Gulf of Mexico. This cross section shows the Quaternary sediments below Gulfport Harbor (left), across Mississippi Sound and West Ship Island, to the Gulf of Mexico (right). Red lines indicate locations of cores that support the stratigraphic interpretation. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Otvos (1981a, figure 3).

beach ridges after 2,100 years ago. The ridges, which run roughly northwest–southeast, are separated by swales; they may indicate an earlier inlet location (Rucker and Snowden 1990).

Cat Island

The core of Cat Island formed approximately 5,400 years ago as a long linear barrier island at the site of the present north-central Cat Island beach ridge complex (Miselis et al. 2014). This took place following transgressive flooding of the inner shelf and formation of the contiguous barrier shoal platform between Dauphin Island, including the Pine Island shoal belt in east New Orleans (Otvos 1978). Approximately 4,000 to 3,600 years ago, westward sediment transport deposited sand under the present-day southern beach ridge complex and the subaqueous sediments to the south and east of the island (Miselis et al. 2014).

Cat Island continued to prograde toward the Gulf of Mexico through ridge development until approximately 3,000 years ago, creating the widest north–south strand plain complex in the Mississippi barrier chain (Otvos 2018; Otvos and Giardino 2004; Otvos and Carter 2008). The St. Bernard lobe of the Mississippi River Delta prograded, depositing sediments to the south and east of Cat Island (fig. 39D) (Miselis et al. 2014) and interrupting the development of Ship Island (Twichell et al. 2011). The resulting mainland extension, shoaling, and marsh development stranded the barrier islands of western Mississippi and southeastern Louisiana within the emerging marshlands.

The expanding delta lobe interrupted westward sediment transport from Ship Island to Cat Island, which led to erosion along the eastern end of Cat Island (Otvos 1979; Otvos and Giardino 2004). The eroded sediments were transported to the northern beach ridge complex (1,500 years ago) and to middle spit (2,000 years ago) (Miselis et al. 2014). The subaqueous island

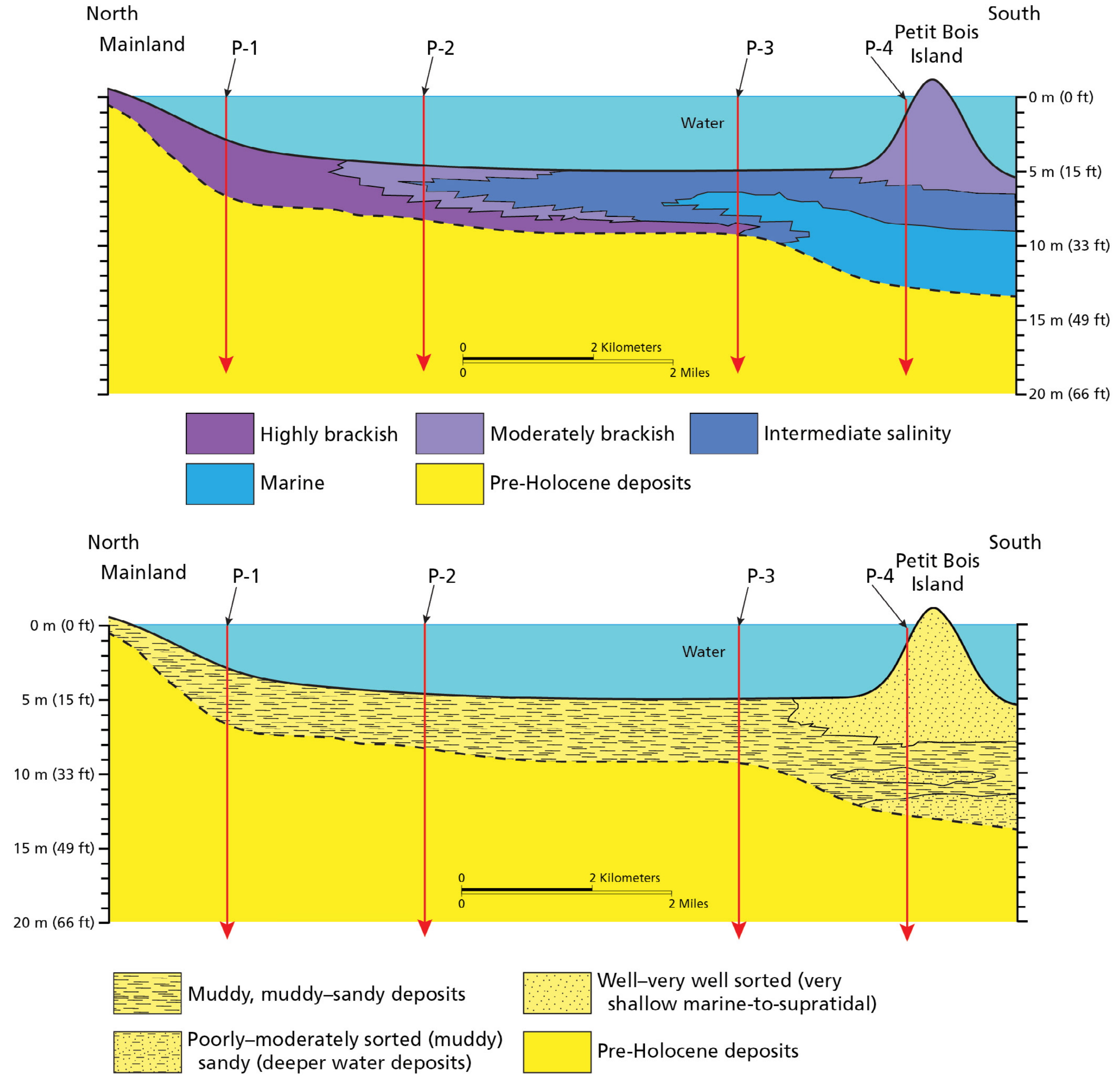

Figure 43. Geologic cross section from mainland Mississippi to Petit Bois Island. This figure includes two cross sections that show the lithology (bottom) and corresponding depositional environments (top). The bottom cross section shows the sediments beneath the Mississippi Sound and Petit Bois Island. Red lines indicate locations of cores that support the stratigraphic interpretation. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Otvos (1981a, figure 4).

platform prograded southward over the deltaic deposits (Miselis et al. 2014). The Mississippi–St. Bernard delta complex continued to subside, exacerbating erosion of Cat Island and eliminating the oldest ridge sets in northern Cat Island and allowing intrusion of Gulf of Mexico waters into the strand plain swales (Otvos 1973a; Otvos and Giardino 2004). The southern ridge set became almost completely submerged and covered by intertidal marshland (Otvos and Giardino 2004; Otvos and Carter 2008; Otvos 2018).

Deltaic deposition declined until finally the St. Bernard lobe of the Mississippi River Delta was abandoned between 2,000 and 1,500 years ago, and river discharge was redirected southward to a new delta complex (Frazier 1967). The St. Bernard delta complex has continued to subside since that abandonment,

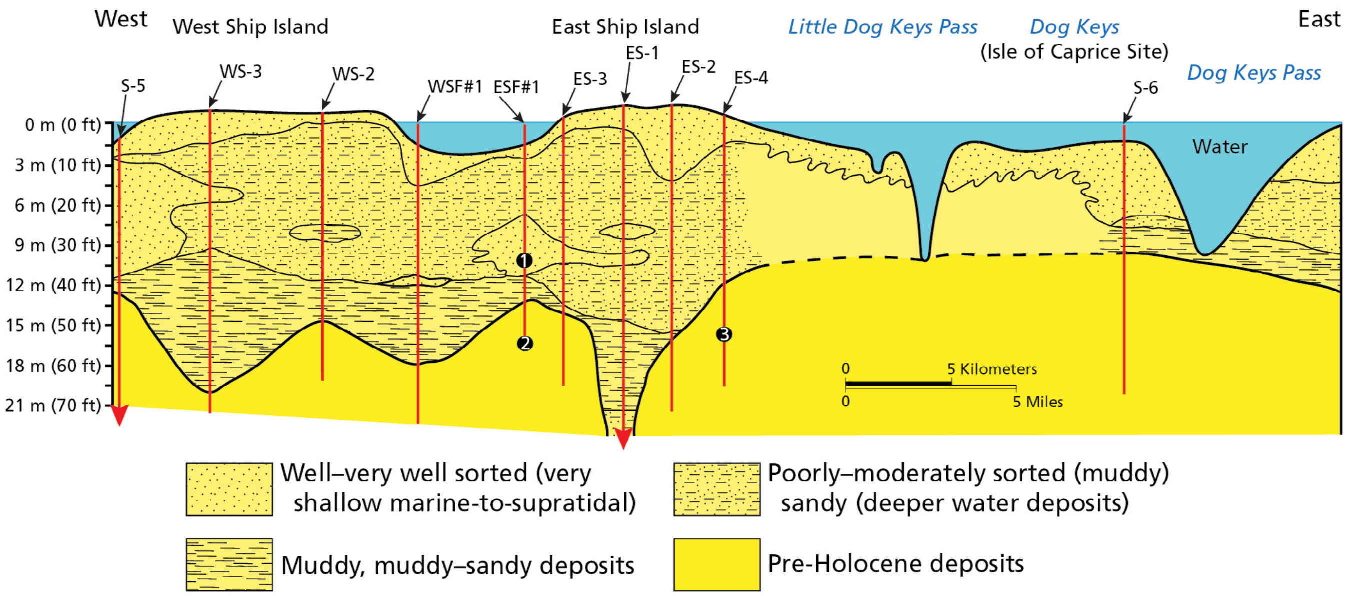

Figure 44. Geologic cross section from West Ship Island through Dog Keys Pass. This cross section shows the shore-parallel lithologic units beneath West and East Ship Islands, as well as those beneath Little Dog Keys Pass, Dog Keys, and Dogs Keys Pass. Red lines indicate locations of cores that support the stratigraphic interpretation. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Otvos (1981a, figure 3).

primarily as a result of Holocene sediment compaction (Jankowski et al. 2017), sediment loading, and glacial isostatic adjustment (Yuill et al. 2009), and to a lesser extent to anthropogenic fluid withdrawal of hydrocarbons (Morton et al. 2006; Kolker et al. 2011). Delta deposits have been reworked and incised by a tidal channel offshore of Cat Island (Miselis et al. 2014).

Recent Barrier Island Evolution (1848–present)

Perdido Key

New Inlet, an intermittent inlet several miles to the west of Pensacola Pass, closed about 1880–1900, causing hydrologic changes in the lagoon behind Perdido Key (Price 1975). The lagoon has been modified multiple times in the last century by the creation of the Intracoastal Waterway to connect Perdido Bay to Pensacola Bay in the early 1900s, a canal to separate O'no Island from the Alabama mainland, and another canal to connect Perdido Bay with Big Lagoon. These changes have increased flushing through the bay.

The Perdido Key area of the park experiences storm-driven overwash and flooding, including during Hurricane Frederic in 1979, which had a storm surge of approximately 4 m (14 ft) (Doyle et al. 1984).

Santa Rosa Island

The modern surface of Santa Rosa Island is very close to the Pleistocene surface/topographic high (fig. 41). Recurved beach ridges that form the western 8 km (5 mi) of the Fort Pickens area formed after 1764 (Lewis et al. 2003).

Parts of the Fort Pickens area are frequently overwashed during storms. More than 90% of Santa Rosa Island was submerged during Hurricane Frederic in 1979, and again in 1995 by Hurricane Opal, which also removed dunes as high as 5 m (16 ft) (Doyle et al. 1984; Pendleton et al. 2004). The island was breached by Hurricane Ivan in 2004 and again by Hurricane Dennis in 2005. Additional information on hurricane impacts is provided in the "Hurricane Impacts and Human Responses" section of the "Geological Resource Management Issues" chapter.

Mississippi-Alabama Barrier Islands

Petit Bois Island and Dauphin Island were once one island known as Isle Dauphin, according to French and British charts from the 18th century. The island was breached by a storm in either August 1717 (Sullivan 2009, as cited in Byrnes et al. 2010) or September 1740 (Otvos 1979; Otvos and Giardino 2004). Petit Bois Island then began migrating westward as the broad, high eastern end eroded (fig. 16). Following separation, a parabola-shaped ebb-tidal delta expanded within Petit Bois Pass, sequestering sediments migrating from the east (Flocks et al. 2015).

The length of Petit Bois Island has fluctuated between 6 and 25 km (4 and 16 mi) and has lost half of its area since 1848 (figs. 16 and 17) (Otvos and Carter 2013). In 1848, the island was 19 km (12 mi) long. By 1912, it was only 9 km (6 mi) long. What was left of the narrowing eastern sector significantly eroded during a 1916 hurricane and converted to a shoal platform, which eventually eroded away (Otvos and Carter 2008). The hurricane also created a 9-km- (6-mi-) wide breach that took 10 years to close (Hardin et al. 1976, as cited in Otvos and Carter 2013).

Between 1882 and 1974, Petit Bois Pass widened from 2 to 8 km (1 to 5 mi) and shifted 12 km (8 mi) westward (figs. 16 and 17) (Otvos and Carter 2008). The widening allowed increased wave energy to reach the mainland shore of the Mississippi Sound, increasing coastal erosion along marshlands. The growing ebb-tidal delta within the pass reduced the downdrift sediment supply to Horn Island, accelerating erosion there (Otvos and Carter 2008; Twichell et al. 2011). Before 1957, most sediment eroded from eastern Petit Bois Island was deposited along the sand spit at the western end of the island and in the Pascagoula Channel through Horn Island Pass; the pass and the island were migrating westward at a rate of about 39 m (128 ft) per year (Byrnes et al. 2013). However, continued maintenance of the navigation channel has prevented accretion along the island's western end. Between the 1960s and 2009, the eastern end of Petit Bois Island continued to erode, and the island retreated to the northwest (fig. 16). A vegetated beach ridge complex (see poster, in pocket) has developed on the eastern end of Petit Bois Island, adding stability to the island and limiting the expansion of Petit Bois Pass (Flocks et al. 2011b).

Sand Island was created from sediment dredged from the Horn Island Pass section of the Pascagoula Harbor Federal Navigation Project, and first appeared on navigation charts in 1970. The island has elevations up to 6 m (20 ft) (Otvos and Carter 2008). Although intended as a spoil area, it now functions as a barrier island, complete with wildlife, vegetation, and a freshwater pond with associated freshwater species (fig. 13) (Gary Hopkins, Gulf Islands National Seashore, biologist, personal communication, 17 August 2015). The island has about 11 ha (27 ac) of interior wetlands with obligate freshwater and saltwater plant species (fig. 7) (Ford 2013).

Historically, Horn Island has measured approximately 1 km (0.6 mi) wide and 18 to 21 km (11 to 13 mi) long. It migrated westward as its eastern end eroded. Interior strand plain ridges, 5–7 m (16–23 ft) high, prevented storm breaches across most of Horn Island. The island has only lost 26% of its area since 1848 (figs. 17 and 18) (Otvos and Carter 2013). Along the western spit, sediment deposition between the 1800s and early 1900s caused Dog Keys Pass, and the smaller Little Dog Keys Pass to the west, to narrow and deepen (Rucker and Snowden 1988, as cited in Buster and Morton 2011).

The former Isle of Caprice was part of the Dog Keys and was located between Horn and Ship Islands intermittently from 1848 to 1940. The Isle of Caprice is believed to have been split during a July 1916 hurricane (Otvos 1979). On the eastern side of the island, the maintained navigation channel at Horn Island Pass has diminished or eliminated sand transport from Petit Bois Island, stopping island progradation (fig. 17) (Knowles and Rosati 1989; Douglass 1994; Otvos and Carter 2013).

East and West Ship Islands lie west of Horn Island. The East Ship Island strand plain may be the remnant western tip of a long-extinct barrier island, as suggested by ridges that trend northwest-to-west (Otvos and Giardino 2004). In the late 1800s, the Gulf shoreline along the eastern and central portions eroded while the seafloor accreted on the inner shelf and off the western spit, providing accommodation space for Ship Island Pass to migrate into (Buster and Morton 2011). Storms continued to impact the island in the following century, and a complex of relict washover lobes on West Ship Island was likely formed by hurricanes in 1906 or 1926 and 1947 (Otvos and Carter 2008).

Ship Island was breached by at least eight hurricanes since 1862, including the 1947 cyclone and Hurricane Betsy in 1965 (Falls 2001; Otvos and Carter 2008). It was again divided by Hurricane Camille in 1969, which removed the spit-like, narrow 3-km- (2-mi-) long island center. In 2005, Hurricane Katrina eroded the islands even more severely. Since 1848, the Ship Islands have lost almost 58% of their combined area (figs. 18 and 19) (Otvos and Carter 2013). Major tropical storms also had a profound impact on changing the composition of the island flora (Carter et al. 2018).

In the first half of the 1900s, the eastern end of Ship Island (fig. 18) continued to retreat toward the northwest while the middle of the island narrowed. Channel dredging at Ship Island Pass caused westward extension to cease (Buster and Morton 2011). Erosion from the beach and nearshore areas of East Ship Island was significant, nearly three times the volume of sand contributed by the Dog Keys Passes to the east. The sand deficit slowed island recovery following Hurricane Katrina in 2005.

The Gulfport Channel off the western end of West Ship Island reduced or eliminated littoral drift. Westward island growth ceased as a result of the deepened navigation channel (Buster and Morton 2011). This effect, combined with channel dredging and placement

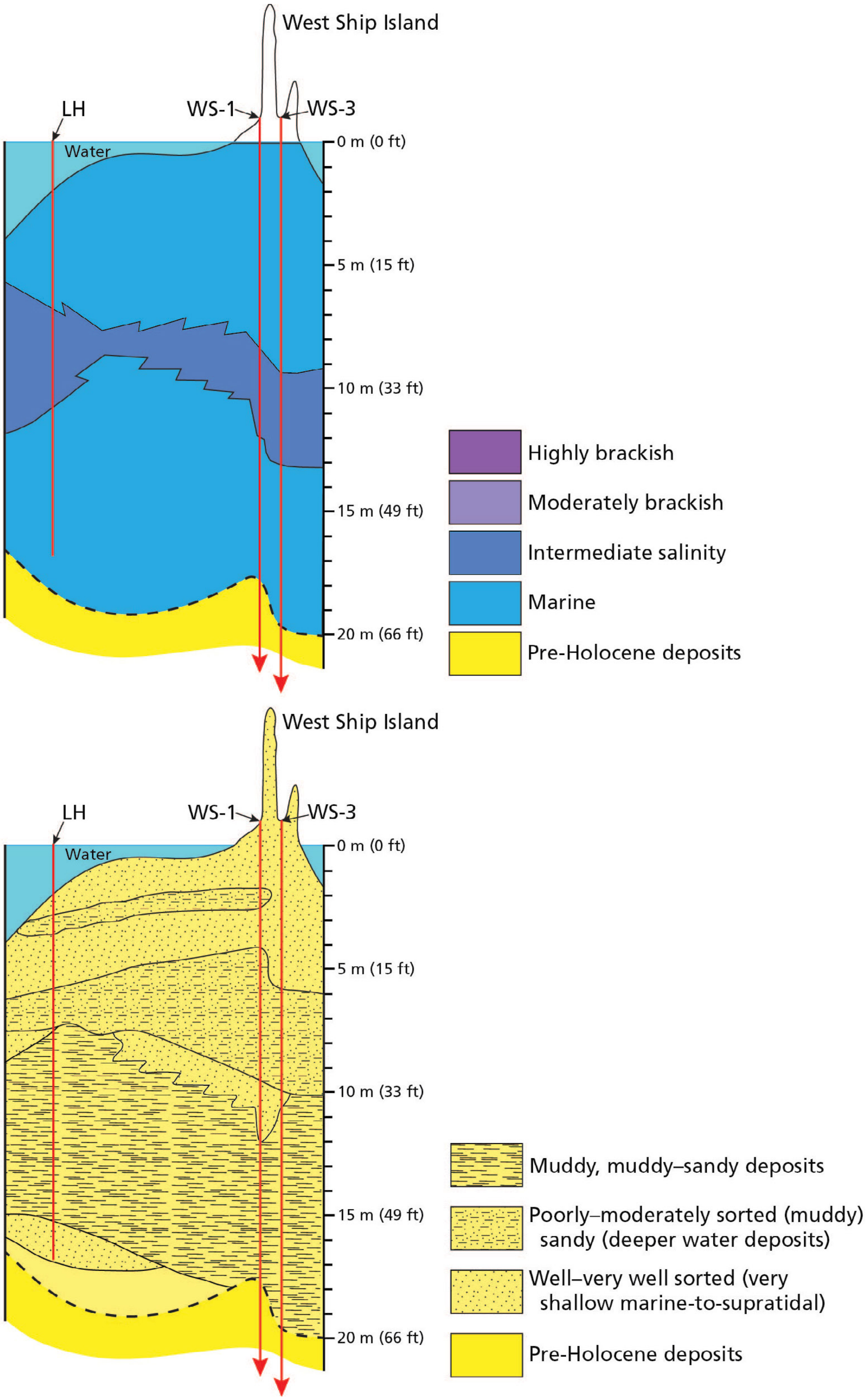

Figure 45. Geologic cross section across West Ship Island.
This figure includes two cross sections that show the lithology (bottom) and corresponding depositional environments (top). Red lines indicate locations of cores that support the stratigraphic interpretation. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Otvos (1981a, figure 4).

of spoil updrift or offshore, has diminished sand transport between the Ship Islands and Cat Island and has slowed or stopped downdrift island progradation (Knowles and Rosati 1989; Douglass 1994; Otvos and Carter 2013). In 1993, the navigation channel was relocated westward, widened, and deepened, creating space for accretion at the western end of the Ship Islands, resulting in infilling of the old channel (Buster and Morton 2011). Additional information on the effects of channel maintenance can be found in the "Dredging of Inlets" section of the "Geological Resource Management Issues" chapter.

Episodic hurricane destruction and island segmentation continues to shape the Mississippi–Alabama barrier islands (Otvos 1979). In 2005, storm surge during Hurricane Katrina completely submerged the entire Mississippi barrier island chain, creating breaches and reducing island size. Detailed measurements of the storm-driven changes in pass widths and island lengths since 1848 are available in Otvos and Carter (2008). The "Hurricane Impacts and Human Response" section of the "Geologic Resource Management Issues" chapter provides additional information.

Cat Island

The evolution of Cat Island was drastically modified by the encroachment of the St. Bernard lobe of the Mississippi River Delta to the south. Delta progradation reduced the wave energy at Cat Island, terminating strand plain growth (Otvos and Giardino 2004) and redirecting sediment transport at the eastern end of the island to the north and south. Sand that eroded from the eastern strand plain margin was carried northward and southwestward, forming the two eastern peninsulas. The northeastern peninsula consists of ridges that are buried by reworked secondary dunes and aeolian sand sheets. Only the northern tip of the northeastern peninsula is a barrier spit, in contrast to the entire southeastern peninsula, which is a longer, narrower barrier spit that is reworked by storms but reforms in calm periods (Otvos and Carter 2008). The formation of the peninsulas further blocked littoral sand flow, allowing sea level rise resulting from ongoing subsidence (due to tectonics and compaction) to flood the narrow swales between strand plain ridges and form tidal marshes within the ridges (fig. 14) (Otvos and Carter 2008).

Cat Island has lost more than 40% of its area since 1848 (fig. 19) despite having low-energy wave conditions on three sides (Otvos and Carter 2013). The northern ridge plain has been eroding because of reduced sediment supply, compaction, and subsidence of the adjacent Mississippi River Delta complex, causing westward retreat of the northeastern peninsula. Hurricane Katrina in 2005 also caused erosion, including excavation of the extensions of the strand plain ridges beneath the east-facing beach (Otvos and Carter 2008).

Future Geomorphology

The Mississippi barrier islands have kept pace with rising sea level during the Holocene Epoch but continue to erode and lose area. This topic is discussed in the "Coastal Vulnerability and Sea Level Rise" section of the "Geological Resource Management Issues" chapter. Ship, Horn, and Petit Bois Islands have lost 26% of their area in 150 years, declining from a combined surface area of about 40 km^2 (15 mi^2) in 1850 to 30 km^2 (12 mi^2) in 2000 (Otvos and Giardino 2004). Ship Island may be the best predictor of future evolution of the Mississippi barrier islands (Morton 2007). Island narrowing, segmentation caused by storms, variations in sediment supply and transport, and continued channel maintenance are the main processes currently resulting in the decline of island area; these processes are expected to continue.

The future of the park's barrier islands will be strongly influenced by continued sea level rise, storms, and anthropogenic actions including the Mississippi Coastal Improvements Program and regular beach renourishment along the Florida Gulf Coast. More information on these activities is provided in the "Geological Resource Management Issues" chapter.

Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI program. GRI GIS data produced for the park follows the source maps listed here and includes components described in this chapter. Two posters (in pocket) display the data over imagery of the park and surrounding area. Complete GIS data are available at the GRI publications website. Refer to Appendix C for URLs.

Geologic Maps

A geologic map is the fundamental tool for depicting the geology of an area. Geologic maps are two-dimensional representations of the three-dimensional geometry of rock and sediment at or beneath the land surface (Evans 2016). Colors and symbols on geologic maps correspond to geologic map units. Typically, the unit symbols consist of an uppercase letter indicating the age (Table 1) and lowercase letters indicating the formation's name, though the unit symbols in the GRI GIS data for the park do not follow this convention, rather they are abbreviations that stand for mapped geomorphic features (discussed below). Other symbols depict structures such as faults or folds, locations of past geologic hazards that may be susceptible to future activity, and other geologic features. 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, provides more information about geologic maps and their uses.

Geologic maps are typically one of two types: surficial or 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. 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.

The GRI team produced a "surficial geologic map" for Gulf Islands National Seashore, consisting of two geospatial data sets and four component maps. Mapping applied a geomorphic approach, focusing on the classification and delineation of landforms such as active dune complexes and beaches, and anthropogenic features such as inlet jetties. The titles of the GRI GIS data sets, as well as the source maps (see below), reflect this approach: Digital Geomorphic Map for the Florida Portions of Gulf Islands National Seashore (gifl_geology.mxd) and Digital Geomorphic Map for the Mississippi Portions of Gulf Islands National Seashore (guis_geology.mxd). The classified map units also reflect this approach. The map unit symbols do not include an uppercase letter indicating age, rather unit symbols consist of lowercase letters indicating the feature's name (table 2).

Source Maps

The GRI team does not conduct original geologic mapping. The team digitizes paper maps and compiles and converts digital data to conform to the GRI GIS data model. The GRI GIS data set includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, figures, and references. These items are included in the guis_geology.pdf. The GRI team used the following USGS publications to produce the digital geologic data set for Gulf Islands National Seashore. These sources also provided information for this report.

Morton, R. A., and B. E. Rogers. 2009. Geomorphology and depositional subenvironments of Gulf Islands National Seashore. Tile 1 of 4: Cat Island, Mississippi (scale 1:11,500). Open File Report 2009-1250. US Geological Survey, Reston, Virginia.

Morton, R. A., and B. E. Rogers. 2009. Geomorphology and depositional subenvironments of Gulf Islands National Seashore. Tile 2 of 4: Ship Island, Mississippi (scale 1:14,000). Open File Report 2009-1250. US Geological Survey, Reston, Virginia.

Morton, R. A., and B. E. Rogers. 2009. Geomorphology and depositional subenvironments of Gulf Islands National Seashore. Tile 3 of 4: Horn Island, Mississippi (scale 1:26,000). Open File Report 2009-1250. US Geological Survey, Reston, Virginia.

Morton, R. A., and B. E. Rogers. 2009. Geomorphology and depositional subenvironments of Gulf Islands National Seashore. Tile 4 of 4: Petit Bois Island, Mississippi (scale 1:12,000). Open File Report 2009-1250. US Geological Survey, Reston, Virginia.

Morton, R. A., and M. C. Montgomery. 2010. Geomorphology and depositional subenvironments of Gulf Islands National Seashore, Perdido Key and Santa Rosa Island, Florida (scale 1:10,000). Open-File Report 2010-1330. US Geological Survey, Reston, Virginia.

The USGS selected Gulf Islands National Seashore for detailed mapping of barrier-island morphology and topography because the islands offer a diversity of depositional subenvironments and the islands' areas and positions have changed substantially in historical time. The geomorphologic and subenvironmental maps emphasize the processes that formed the surficial features and also serve as a basis for documenting which subenvironments are relatively stable, such as the beach ridge complex, and those which are highly dynamic, such as the beach and active overwash zones (Morton and Mongomer 2010).

The primary mapping procedures used supervised functions (manually captured and classified features) within a geographic information system (GIS); that is, during digitization, individual features (map units) and delineated boundaries of these features (shapefiles) were captured and classified, feature by feature. The GIS classified units on the basis of tonal patterns of a feature in contrast to adjacent features as captured in georeferenced aerial photographs. Orthophotographs for the Mississippi islands were from September and October 2007; boundary delineation was supplemented by land elevations from June 2007 lidar surveys with 1-meter-pixel resolution. For the Florida islands, 1-foot resolution true-color orthophotographs from 2006–2007 were supplemented by land elevation data from 2006–2008 lidar-derived digital elevation models and hillshades from the Northwest Florida Water Management District, as well as 2004 and 2005 bare-earth surface lidar-derived digital elevation models and hillshades, and low-altitude videography collected by the USGS in 2004, 2005, and 2008. The shoal map unit (**shoal**) was delineated from 2007 USGS bathymetric data. Polygon units that are 1.8 m2 (19 ft2) or less may have been misclassified.

GRI GIS Data

The GRI team standardizes map deliverables by using a data model. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI GIS data for Gulf Islands National Seashore was compiled using data model version 2.1.

GRI GIS data are available on the GRI publications website and through the NPS Integrated Resource Management Applications (IRMA) portal. Enter “GRI” as the search text and select a park from the unit list.

The following components are part of the data sets:

- A GIS readme file (guis_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information.
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology (table 12);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (guis_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross sections, and figures; and
- ESRI map documents that display the digital geologic data for the Florida (gifl_geology.mxd) and Mississippi (gims_geology.mxd) islands.

GRI Map Posters

Two posters of the GRI digital geologic data are included with this report. One of the posters displays five segments that compose Santa Rosa Island and Perdido Key (Florida). Another poster displays Cat Island, East and West Ship Islands, Horn Island, and Petit Bois Island (Mississippi); Sand Island is not included on this poster, but figure 7 of this report illustrates ecological habitats and geomorphic features (marsh shrubland, beach dune herbland, water, and bare sand) that make up Sand Island.

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 in locating these data.

Use Constraints

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

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographical features on the poster. The source maps were produced at a variety of scales: 1:10,000; 1:11,500; 1:12,000, 1:14,000, and 1:26,000. Based on those scales and US National Map Accuracy Standards, geologic features represented in the GRI GIS data and on the posters are expected to be horizontally within 5 m (17 ft) for 1:10,000 scale maps, 5.8 m (19 ft) for 1:11,500 scale maps; 6.1 m (20 ft) for 1:12,000 scale maps, 7.1 m (23 ft) for 1:14,000 scale maps, and 13.2 m (43 ft) for 1:26,000 scale maps, respectively, of their true locations.

Mapping Issues and Data Needs

Primary data used in creating the source maps for the GRI GIS data were collected from 2004 to 2008. Thus, these maps provide “snapshots” of ever-changing, very dynamic island systems. Since publication of these maps

Table 12. GRI GIS data layers in gifl_geology.mxd and gims_geology.mxd.

Data Layer	On Poster?
Geomorphic Unit Contacts	Yes
Geomorphic Units	Yes

(and creation of the GRI GIS data), the barrier islands have been influenced by hurricanes, tropical storms, and restoration projects. In some cases, areas that were actively overwashing at the time of mapping were no longer overwashing and had become stabilized by vegetation by 2017 (at the time of preparing this report); examples include the east end of West Ship Island, both ends of East Ship Island, and both ends of Horn Island. Another area of significant change is the middle portion of the Fort Pickens area of the park, which was an area of active overwash when mapped; now, swales are vegetated wetlands (Mark Ford, Southeast Regional Office, ecologist, email communication, 31 August 2017). In addition, GRI reviewers noted that salt marsh is no longer along the sound side of islands. Moreover, areas of dredged material were mapped incorrectly (at Fort Pickens) or not mapped (on Perdido Key) (Jolene Williams, Gulf Islands National Seashore, environmental protection specialist, GRI review comments, 3 September 2017), and some vegetation communities were improperly associated with geomorphologic units (e.g., vegetated barrier flats not only have salt-tolerant grasses but also have freshwater and brackish water species).

Thus, a significant issue for these maps and their use in resource management is the dynamic nature of barrier islands. Future mapping projects should consider what should really be mapped. Are there approaches or map units that would still be current by the time a map goes through a review process and is published? Groundwater flow and vulnerability might be two key aspects that could be mapped, whereas the locations of overwash zones might not. Another issue that was revealed during the GRI review process is the need for mapping of barrier island systems to incorporate both ecological and geological perspectives. That is, if maps are done by an ecologist, they need to be reviewed by a geologist, and vice versa. This is particularly important if these maps are to be used for resource management in parks. Furthermore, input from resource managers about large-scale anthropogenic changes would improve mapping accuracy, for example, including the locations of recent renourishment projects and placement of dredge material.

In addition, nearshore geology and geomorphology exert significant control on island landforms and coastal processes. Thus to best manage the park’s coastal resources, both the GRI GIS data, which consist of subaerial maps, and the USGS subaqueous maps, which are not currently part of the GRI GIS data set, should be used to understand regional sediment availability and bathymetric control on island dynamics. The USGS data could be converted into the GRI GIS data model and used in conjunction with the existing geomorphic maps of the barrier islands. A combined data set of subaerial and subaqueous map information would be a valuable expansion of the GRI GIS data for resource management. Park managers may consider requesting this as part of an “Inventories 2.0” project.

Literature Cited

These references are cited in this report. Contact the Geologic Resources Division for assistance in obtaining them. Refer to Appendix C for URLs.

Aagaard, T., K. P. Black, and B. Greenwood. 2002. Cross-shore suspended sediment transport in the surf zone: a field-based parameterization. Marine Geology 185(3–4):283–302.

Anderson, C., G. Carter, and W. Funderburk. 2016a. The use of aerial RGB imagery and LiDAR in comparing ecological habitats and geomorphic features on a natural versus man-made barrier island. Remote Sensing 8(7):602.

Anderson, J. B., D. J. Wallace, A. R. Simms, A. B. Rodriguez, and K. T. Milliken. 2014. Variable response of coastal environments of the northwestern Gulf of Mexico to sea-level rise and climate change: implications for future change. Marine Geology 352:348–366.

Anderson, J. B., D. J. Wallace, A. R. Simms, A. B. Rodriguez, R. W. R. Weight, and Z. P. Taha. 2016b. Recycling sediments between source and sink during a eustatic cycle: systems of late Quaternary northwestern Gulf of Mexico basin. Earth-Science Reviews 153:111–138.

Balsillie, J. H., and J. F. Donoghue. 2011. Northern Gulf of Mexico sea-level history for the past 20,000 years. Pages 53–69 (Chapter 4) in N. A. Buster and C. W. Holmes, editors. Gulf of Mexico: origin, waters, and biota. Volume 3, geology. Texas A&M University Press, College Station, Texas.

Bambach, P. W. 2013. Dune and shoreline evolution of western Santa Rosa Island, Florida, 1973–2013. Thesis. Florida State University, Tallahassee, Florida.

Barrett, G., and C. Houser. 2012. Identifying hotspots of rip current activity using wavelet analysis at Pensacola Beach, Florida. Physical Geography 33(1):32–49.

Bartek, L. R., B. S. Cabote, T. Young, and T. Schroeder. 2004. Sequence stratigraphy of a continental margin subjected to low-energy and low-sediment-supply environmental boundary conditions: Late Pleistocene–Holocene deposition offshore Alabama. Pages 85–109 in J. B. Anderson and R. H. Fillon, editors. Late Quaternary stratigraphic evolution of the northern Gulf of Mexico. Special Publication 79. Society for Sedimentary Geology, Tulsa, Oklahoma.

Beavers, R. L., A. L. Babson, and C. A. Schupp. 2016a. Coastal adaptation strategies handbook. NPS 999/134090. National Park Service, Washington, DC.

Beavers, R., and J. Selleck. 2005. Impacts to national parks from 2005 hurricane season coming to light—a preliminary overview. Pages 13–15 in J. Selleck, editor. Natural Resource Year in Review—2005. National Park Service, Denver, Colorado.

Belknap, D. F., and J. C. Kraft. 1985. Influence of antecedent geology on stratigraphic preservation potential and evolution of Delaware's barrier systems. Marine geology 63(1):235–262.

Bracewell, J. 2017a. Monitoring shoreline position at Gulf Coast Network parks: protocol implementation plan. Natural Resource Report NPS/GULN/NRR—2017/1502. National Park Service, Fort Collins, Colorado.

Bracewell, J. 2017b. Monitoring coastal topography at Gulf Coast Network parks: protocol implementation plan. Natural Resource Report. NPS/GULN/NRR—2017/1522. National Park Service, Fort Collins, Colorado.

Browder, A. E., and R. G. Dean. 1999. Coastal impacts of the Pensacola Pass entrance, Florida, USA. Pages 719–733 in N. C. Kraus and W. G. McDougal, editors. Coastal Sediments '99. Proceedings of the Fourth International Symposium on Coastal Engineering and Science of Coastal Sediment Processes, June 21–23, 1999, Long Island, New York. American Society of Civil Engineers, Long Island, New York.

Browder, A. E., and R. G. Dean. 2000. Monitoring and comparison to predictive models of the Perdido Key beach nourishment project, Florida, USA. Coastal Engineering 39(2):173–191.

Browder, A. G., and J. E. McNinch. 2006. Linking framework geology and nearshore morphology: correlation of paleo-channels with shore-oblique sandbars and gravel outcrops. Marine Geology 231:141–162.

Brown, D. 2015. Case study 19: establishing alternative transportation to Fort Pickens to supplement vulnerable road access, Gulf Islands National Seashore, Florida. Pages 46–47 in C. A. Schupp, R. L. Beavers, and M. A. Caffrey, editors. Coastal adaptation strategies: case studies. NPS 999/129700. National Park Service, Fort Collins, Colorado.

Brown, G. F., V. M. Foster, R. W. Adams, E. W. Reed, and H. D. Padgett. 1944. Geology and groundwater resources of the coastal area in Mississippi. Bulletin 60. Mississippi Department of Environmental Quality, Office of Geology, Jackson, Mississippi.

Brunner, J., J. Kenworthy, and V. Santucci. 2009. Unauthorized fossil collecting from National Park Service shorelines: servicewide policy and perspectives. Pages 319–323 in S. Weber, editor. Rethinking protected areas in a changing world. Proceedings of the 2009 George Wright Society Biennial Conference on Parks, Protected Areas, and Cultural Sites. The George Wright Society, Hancock, Michigan.

Burghardt, J. E., E. S. Norby, and H. S. Pranger II. 2014. Abandoned mineral lands in the National Park System: comprehensive inventory and assessment. Natural Resource Technical Report NPS/NRSS/GRD/NRTR—2014/906. National Park Service, Fort Collins, Colorado.

Bush, D. M., and R. Young. 2009. Coastal features and processes. Pages 47–67 in R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado.

Buster, N. A., and R. A. Morton. 2011. Historical bathymetry and bathymetric change in the Mississippi–Alabama coastal region, 1847–2009. Scientific Investigations Map 3154. US Geological Survey, Reston, Virginia.

Byrnes, M. R., S. F. Griffee, and M. S. Osler. 2010. Channel dredging and geomorphic response at and adjacent to Mobile Pass, Alabama. Defense Technical Information Center (DTIC) accession number ADA536622. US Department of Defense, Fort Belvoir, Virginia.

Byrnes, M. R., R. M. Hammer, T. D. Thibaut, and D. B. Snyder. 2004. Physical and biological effects of sand mining offshore Alabama, USA. Journal of Coastal Research 20(1):6–24.

Byrnes, M. R., J. D. Rosati, S. F. Griffee, and J. L. Berlinghoff. 2012. Littoral sediment budget for the Mississippi Sound barrier islands. Defense Technical Information Center (DTIC) accession number ADA572117. US Army Corps of Engineers, Mobile District, Mississippi Coastal Improvements Program (MsCIP), Mobile, Alabama.

Byrnes, M. R., J. D. Rosati, S. F. Griffee, and J. L. Berlinghoff. 2013. Historical sediment transport pathways and quantities for determining an operational sediment budget: Mississippi Sound barrier islands. Journal of Coastal Research 63:166–183.

Caffrey, M. A., and R. Beavers. 2015. Sea level and storm trends, Gulf Islands National Seashore. University of Colorado, Department of Geologic Sciences, Boulder, Colorado.

Caffrey, M. A., R. L. Beavers, and C. H. Hoffman. 2018. Sea level rise and storm surge projections for the National Park Service. Natural Resource Report NPS/NRSS/NRR—2018/1648. National Park Service, Fort Collins, Colorado.

Cahoon, D. R., and D. J. Reed. 1996. Relationships among marsh surface topography, hydroperiod, and soil accretion in a deteriorating Louisiana salt marsh. Oceanographic Literature Review 2(43):136.

Caldwell, N., C. Houser, and K. Meyer-Arendt. 2013. Ability of beach users to identify rip currents at Pensacola Beach, Florida. Natural Hazards 68(2):1041–1056.

Cantor, J. 2012. PropScars2011. Unpublished geospatial data. NPS Water Resources Division, Ocean and Coastal Resources Branch, Fort Collins, Colorado.

Cantor, J. 2013. Seagrass—Gulf Islands National Seashore—2011/10/04. ArcGIS geospatial data set. NPS Water Resources Division, Ocean and Coastal Resources Branch, Fort Collins, Colorado.

Carter, G. A., K. L. Lucas, P. D. Biber, G. A. Criss, and G. A. Blossom. 2011. Historical changes in seagrass coverage on the Mississippi barrier islands, northern Gulf of Mexico, determined from vertical aerial imagery (1940–2007). Geocarto International 26(8):663–673. http://www.tandfonline.com/doi/abs/10.1080/10106049.2011.620634.

Carter, G. A., E. G. Otvos, C. P. Anderson, W. R. Funderburk, and K. L. Lucas. 2018. Catastrophic storm impact and gradual recovery on the Mississippi-Alabama barrier islands, 2005–2010: Changes in vegetated and total land area, and relationships of post-storm ecological communities with surface elevation. Geomorphology 321:72–86.

Carter, L. M., J. W. Jones, L. Berry, V. Burkett, J. F. Murley, S. F. R. P. Council, P. J. Schramm, and D. Wear. 2014. Chapter 17: Southeast and the Caribbean. Pages 396–417 in J. M. Melillo, T. C. Richmond, and G. W. Yohe, editors. Climate change impacts in the United States: the third national climate assessment. US Global Change Research Program, Washington, DC.

Cazenave, A., H. B. Dieng, B. Meyssignac, K. Von Schuckmann, B. Decharme, and E. Berthier. 2014. The rate of sea-level rise. Nature Climate Change 4(5):358–361.

Champlin, S. D., S. C. Knox, and T. M. Puckett. 1994. Regional geologic framework of the Miocene, coastal and offshore Mississippi. Open-File Report 23. Mississippi Department of Environmental Quality, Office of Geology, Jackson, Mississippi.

Chaney, P. L. 1993. Soundside coastal erosion along West Ship Island, Mississippi, Gulf Islands National Seashore—a report on the results of a beach monitoring program conducted by the National Park Service, April 1989 to July 1993. Gulf Islands National Seashore, Ocean Springs, Mississippi.

Chaney, P. L. 1999. Extratropical storms of the Gulf of Mexico and their effects along the northern coast of a barrier island: West Ship Island, Mississippi. Dissertation. Louisiana State University, Baton Rouge, Louisiana.

Christmas, J. Y., editor. 1973. Cooperative Gulf of Mexico estuarine inventory and study, Mississippi. Gulf Coast Research Laboratory, Ocean Springs, Mississippi.

Church, J. A., P. U. Clark, A. Cazenave, J. M. Gregory, S. Jevrejeva, A. Levermann, G. A. Merrifield, R. S. Milne, R. S. Nerem, P. D. Nunn, A. J. Payne, W. T. Pfeffer, D. Stammer, and A. S. Unnikrishnan. 2013. Sea level change. Pages 1137–1216 in T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley, editors. Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, and New York, New York.

Church, J. A., and N. J. White. 2006. A 20th century acceleration in global sea- level rise. Geophysical Research Letters 33(1):L01602.

Cipriani, L. E., and G. W. Stone. 2001. Net longshore sediment transport and textural changes in beach sediments along the southwest Alabama and Mississippi barrier islands, USA. Journal of Coastal Research 17(2):443–458.

Clark, H. 2014. Boundary and regulatory issues at Gulf Islands National Seashore. Memo to Stan Austin, Southeast Regional Director, 21 July 2014. Office of the Solicitor, US Department of the Interior, Atlanta, Georgia.

Claudino-Sales, V., P. Wang, and M. H. Horwitz. 2008. Factors controlling the survival of coastal dunes during multiple hurricane impacts in 2004 and 2005: Santa Rosa barrier island, Florida. Geomorphology 95(3):295–315.

Claudino-Sales, V., P. Wang, and M. H. Horwitz. 2010. Effect of Hurricane Ivan on coastal dunes of Santa Rosa barrier island, Florida: characterized on the basis of pre-and post-storm LiDAR surveys. Journal of Coastal Research 26(3):470–484.

Cooper, J. A. G., and F. Navis. 2004. Natural bathymetry change as a control on century-scale shoreline behavior. Geology 32:513–516.

Cooper, R. J., G. Sundin, S. B. Cederbaun, and J. J. Gannon. 2005. Natural resource summary for Gulf Islands National Seashore. Final report. University of Georgia, Warnell School of Forest Resources, Athens, Georgia.

Crowley, T. 1996. Pliocene climates: the nature of the problem. Marine Micropaleontology 27:3–12.

Curdts, T. 2011. Shoreline length and water area in the ocean, coastal and Great Lakes parks: updated statistics for shoreline miles and water acres (rev1b). Natural Resource Report NPS/WASO/NRR—2011/464. National Park Service, Fort Collins, Colorado.

Dalal, M. 2006. Sedimentation from 2005 Hurricane Katrina on the Mississippi and Alabama Gulf Coast barrier islands. Geological Society of America Abstracts with Programs 38(7):36.

Dallas, K., J. Eshleman, and R. Beavers. 2012. National Park Service beach nourishment guidance. National Park Service, Fort Collins, Colorado.

Dean, R. G., R. A. Davis, and K. M. Erickson. 2006. Beach nourishment: a guide for local government officials. Online information. NOAA Coastal Services Center, Charleston, South Carolina.

Deltares. 2013. Mississippi barrier island restoration: part I—morphological study for the restoration of the Ship Island. Numerical modeling. Report prepared for USACE, Mississippi Coastal Improvements Program (MsCIP), Mobile, Alabama. Deltares, Delft, The Netherlands.

Dockery, D. T. III. 2008. Cenozoic stratigraphic units in Mississippi. Mississippi Department of Environmental Quality, Office of Geology, Jackson, Mississippi. Mississippi Geology 17(1):1–8.

Dolan, R., and P. Godfrey. 1972. Dune stabilization and beach erosion, Cape Hatteras National Seashore, North Carolina. National Park Service, Washington, DC.

Dolan, R., and H. F. Lins. 1986. The Outer Banks of North Carolina. Professional Paper 1177-B. US Geological Survey, Reston, Virginia.

Douglass, S. L. 1994. Beach erosion and deposition on Dauphin Island, Alabama, USA. Journal of Coastal Research 10(2):306–328.

Dowsett, H. J., and T. M. Cronin. 1990. High eustatic sea level during the middle Pliocene: evidence from the southeastern US Atlantic coastal plain. Geology 18:435–438.

Doyle, L., C. Dinesh, A. C. Hine, O. Pilkey Jr., W. Neal, O. Pilkey Sr., D. Martin, and D. F. Belknap. 1984. Living with the west Florida shore. Duke University Press, Durham, North Carolina.

Duarte, C. M., J. Terrados, N. S. Agawin, M. D. Fortes, S. Bach, and W. J. Kenworthy. 1997. Response of a mixed Philippine seagrass meadow to experimental burial. Marine Ecology Progress Series 147(1/3):185–294.

Ellis, A. M., C. G. Smith, and M. E. Marot. 2018. The sedimentological characteristics and geochronology of the marshes of Dauphin Island, Alabama. Open-File Report 2017-1165. US Geological Survey, Reston, Virginia.

Fagherazzi, S., L. Carniello, L. D'Alpaos, and A. Defina. 2006. Critical bifurcation of shallow microtidal landforms in tidal flats and salt marshes. Proceedings of the National Academy of Sciences 103(22):8337–8341.

Fairbanks, R. G. 1989. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. Nature 342(6250):637–642.

Falls, R. P. 2001. Exploring Gulf Islands National Seashore. Falcon, Guilford, Connecticut.

Fasullo, J. T., R. S. Nerem, and B. Hamlington. 2016. Is the detection of accelerated sea level rise imminent? Nature.com, Scientific Reports 6, Article number 31245.

Finkl, C. W. 2012. Pitfalls of ebb-shoal mining. Pages 37–52 in J. A. G. Cooper and O. H. Pilkey, editors. Pitfalls of shoreline stabilization: selected case studies. Springer Netherlands, Dordrecht.

FitzGerald, D. M., and M. O. Hayes. 1980. Tidal inlet effects on barrier island management. Pages 2355–2379 in B. L. Edge, editor. Coastal Zone'80. Second Symposium on Coastal and Ocean Management, November 17–20, 1980, Hollywood, Florida, United States. American Society of Civil Engineers, New York, New York.

Flocks, J. G., N. F. Ferina, and J. L. Kindinger. 2011a. Recent geologic framework and geomorphology of the Mississippi–Alabama shelf, northern Gulf of Mexico. Pages 157–173 in N. A. Buster and C. W. Holmes, editors. Gulf of Mexico: origin, waters, and biota. Volume 3, geology. Texas A&M University Press, College Station, Texas.

Flocks, J. G., J. L. Kindinger, and K. Kelso. 2015. Geologic control on the evolution of the inner shelf morphology offshore of the Mississippi barrier island, northern Gulf of Mexico, USA. Continental Shelf Research 101:59–70.

Flocks, J. G., J. Sanford, and J. L. Smith. 2010. Sediment distribution on the Mississippi-Alabama Shelf, northern Gulf of Mexico. Open-File Report 2010-1002. US Geological Survey, Reston, Virginia.

Flocks, J., K. Kelso, D. Twichell, N. A. Buster, and J. Baehr. 2011b. Offshore sand-shoal development and evolution of Petit Bois Pass, Mississippi–Alabama barrier islands, Mississippi, USA. Pages 2170–2183 in J. D Rosati, P. Wang, and T. M. Roberts, editors. The Proceedings of the Coastal Sediments 2011, in 3 volumes; 2–6 May 2011; Miami, Florida. Volume 3: northern Gulf of Mexico. World Scientific Publishing Company, Singapore, China.

Flocks, J., J. L. Kindinger, K. Kelso, J. Bernier, N. DeWitt, and M. FitzHarris. 2014. Near-surface stratigraphy and morphology, Mississippi inner shelf, northern Gulf of Mexico. Open-File Report 2015–1014. US Geological Survey, Reston, Virginia.

Florida Department of Environmental Protection. 2000. Strategic beach nourishment plan: Panhandle Gulf Coast Region. Florida Department of Environmental Protection, Tallahassee, Florida.

Florida Department of Environmental Protection. 2001. Seagrass management plan for Big Lagoon and Santa Rosa Sound. Florida Department of Environmental Protection, Ecosystem Restoration Section, Pensacola, Florida.

Florida Department of Environmental Protection. 2015. Strategic beach management plan: Panhandle Gulf Coast Region. Florida Department of Environmental Protection, Division of Water Resource Management, Tallahassee, Florida.

Florida Oceans and Coastal Council. 2010. Climate change and sea-level rise in Florida: an update of the effects of climate change on Florida's ocean and coastal resources. Florida Oceans and Coastal Council, Tallahassee, Florida.

Ford, M. 2013. Sand Spoil Island, wetland mapping (May 2013). NPS Southeast Regional Office, Atlanta, Georgia.

Foster, E. R., D. L. Spurgeon, and J. Cheng. 1999. Shoreline change rate estimates, Escambia and Santa Rosa Counties. Report BCS-99-03. Florida Department of Environmental Protection, Office of Beaches and Coastal Systems, Tallahassee, Florida.

Foxworth, R. D., R. R. Priddy, W. B. Johnson, and W. S. Moore. 1962. Heavy minerals of sand from recent beaches of the Gulf Coast of Mississippi and associated islands. Bulletin 93.Mississippi Department of Environmental Quality, Office of Geology, Jackson, Mississippi.

Frazier, D. E. 1967. Recent deltaic deposits of the Mississippi River: their development and chronology. Gulf Coast Association of Geological Societies Transactions 37:287–315.

French, J. R. 1993. Numerical simulation of vertical marsh growth and adjustment to accelerated sea-level rise, North Norfolk, UK. Earth Surface Processes and Landforms 18(1):63–81.

Fritz, H. M., C. Blount, R. Sokoloski, J. Singleton, A. Fuggle, B. G. McAdoo, A. Moore, C. Grass, and B. Tate. 2007. Hurricane Katrina storm surge distribution and field observations on the Mississippi barrier islands. Estuarine, Coastal and Shelf Science 74 (1–2):12–20.

Fritz, H. M., C. Blount, R. Sokoloski, J. Singleton, A. Fuggle, B. G. McAdoo, A. Moore, C. Grass, and B. Tate. 2008. Hurricane Katrina storm surge reconnaissance. Journal of Geotechnical and Geoenvironmental Engineering 134(5):644–656.

Gabler, C. A., M. J. Osland, J. B. Grace, C. L. Stagg, R. H. Day, S. B. Hartley, N. M. Enwright, A. S. From, M. L. McCoy, and J. L. McLeod. 2017. Macroclimatic change expected to transform coastal wetland ecosystems this century. Nature Climate Change 7:142–147.

Gabriel, M. N. 2017. NPS continues to remove asphalt chunks from Gulf Islands National Seashore. Online article (11 December 2017). Pensacola News Journal. Pensacola, Florida.

Gardner, J. V., P. Dartnell, and K. J. Sulak. 2002. Multibeam mapping of the Pinnacles region, Gulf of Mexico. Open-File Report 02-06. US Geological Survey, Washington, DC.

Gohn, G. S., G. L. Brewster-Wingard, T. M. Cronin, L. E. Edwards, T. G. Gibson, M. Rubin, and D. A. Willard. 1996. Neogene and Quaternary geology of a stratigraphic test hole on Horn Island, Mississippi Sound. Open-File Report 96-20A. US Geological Survey, Reston, Virginia.

Goldstein, E. B., and L. J. Moore. 2016. Stability and bistability in a one-dimensional model of coastal foredune height: A 1-D model of coastal foredune height. Journal of Geophysical Research: Earth Surface 12 (5):964–977.

Graham, B., C. A. Cherry, A. Murray, D. F. Boesch, and F. Ulmer. 2011. Deep Water: the Gulf oil disaster and the future of offshore drilling, report to the president, January 2011. National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling.

Green, E. P., and F. Short. 2003. World atlas of seagrasses. University of California Press, Berkley, California.

Gulf Islands National Seashore. 2016. Superintendent's compendium. Gulf Islands National Seashore, Gulf Breeze, Florida.

Gunnell, J. R., A. B. Rodriguez, and B. A. McKee. 2013. How a marsh is built from the bottom up. Geology 41:859–862. doi:10.1130/G34582.1.

Gutierrez, B. T., S. J. Williams, and E. R. Thieler. 2007. Potential for shoreline changes due to sea-level rise along the US Mid-Atlantic region. Open-File Report 2007-1278. US Geological Survey, Reston, Virginia.

Gutierrez, B. T., S. J. Williams, and E. R. Thieler. 2009. Ocean coasts. Pages 43–56 in J. G. Titus, coordinating lead author, and K. E. Anderson, D. R. Cahoon, D. B. Gesch, S. K. Gill, B. T. Gutierrez, E. R. Thieler, and S. J. Williams, lead authors. Coastal sensitivity to sea-level rise: a focus on the mid-Atlantic region. A report by the US Climate Change Science Program and the Subcommittee on Global Change Research. US Environmental Protection Agency, Washington, DC.

Guvansen, V. 2000. Modeling of ground water flow in Walton, Okaloosa and Santa Rosa Counties, Florida. HydroGeoLogic, Inc., Herndon, Virginia.

Handley, L. R., R. Mouton, A. Calix, and J. Thibodeaux. 2003. Seagrass of the northern Gulf of Mexico: status and trend. Abstract. Wetland Stewardship—Changing Landscapes and Interdisciplinary Challenges, 24th Annual Conference of the Society of Wetland Scientists, 8–13 June 2003, New Orleans, Louisiana.

Hapke, C. J., and M. Christiano. 2007. Long-term and storm-related shoreline change trends in the Florida Gulf Islands National Seashore. Open-File Report 2007-1392. US Geological Survey, Reston, Virginia.

Hardin, J. D., C. D. Sapp, J. L. Emplaincourt, and K. E. Richter. 1976. Shoreline and bathymetric changes in the coastal area of Alabama. Information Series 50. Geological Survey of Alabama, Atlanta, Georgia.

Hatt, J., L. Worsham, G. Sundin, G. Grossman, M. Mengak, and N. Nibbelink. 2016. Natural resource condition assessment for Gulf Islands National Seashore. Natural Resource Report NPS/GUIS/NRR—2016/1135. National Park Service, Fort Collins, Colorado.

Hayes, M. O., and R. B. Nairn. 2004. Natural maintenance of sand ridges and linear shoals on the US Gulf and Atlantic continental shelves and the potential impacts of dredging. Journal of Coastal Research 20(1):138–148.

Henry, V. J. 1978. Final report for west Ship Island/Ft. Massachusetts beach nourishment and shore protection study, Gulf Islands, National Seashore (contract no. CX50041681). National Park Service, Southeast Regional Office, Atlanta, Georgia.

Holdahl, S. R., and N. L. Morrison. 1974. Regional investigations of vertical crustal movements in the US using precise relevelings and mareograph data. Tectonophysics 23:373–390.

Honeycutt, M. G., and D. E. Krantz. 2003. Influence of geologic framework on spatial variability in long-term shoreline change, Cape Henlopen to Rehoboth Beach, Delaware. Journal of Coastal Research Special Issue 38:147–167.

Houser, C. 2009. Geomorphological controls on road damage during Hurricanes Ivan and Dennis. Journal of Coastal Research 253:558–568.

Houser, C. 2011. Geologic framework of the Gulf Islands National Seashore. Report submitted to National Park Service. Texas A&M University, College Station, Texas.

Houser, C. 2012. Feedback between ridge and swale bathymetry and barrier island storm response and transgression. Geomorphology 173–174:1–16.

Houser, C., G. Barrett, and D. Labude. 2011. Alongshore variation in the rip current hazard at Pensacola Beach, Florida. Natural Hazards 57(2):501–523.

Houser, C., J. Ellis. 2013. Beach and dune interaction. Pages 267–288 in J. Shroder and D. J. Sherman, editors. Treatise on geomorphology. Volume 10: coastal geomorphology. Academic Press, San Diego, California.

Houser, C., and B. Greenwood. 2007. Onshore Migration of a swash bar during a storm. Journal of Coastal Research 23(1):1–14.

Houser, C., and S. Hamilton. 2009. Sensitivity of post-hurricane beach and dune recovery to event frequency. Earth Surface Processes and Landforms 34(5):613–628.

Houser, C., S. Hamilton, K. Meyer-Arendt, and J. Oravetz. 2007. EOF analysis of morphological response to Hurricane Ivan. Pages 986–995 in N. C. Kraus and J. D. Rosati, editors. Coastal Sediments '07. Proceedings of the Sixth International Symposium on Coastal Engineering and Science of Coastal Sediment Process, 13–17 May 2007, New Orleans, Louisiana. American Society of Civil Engineers, Long Island, New York.

Houser, C., C. Hapke, and S. Hamilton. 2008a. Controls on coastal dune morphology, shoreline erosion and barrier island response to extreme storms. Geomorphology 100(3–4):223–240.

Houser, C., C. Hobbs, and B. Saari. 2008b. Posthurricane airflow and sediment transport over a recovering dune. Journal of Coastal Research 244:944–953.

Houser, C., T. Murphy, and D. Labude. 2015a. Alongshore correspondence of beach users and rip channels at Pensacola Beach, Florida. Natural Hazards 78(3):2175–2183.

Houser, C., P. Wernette, E. Rentschlar, H. Jones, B. Hammond, and S. Trimble. 2015b. Post-storm beach and dune recovery: Implications for barrier island resilience. Geomorphology 234:54–63.

Houser, C., P. Wernette, and B. Weymer. 2015c. Scale dependent behavior of the foredune: implications for barrier island response to storms and sea level rise. Abstract EP22A-05. AGU Fall Meeting, 14–18 December 2015, San Francisco, California.

Hsu, K. J. 1960. Texture and mineralogy of the recent sands of the Gulf Coast. Journal of Sedimentary Petrology 30(3):380–403.

Hubertz, J. M., and R. B. Brooks. 1992. Verification of the Gulf of Mexico hindcast wave information. Wave Information Studies of US Coastlines. WIS Report 28. US Army Corps of Engineers, Coastal Engineering Research Center, Vicksburg, Mississippi.

Jankowski, K. L., T. E. Törnqvist, and A. M. Fernandes. 2017. Vulnerability of Louisiana's coastal wetlands to present-day rates of relative sea-level rise. Nature Communications 8:14792.

Jarrell, J. P. 1981. Hydrodynamics of Mobile Bay and Mississippi Sound pass-exchange studies. MASGP-80-023. Mississippi-Alabama Sea Grant Consortium, Ocean Springs, Mississippi.

Karl, T. R., J. M. Melillo, and T. C. Peterson, editors. 2009. Global climate change impacts in the United States. Cambridge University Press.

Katsman, C. A., A. Sterl, J. J. Beersma, H. W. van den Brink, J. A. Church, W. Hazeleger, R. E. Kopp, D. Kroon, J. Kwadijk, R. Lammersen, J. Lowe, M. Oppenheimer, H.-P. Plag, J. Ridley, H. von Storch, D. G. Vaughan, P. Vellinga, L. L. A. Vermeersen, R. S. W. van de Wal, and R. Weisse. 2011. Exploring high-end scenarios for local sea level rise to develop flood protection strategies for a low-lying delta—The Netherlands as an example. Climatic Change 109(3–4):617–645.

Katz, B. G., and A. F. Choquette. 1991. Aqueous geochemistry of the sand-and-gravel aquifer, northwest Florida. Ground Water 29(1):47–55.

Kennett, J. P., and D. A. Hodell. 1995. Stability or instability of Antarctic ice sheets during warm climates of the Pliocene? GSA Today 5(1):1, 10–13, and 22.

Kenney, P. 2006. Natural resources review for the general management plan for Gulf Islands National Seashore, Gulf Breeze, Florida, and Ocean Springs, Mississippi. Draft report. Gulf Islands National Seashore, Gulf Breeze, Florida.

Kenworthy, J. P., V. Santucci, and C. C. Visaggi. 2007. Paleontological resource inventory and monitoring, Gulf Coast Network. Technical Information Center (TIC) number D-750. National Park Service, Geologic Resources Division, Lakewood, Colorado.

Kindinger, J. L. 1988. Seismic stratigraphy of the Mississippi–Alabama shelf and upper continental slope. Marine Geology 83(1–4):79–94.

Kindinger, J. L., P. S. Balson, and J. G. Flocks. 1994. Stratigraphy of the Mississippi–Alabama shelf and the Mobile River incised-valley system. Pages 83-95 in R. W. Dalrymple, R. Boyd, and B. Zaitlin, editors. Incised-valley systems: origin and sedimentary sequences. Special Publication 51. Society for Sedimentary Geology (SEPM), Tulsa, Oklahoma.

Kirwan, M. L., A. B. Murray, J. P. Donnelly, and D. R. Corbett. 2011. Rapid wetland expansion during European settlement and its implication for marsh survival under modern sediment delivery rates. Geology 39(5):507–510.

Kish, S. A., and J. F. Donoghue. 2013. Coastal response to storms and sea-level rise: Santa Rosa Island, northwest Florida, USA. Journal of Coastal Research 63:131–140.

Kjerfve, B., and J. E. Sneed. 1984. Analysis and synthesis of oceanographic conditions in the Mississippi Sound offshore region. Final report, volume 1. University of South Carolina Department of Geology, Columbia, South Carolina.

Knowles, S. C., and J. D. Rosati. 1989. Geomorphic and coastal process analysis for ship channel planning at Ship Island, Mississippi. Technical Report CERC-89-1. US Army Corps of Engineers, Coastal Engineering Research Center, Vicksburg, Mississippi.

Kolker, A. S., M. A. Allison, and S. Hameed. 2011. An evaluation of subsidence rates and sea-level variability in the northern Gulf of Mexico. Geophysical Research Letters 38, L21404, doi:10.1029/2011GL049458.

Krantz, D. E. 1991. A chronology of Pliocene sea-level fluctuation: the US middle Atlantic coastal plain record. Quaternary Science Reviews 10:165–174.

Kwon, H. J. 1969. Barrier Islands of the northern Gulf of Mexico Coast: sediment source and development. Technical report. Louisiana State University, Coastal Studies Institute, Baton Rouge, Louisiana.

Lavoie, D., J. Flocks, D. Twichell, and K. Rose. 2013. Benthic substrate classification map: Gulf Islands National Seashore. Open-File Report 2012-1051. US Geological Survey, Reston, Virginia.

Lawless, P. N., R. H. Fillon, and R. G. Lytton. 1997. Gulf of Mexico Cenozoic biostratigraphic, lithostratigraphic, and sequence stratigraphic event chronology. Gulf Coast Association of Geological Societies Transactions 47:271–282.

Leatherman, S. P. 1988. Barrier island handbook. Third edition. Coastal Publication Series. University of Maryland, College Park, Maryland.

Lentz, E. E., and C. J. Hapke. 2011. Geologic framework influences on the geomorphology of an anthropogenically modified barrier island: assessment of dune/beach changes at Fire Island, New York. Geomorphology 126(1–2):82–96.

Lewis, B. A., J. H. Wrenn, A. J. Lewis, J. J. Alford, and D. Alford. 2003. Middle Wisconsinan and recent wet site mummified wood, humus, peat, and pollen, Santa Rosa Island, Florida. Review of Palaeobotany and Palynology 126:243–266.

Loehman, R., and G. Anderson. 2010. Understanding the science of climate change: talking points—impacts to the Gulf Coast. Natural Resource Report NPS/NRPC/NRR—2010/210. National Park Service, Fort Collins, Colorado.

Lucas, K. L., and G. A. Carter. 2013. Change in distribution and composition of vegetated habitats on Horn Island, Mississippi, northern Gulf of Mexico, in the initial five years following Hurricane Katrina. Geomorphology 199:129–137.

Ludwick, J. C., and W. R. Walton. 1957. Shelf edge calcareous prominences in the northeastern Gulf of Mexico. American Association of Petroleum Geologists Bulletin 41:2054–101.

Mallinson, D. J., S. J. Culver, S. R. Riggs, J. P. Walsh, D. V. Ames, and C. W. Smith. 2008. Past, present and future inlets of the Outer Banks barrier islands, North Carolina: a white paper. East Carolina University, Greenville, North Carolina.

Mallinson, D. J., C. W. Smith, S. J. Culver, S. R. Riggs, and D. Ames. 2010. Geologic characteristics and spatial distribution of paleo-inlet channels beneath the outer banks barrier islands, North Carolina, USA. Estuarine, Coastal and Shelf Science 88(2):175–189.

Mariotti, G., S. Fagherazzi, P. L. Wiberg, K. J. McGlathery, L. Carniello, and A. Defina. 2010. Influence of storm surges and sea level on shallow tidal basin erosive processes. Journal of Geophysical Research: Oceans 115, C11012, doi:10.1029/2009JC005892.

Marsh, O. T. 1966. Geology of Escambia and Santa Rosa Counties, western Florida Panhandle. Bulletin 46. Florida Geological Survey, Tallahassee, Florida.

Marsh, P. 2016. West Ship Island north shore restoration project summary (Gulf Islands National Seashore). Gulf Islands National Seashore, Ocean Springs, Mississippi.

Martin, R. G. 1976. Geologic framework of northern and eastern Gulf of Mexico. Page A-1–A-28 in A. H. Bouma, G. T. Moore, and J. M. Coleman, editors. Beyond the shelf break. Short course. American Association of Petroleum Geologists, Tulsa, Oklahoma.

Masetti, R., S. Fagherazzi, and A. Montanari. 2008. Application of a barrier island translation model to the millennial-scale evolution of Sand Key, Florida. Continental Shelf Research 28(9):1116–1126.

Masterson, J. P., M. N. Fienen, E. R. Thieler, D. B. Gesch, B. T. Gutierrez, and N. G. Plant. 2014. Effects of sea-level rise on barrier island groundwater system dynamics—ecohydrological implications. Ecohydrology 7(3):1064–1071.

Matson, G. C. 1916. The Pliocene Citronelle Formation of the Gulf coastal plain. Professional Paper 98-L. US Geological Survey, Reston, Virginia.

McBride, R. A., L. Anderson, A. Tudoran, and H. Roberts. 1999. Holocene stratigraphic architecture of a sand-rich shelf and the origin of linear shoals: northeastern Gulf of Mexico. Pages 95–126 in K. M. Bergman and J. W. Snedden, editors. Isolated shallow marine sand bodies: sequence stratigraphy analysis and sedimentologic interpretation. Special Publication 64. Society for Sedimentary Geology (SEPM), Tulsa, Oklahoma.

McBride, R. A., and M. R. Byrnes. 1995. Surficial sediments and morphology of the southwestern Alabama/western Florida Panhandle coast and shelf. Gulf Coast Association of Geological Societies Transactions 45:393–404.

McBride, R. A., T. F. Moslow, H. H. Roberts, and R. J. Diecchio. 2004. Late Quaternary geology of the northeastern Gulf of Mexico shelf: sedimentology, depositional history, and ancient analogs of a major shelf sand sheet of the modern transgressive systems tract. Pages 55–85 in J. B. Anderson and R. H. Fillon, editors. Late Quaternary stratigraphic evolution of the northern Gulf of Mexico. Special Publication 79. Society for Sedimentary Geology (SEPM), Tulsa, Oklahoma.

McDowell Peek, R. L., C. A. Schupp, and A. Babson. 2016. Protecting infrastructure: costs and impacts. Pages 97–114 (Chapter 8) in R. L. Beavers, A. L. Babson, and C. A. Schupp. Coastal adaptation strategies handbook. NPS 999/134090. National Park Service, Washington, DC.

McKeown, H. E., P. J. Bart, and J. B. Anderson. 2012. High-resolution stratigraphy of a sandy, ramp-type margin, Apalachicola, Florida, USA. Pages 25–41 5 in J. B. Anderson and R. H. Fillon, editors. Late Quaternary stratigraphic evolution of the northern Gulf of Mexico. Special Publication 79. Society for Sedimentary Geology (SEPM), Tulsa, Oklahoma.

McNinch, J. E. 2004. Geologic control in the nearshore: shore-oblique sandbars and shoreline erosional hotspots, Mid-Atlantic Bight, USA. Marine Geology 211:121–141.

McNinch, J. E., and R. A. Luettich. 2000. Physical processes around a cuspate foreland: implications to the evolution and long-term maintenance of a cape-associated shoal. Continental Shelf Research 20:2367–2389.

Miselis, J. L., N. A. Buster, and J. L. Kindinger. 2014. Refining the link between the Holocene development of the Mississippi River Delta and the geologic evolution of Cat Island, MS: implications for delta-associated barrier islands. Marine Geology 355:274–290.

Miselis, J. L., and J. E. McNinch. 2006. Calculating shoreline erosion potential using nearshore stratigraphy and sediment volume: Outer Banks, North Carolina. Journal of Geophysical Research 111, F02019, doi:10.1029/2005JF000389.

Moncreiff, C. 2007a. Mississippi Sound and the Gulf Islands. Pages 77–86 in L. Handley, D. Altsman and R. DeMay, editors. Seagrass status and trends in the Northern Gulf of Mexico: 1940–2002. Scientific Investigations Report 2006-5287. US Geological Survey, Reston, Virginia.

Moncreiff, C. A. 2007b. Statewide summary of Mississippi. Pages 73–76 in L. Handley, D. Altsman, and R. DeMay, editors. Seagrass status and trends in the northern Gulf of Mexico: 1940–2002. Scientific Investigations Report 2006-5287. US Geological Survey, Reston, Virginia.

Moncreiff, C. A., T. A. Randall, and J. D. Caldwell. 1998. Mapping of seagrass resources in Mississippi Sound. University of Southern Mississippi, Gulf Coast Research Laboratory, Ocean Springs, Mississippi.

Moore, L. J., O. Durán Vinent, D. Walters, and E. Goldstein. 2015. Ecomorphodynamic feedbacks and couplings between landscape units affect barrier island response to changing climate. In P. Wang, J. D. Rosati, and J. Cheng, editors. The Proceedings of the Coastal Sediments 2015, 11–15 May 2015, San Diego, California. World Scientific Publishing Company, Singapore, China.

Moore, L. J., J. H. List, S. J. Williams, and K. Patsch. 2011. Barriers on the brink? The complex intertwined roles of geologic framework, sediment availability and sea-level rise in island evolution. Pages 272–285 in P. Wang, J. D. Rosati, and T. M. Roberts, editors. The Proceedings of the Coastal Sediments 2011, in 3 volumes; 2–6 May 2011; Miami, Florida. World Scientific Publishing Company, Singapore, China.

Moore, L. J., J. H. List, S. J. Williams, and D. Stolper. 2007. Modeling barrier island response to sea-level rise in the Outer Banks, North Carolina. Pages 1153–1164 in N. Kraus and J. Rosati, editors. Coastal Sediments '07. Proceedings of the Sixth International Symposium on Coastal Engineering and Science of Coastal Sediment Process, 13–17 May 2007, New Orleans, Louisiana. American Society of Civil Engineers, Long Island, New York.

Moore, L. J., J. H. List, S. J. Williams, and D. Stolper. 2010. Complexities in barrier island response to sea level rise: insights from numerical model experiments, North Carolina Outer Banks. Journal of Geophysical Research: Earth Surface 115, F03004, doi:10.1029/2009JF001299.

Morang, A. 1992. Inlet migration and hydraulic processes at East Pass, Florida. Journal of Coastal Research 8(2):457–481.

Morang, A., J. P. Waters, and S. M. Khalil. 2012. Gulf of Mexico regional sediment budget. Journal of Coastal Research 60:14–29.

Morgan, K. L. M. 2009. Coastal change during Hurricane Isabel 2003. Fact Sheet 2009-3025. US Geological Survey, Reston, Virginia.

Morgan, K. L. M. 2015. Baseline coastal oblique aerial photographs collected from Navarre Beach, Florida, to Breton Island, Louisiana, September 1, 2014. Data Series 952. US Geological Survey, Reston Virginia.

Morgan, K. L. M. 2016. Baseline coastal oblique aerial photographs collected from Navarre Beach, Florida, to Breton Island, Louisiana, September 18–19, 2015. Data Series 1008. US Geological Survey, Reston, Virginia.

Morris, J. T., P. V. Sundareshwar, C. T. Nietch, B. Kjerfve, and D. R. Cahoon. 2002. Responses of coastal wetlands to rising sea level. Ecology 83(10):2869–2877.

Morton, R. A. 2007. Historical changes in the Mississippi–Alabama barrier islands and the roles of extreme storms, sea level, and human activities. Open-File Report 2007–1161. US Geological Survey, Reston, Virginia.

Morton, R. A. 2010. First-order controls of extreme-storm impacts on the Mississippi–Alabama barrier-island chain. Journal of Coastal Research 26(4):635–648.

Morton, R. A., J. C. Bernier, and J. A. Barras. 2006. Evidence of regional subsidence and associated interior wetland loss induced by hydrocarbon production, Gulf Coast region, USA. Environmental Geology 50:261–274.

Morton, R. A., T. L. Miller, and L. J. Moore. 2004. The national assessment of shoreline change: part 1–historic shoreline change and associated coastal land loss along the US Gulf of Mexico. Open File Report 2004-1043. US Geological Survey, St. Petersburg, Florida.

Morton, R. A., and M. C. Montgomery. 2010. Geomorphology and depositional subenvironments of Gulf Islands National Seashore, Perdido Key and Santa Rosa Island, Florida. Open-File Report 2010-1330. US Geological Survey, Reston, Virginia.

Morton, R. A., and N. Purcell. 2001. Wetland subsidence, fault reactivation, and hydrocarbon production in the US Gulf Coast region. Fact Sheet FS-091-01. US Geological Survey, St. Petersburg, FL.

Morton, R. A., and B. E. Rogers. 2009. Geomorphology and depositional subenvironments of Gulf Islands National Seashore. Open File Report 2009-1250. US Geological Survey, Reston, Virginia.

Mudd, S. M. 2011. The life and death of salt marshes in response to anthropogenic disturbance of sediment supply. Geology 39:511–512.

Mudd, S. M., A. D'Alpaos, and J. T. Morris. 2010. How does vegetation affect sedimentation on tidal marshes? Investigating particle capture and hydrodynamic controls on biologically mediated sedimentation. Journal of Geophysical Research: Earth Surface 115, F03029, doi:10.1029/2009JF001566.

Muller, R. A., and G. W. Stone. 2001. A climatology of tropical storm and hurricane strikes to enhance vulnerability prediction for the southeast US coast. Journal of Coastal Research 17(4):949–956.

National Weather Service. 2004. Rip current science. Online information. NOAA, National Weather Service, Silver Spring, Maryland.

NOAA. 2016. Tides & currents: sea level trends. Online information. National Oceanic and Atmospheric Administration, Silver Spring, Maryland.

NOAA. 2017. Datums for 8745557, Gulfport Harbor MS. 1983–2001 tidal epoch. Online information. National Oceanic and Atmospheric Administration, Silver Spring, Maryland.

NPS. 1978. Final environmental statement, general management plan, development concept plan, Gulf Islands National Seashore, Mississippi-Florida. National Park Service, Denver Service Center, Denver, Colorado.

NPS. 2007. Gulf Islands National Seashore geologic resource evaluation scoping summary. NPS Geologic Resources Division, Lakewood, Colorado.

NPS. 2011. Finding of no significant impact: lower Pensacola Harbor Federal Navigation Channel, littoral zone placement of dredge spoil on Perdido Key during maintenance of the lower entrance of the Pensacola Federal Navigation Channel, Perdido Key, Escambia County, Florida. Gulf Islands National Seashore, Gulf Breeze, Florida.

NPS. 2014. Final general management plan / environmental impact statement (July 2014). National Park Service, Gulf Islands National Seashore, Florida and Mississippi.

NPS. 2015. Record of decision for the general management plan: Gulf Islands National Seashore, Florida and Mississippi. Federal Register 80:1048.

NPS. 2016a. Gulf Islands National Seashore foundation document. National Park Service, Washington, DC.

NPS. 2016b. US Department of Interior, National Park Service, record of decision: Mississippi Coastal Improvements Program, comprehensive barrier island restoration, August 2016. Gulf Islands National Seashore, Gulf Breeze, Florida.

NPS. 2018. Operating hours & seasons. Online information. Gulf Islands National Seashore, Gulf Breeze, Florida, and Ocean Springs, Mississippi.

NPS and University of Maryland Center for Environmental Science. 2012. Barrier islands and sea level rise. Teach Ocean Science online module. Module is based on work supported by the National Park Service at Assateague Island National Seashore, Berlin, Maryland.

Oivanki, S. M. 1995. Ship Island project: Fort Massachusetts erosion control study. Final report. Submitted to National Park Service under cooperative agreement 1443PX532095270. Mississippi Department of Environmental Quality, Office of Geology, Jackson, Mississippi.

Oivanki, S. M., and E. G. Otvos. 2005. Geologic framework of coastal Harrison County and Mississippi Sound. Mississippi coastal geology and regional marine study 1990–1994. Volume 2. Submitted to US Geological Survey, Center for Coastal and Regional Marine Studies, St. Petersburg, Florida, under cooperative agreement 14-08-0001-A0827. Mississippi Department of Environmental Quality, Office of Geology, Jackson, Mississippi.

Otay, E., and R. G. Dean. 1993. Perdido Key beach nourishment project: Gulf Islands National Seashore 1992 annual report. UFL/COEL-93/005. Report submitted to Department of the Navy, Southern Division, Charleston, South Carolina. University of Florida, Gainesville, Florida.

Otvos, E. 1970. Development and migration of barrier islands, Northern Gulf of Mexico. Geological Society of America Bulletin 81:241– 246.

Otvos, E. G. 1973a. Areas of recent sedimentation, sedimentary processes. Pages 134–137 in J. Y. Christmas, editor. Cooperative Gulf of Mexico estuarine inventory and study, Mississippi: Phase III—sedimentology. Gulf Coast Research Laboratory, Ocean Springs, Mississippi.

Otvos, E. G. 1973b. Geology of Mississippi–Alabama coastal area and nearshore zone. Guidebook for field trip, 19–20 May 1973. New Orleans Geological Society, New Orleans, Louisiana.

Otvos, E. G. 1975. Late Pleistocene transgressive unit (Biloxi Formation), northern Gulf Coast: geologic notes. American Association of Petroleum Geologists Bulletin 59(1):148–154.

Otvos, E. G. 1978. New Orleans—South Hancock Holocene barrier trends and origins of Lake Pontchartrain. Gulf Coast Association of Geological Societies Transactions 28:337–355.

Otvos, E. G. 1979. Barrier island evolution and history of migration, north central Gulf Coast. Pages 291–319 in S. P. Leatherman, editor. Barrier Islands from the Gulf of St. Lawrence to the Gulf of Mexico. Academies Press, New York, New York.

Otvos, E. G. 1981a. Barrier island formation through nearshore aggradation: stratigraphic and field evidence. Marine Geology 43(3–4):195–243.

Otvos, E. G. 1981b. Tectonic lineaments of Pliocene and Quaternary shorelines, northeast Gulf Coast. Geology 9:398–404.

Otvos, E. G. 1982a. Santa Rosa island, Florida Panhandle: origins of a composite barrier island. Southeastern Geology 23(1):15–23.

Otvos, E. G. 1982b. Coastal geology of Mississippi, Alabama and adjacent Louisiana areas. Field trip guidebook. New Orleans Geological Society, New Orleans, Louisiana.

Otvos, E. G. 1985a. Coastal evolution—Louisiana to northwest Florida. Guidebook for the American Association of Petroleum Geologists Annual Meeting, 27–29 March 1985, New Orleans, Louisiana. New Orleans Geological Society, New Orleans, Louisiana.

Otvos, E. G. 1985b. Barrier platforms: northern Gulf of Mexico. Marine Geology 63:285–305.

Otvos, E. G. 1988. Pliocene age of coastal units, northeastern Gulf of Mexico. Gulf Coast Association of Geological Societies Transactions 38:485–494.

Otvos, E. G. 1994. Mississippi's revised Neogene stratigraphy in northern Gulf context. Gulf Coast Association of Geological Societies Transactions 44:541–554.

Otvos, E. G. 1995. Multiple Pliocene–Quaternary marine highstands, northeast Gulf coastal plain: fallacies and facts. Journal of Coastal Research 11(4):984–1002.

Otvos, E. G. 1997. Northeastern Gulf coastal plain revisited—Neogene and Quaternary units and events, old and new concepts. Guidebook. Gulf Coast Association of Geological Societies Annual Meeting. Gulf Coast Association of Geological Societies, New Orleans, Louisiana.

Otvos, E. G. 1998. Citronelle Formation, northeastern Gulf coastal plain: Pliocene stratigraphic framework and age issues. Gulf Coast Association of Geological Societies Transactions 48:321–333.

Otvos, E. G. 2001. Mississippi coast: stratigraphy and Quaternary evolution in the northern Gulf coastal plain framework. Chapter H in G. S. Gohn, editor. Stratigraphic and paleontologic studies of the Neogene and Quaternary sediments in southern Jackson County, Mississippi. Open-file Report 01-415-H. US Geological Survey, Reston, Virginia.

Otvos, E. G. 2004a. Prospects for interregional correlations using Wisconsin and Holocene aridity episodes, northern Gulf of Mexico coastal plain. Quaternary Research 61 (1):105–118.

Otvos, E. G. 2004b. Holocene Gulf levels: recognition issues and an updated sea-level curve. Journal of Coastal Research 20(3):680–699.

Otvos, E. G. 2005a. Numerical chronology of the late Quaternary Gulf coastal plain: barrier evolution and an updated Holocene sea-level curve. Gulf Coast Association of Geological Societies Transactions 55:629–641.

Otvos, E. G. 2005b. Coastal barriers, Gulf of Mexico: Holocene evolution and chronology. Journal of Coastal Research, Special Issue 42:141–163.

Otvos, E. G. 2005c. Numerical chronology of Pleistocene coastal plain and valley development: extensive aggradation during glacial low sea-levels. Quaternary International 135(1):91–113.

Otvos, E. G. 2009. Pleistocene Gulf coastal plain: regional stratigraphic and geomorphic contrasts. Intensive erosion related to sea-level decline and hinterland uplift. Gulf Coast Association of Geological Societies Transactions 59:585–600.

Otvos, E. G. 2015. The last interglacial stage: definitions and marine highstand, North America and Eurasia. Quaternary International 383:158–173.

Otvos, E. G. 2018. Last interglacial, Gulf shorelines during last eustatic cycle; barrier island formation and development; and barrier island preservation and destruction. Entries in C. Finkl and C. Makowski, editors. Encyclopedia of Coastal Science (2nd edition). Encyclopedia of Earth Sciences Series. Springer Nature Switzerland AG.

Otvos, E. G., and G. A. Carter. 2008. Hurricane degradation—barrier development cycles, northeastern Gulf of Mexico: landform evolution and island chain history. Journal of Coastal Research 242:463–478.

Otvos, E. G., and G. A. Carter. 2013. Regressive and transgressive barrier islands on the north-central Gulf Coast—contrasts in evolution, sediment delivery, and island vulnerability. Geomorphology 198:1–19.

Otvos, E. G., and M. J. Giardino. 2004. Interlinked barrier chain and delta lobe development, northern Gulf of Mexico. Sedimentary Geology 169(1–2):47–73.

Parker, S. J., W. Shultz, and W. W. Schroeder. 1992. Sediment characteristics and seafloor topography of a palimpsest shelf, Mississippi–Alabama continental shelf. Pages 243–251 in C. H. Fletcher and J. F. Wehmiller, editors. Quaternary coasts of the United States: marine and lacustrine systems. Special Publication 48. Society for Sedimentary Geology (SEPM), Tulsa, Oklahoma.

Parris, A., P. V. Bromirski, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, K. Knuuti, R. Moss, J. Obeysekera, A. Sallenger, and J. Weiss. 2012. Global sea level rise scenarios for the United States national climate assessment. Technical Report OAR CPO-1. National Oceanic and Atmospheric Administration, Climate Program Office, Silver Spring, Maryland.

Peek, K. M., R. S. Young, R. L. Beavers, C. H. Hoffman, B. T. Diethorn, and S. Norton. 2015. Adapting to climate change in coastal national parks: estimating the exposure of park assets to 1 m of sea-level rise. National Park Service, Fort Collins, Colorado.

Pendleton, E. A., E. S. Hammar-Klose, E. R. Thieler, and S. J. Williams. 2004. Coastal vulnerability assessment of Gulf Islands National Seashore (GUIS) to sea-level rise. Open-File Report 03-108 (electronic book). US Geological Survey, Woods Hole, Massachusetts.

Pensacola News Journal. 2016. Navarre Beach renourishment done early, under budget. Online article (2 May 2016). Pensacola News Journal. Pensacola, Florida.

Pham, L. T., P. D. Biber, and G. A. Carter. 2014. Seagrasses in the Mississippi and Chandeleur Sounds and problems associated with decadal-scale change detection. Gulf of Mexico Science 32:24–43.

Price, D. J. 1975. The apparent growth of Gulf Beach, extreme west Florida. Gulf Coast Association of Geological Societies Transaction 25:369–371.

Rahmstorf, S. 2007. A semi-empirical approach to projecting future sea-level rise. Science 315(5810):368–370.

Read, L. 2015. Case study 14: large-scale restoration of barrier island systems and cultural resource protection through sediment placement, Gulf Islands National Seashore, Mississippi. Pages 34–36 in C. A. Schupp, R. L. Beavers, and M. A. Caffrey, editors. Coastal adaptation strategies: case studies. NPS 999/129700. National Park Service, Fort Collins, Colorado.

Reed, D. J., D. A. Bishara, D. R. Cahoon, J. P. Donnelly, M. Kearney, A. S. Kolker, L. L. Leonard, R. A. Orson, and J. C. Stevenson. 2008. Site-specific scenarios for wetlands accretion as sea level rises in the mid-Atlantic region. Section 2.1 in J. G. Titus and E. M. Strange, editors. Background documents supporting Climate Change Science Program synthesis and assessment product 4.1. EPA 430R07004. US Environmental Protection Agency, Washington, DC.

Riggs, S. R., and D. V. Ames. 2007. Effect of storms on barrier island dynamics, Core Banks, Cape Lookout National Seashore, North Carolina, 1960–2001. Scientific Investigations Report 2006-5309. US Geological Survey, Reston, Virginia.

Riggs, S. R., D. V. Ames, S. J. Culver, D. J. Mallinson, D. R. Corbett, and J. P. Walsh. 2009. Eye of a human hurricane: Pea Island, Oregon Inlet, and Bodie Island, northern Outer Banks, North Carolina. Pages 43–72 in J. T. Kelley, O. H. Pilkey, J. Andrew, and G. Cooper, editors. America's most vulnerable coastal communities. Special Papers 460. Geological Society of America, Boulder, Colorado.

Riggs, S. R., W. J. Cleary, and S. W. Snyder. 1995. Influence of inherited geologic framework on barrier shoreface morphology and dynamics. Marine Geology 12 (1):213–234.

Riggs, S. R., S. W. Snyder, A. C. Hine, and D. L. Mearns. 1996. Hardbottom morphology and relationship to the geologic framework: mid-Atlantic continental shelf. Journal of Sedimentary Research 66:830–846.

Riggs, S. R., L. L. York, J. F. Wehmiller, and S. W. Snyder. 1992. Depositional patterns resulting from high-frequency Quaternary sea level fluctuations in northeastern North Carolina. Pages 141–153 in C. H. Fletcher and J. F. Wehmiller, editors. Quaternary coasts of the United States marine and lacustrine systems. Special Publication 48. Society of Economic Paleontology and Mineralogy (SEPM), Tulsa, Oklahoma.

Rockman, M., M. Morgan, S. Ziaja, G. Hambrecht, and A. Meadow. 2016. Cultural resources climate change strategy. National Park Service; Cultural Resources, Partnerships, and Science and Climate Change Response Program; Washington, DC.

Rodriguez, A. B., D. L. Greene, J. B. Anderson, and A. R. Simms. 2008. Response of Mobile Bay and eastern Mississippi Sound, Alabama, to changes in sediment accommodation and accumulation. Pages 13–29 in J. B. Anderson and A. B. Rodriguez, editors. Response of Upper Gulf Coast Estuaries to Holocene Climate Change and Sea-Level Rise. Special Papers 443. Geological Society of America, Boulder, Colorado.

Rosati, J. D., M. R. Byrnes, B. Gravens, and S. F. Griffee. 2007. Mississippi Coastal Improvements Program: regional sediment budget for the Mississippi mainland and barrier island coasts. US Army Corps of Engineers Mobile District, Mobile, Alabama.

Rucker, J. B., and J. O. Snowden. 1988. Recent morphologic changes at Dog Keys Pass, Mississippi: the formation and disappearance of the Isle of Caprice. Gulf Coast Association of Geological Societies Transactions 37:343–349.

Rucker, J. B., and J. O. Snowden. 1990. Barrier island evolution and reworking by inlet migration along the Mississippi–Alabama Gulf Coast. Gulf Coast Association of Geological Societies Transactions 40:745–753.

Runkle, J., K. Kunkel, S. Champion, R. Frankson, B. Stewart, and W. Sweet. 2017. Florida state summary. Technical Report NESDIS 149-FL. National Oceanic and Atmospheric Administration, National Centers for Environmental Information, Silver Spring, Maryland.

Sager, W. W., W. W. Schroeder, J. S. Laswell, K. S. Davis, R. Rezak, and S. R. Gittings. 1992. Mississippi–Alabama outer continental shelf topographic features formed during the late Pleistocene–Holocene transgression. Geo-Marine Letters 12:41–48.

Sallenger, A. H. 2000. Storm impact scale for barrier islands. Journal of Coastal Research 16(3):890–895.

Sankar, R. D. 2015. Quantifying the effects of increased storminess and sea-level change on the morphology of sandy barrier islands along the northwestern and Atlantic coasts of Florida. Dissertation. Florida State University, Tallahassee, Florida.

Santucci, V., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 in R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado.

Schellnhuber, H. J., W. Hare, O. Serdeczny, S. Adams, D. Coumou, K. Frieler, M. Martin, I. M. Otto, M. Perrette, A. Robinson, M. Rocha, M. Schaeffer, J. Schewe, X. Wang, and L. Warszawski. 2012. Turn down the heat: why a 4°C warmer world must be avoided. World Bank, Washington, DC.

Schroeder, W. W., A. W. Schultz, and J. J. Dindo. 1988. Inner–shelf hardbottom areas, northeastern Gulf of Mexico. Gulf Coast Association of Geological Societies Transactions 38:535-541.

Schupp, C. A., R. L. Beavers, and M. A. Caffrey. 2015. Coastal adaptation strategies: case studies. NPS 999/129700. National Park Service, Fort Collins, Colorado.

Schupp, C. A., J. E. McNinch, and J. H. List. 2007. Nearshore shore-oblique bars, gravel outcrops, and their correlation to shoreline change. Marine Geology 233:63–79.

Shabica, C. W., S. V. Cofer-Shabica, S. L. Boom, and D. E. Anderson. 1993. Inlets of the Southeast Region national seashore units—effects of inlet maintenance and recommended action. US Department of Interior, Washington, DC.

Short, A. D., and P. A. Hesp. 1982. Wave, beach and dune interactions in southeastern Australia. Marine geology 48(3–4):259–284.

Slangen, A. B., J. A. Church, C. Agosta, X. Fettweis, B. Marzeion, and K. Richter. 2016. Anthropogenic forcing dominates global mean sea-level rise since 1970. Nature Climate Change 6(7):701.

Stevens, S., B. Mitchell, M. Brown, and P. Campbell. 2010. Strategy for enhanced monitoring of natural resource condition in North Atlantic coastal parks to address the effects of rapid climate change. Natural Resource Report NPS/NCBN/NRR—2010/272. National Park Service, Fort Collins, Colorado.

Stockdon, H. F., A. H. Sallenger, R. A. Holman, and P. A. Howd. 2007. A simple model for the spatially-variable coastal response to hurricanes. Marine Geology 238(1–4):1–20.

Stone, G. W.; P. Chaney, P. Wang, and X. Zhan. 1998. Beach nourishment monitoring program at Fort Massachusetts, West Ship Island, Mississippi, volumes 1–4. Report to National Park Service. Louisiana State University, Coastal Studies Institute, Baton Rouge, Louisiana.

Stone, G. W., B. Liu, D. A. Pepper, and P. Wang. 2004. The importance of extratropical and tropical cyclones on the short-term evolution of barrier islands along the northern Gulf of Mexico, USA. Marine Geology 210(1):63–78.

Stone, G. W., F. W. Stapor, J. P. May, and J. P. Morgan. 1992. Multiple sediment sources and a cellular, non-integrated, longshore drift system: northwest Florida and southeast Alabama coast, USA. Marine Geology 105(1):141–154.

Stone, G. W., and F. W. Stapor Jr. 1996. A nearshore sediment transport model for the northeast Gulf of Mexico coast, USA. Journal of Coastal Research 12(3):786–793.

Storms, J. E., G. J. Weltje, J. J. Van Dijke, C. R. Geel, and S. B. Kroonenberg. 2002. Process-response modeling of wave-dominated coastal systems: simulating evolution and stratigraphy on geologic timescales. Journal of Sedimentary Research 72(2):226–239.

Sullivan, C. L. 2009. Hurricanes of the Mississippi Gulf Coast: three centuries of destruction. Mississippi Gulf Coast Community College Press, Perkinston, Mississippi.

Sweet, W. V., R. Horton, R. E. Kopp, A. N. LeGrande, and A. Romanou. 2017. Sea level rise. Pages 333–363 (Chapter 12) in D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, editors. Climate science special report: fourth national climate assessment, volume I. US Global Change Research Program, Washington, DC.

Sydow, J. C., and H. H. Roberts. 1994. Stratigraphic framework of a late Pleistocene shelf edge delta, northeast Gulf of Mexico. AAPG Bulletin 78(8):1276–312.

Tebaldi, C., B. H. Strauss, and C. E. Zervas. 2012. Modelling sea level rise impacts on storm surges along US coasts. Environmental Research Letters 7(1), 014032, doi:10.1088/1748-9326/7/1/014032.

Thieler, E. R., E. A. Himmelstoss, J. L. Zichichi, and A. Ergul. 2017. Digital Shoreline Analysis System (DSAS) version 4.0—an ArcGIS extension for calculating shoreline change (ver. 4.4, July 2017). Open-File Report 2008-1278. US Geological Survey, Woods Hole, Massachusetts.

Toscano, M. A. 2004. Assessment of vulnerability of coastal cultural and archaeological resources of sea level rise and coastal processes, Gulf Islands National Seashore, Florida and Mississippi—recommendations for protection and preservation. Final report. National Park Service, Geoscientist-in-the-Park Program, Lakewood, Colorado.

Twichell, D. C., J. G. Flocks, E. A. Pendleton, and W. E. Baldwin. 2013. Geologic controls on regional and local erosion rates of three northern Gulf of Mexico barrier-island systems. Journal of Coastal Research, Special Issue 63:32–45.

Twichell, D., E. A. Pendleton, W. Baldwin, D. Foster, J. Flocks, K. Kelso, N. DeWitt, W. Pfeiffer, A. Forde, J. Krick, and J. Baehr. 2011. The shallow stratigraphy and sand resources offshore of the Mississippi Barrier Islands. Open-File Report 2011-1173. US Geological Survey, Reston, Virginia.

Upshaw, C. F., W. B. Creath, and F. L. Brooks. 1966. Sediments and microfauna off the coast of Mississippi and adjacent states. Bulletin 106. Mississippi Geological, Economic, and Topographical Survey, Jackson, Mississippi.

USACE. 2009. Barrier islands. Appendix H in Monitoring and adaptive management plan. Mississippi Coastal Improvements Program, comprehensive barrier island restoration, Hancock, Harrison, and Jackson Counties, Mississippi. US Army Corps of Engineers, Mobile District, Mobile, Alabama.

USACE. 2013. Memo to the Santa Rosa County Board of County Commissioners. SAJ-2003-10496 (SP-TSH), 8 November 2013. US Army Corps of Engineers, Jacksonville, Florida.

USACE. 2015. Draft environmental impact statement for the proposed Port of Gulfport expansion project, Gulfport, Harrison County, Mississippi. US Army Corps of Engineers, Mobile District, Mobile, Alabama.

USACE. 2016a. Final supplemental environmental impact statement (6 January 2016). Mississippi Coastal Improvements Program, Hancock, Harrison, and Jackson Counties, Mississippi. US Army Corps of Engineers, Mobile District, Mobile, Alabama.

USACE. 2016b. Comprehensive barrier island restoration. Appendix S in Monitoring and adaptive management plan. Mississippi Coastal Improvements Program, Hancock, Harrison, and Jackson Counties, Mississippi. US Army Corps of Engineers, Mobile District, Mobile, Alabama.

USGS. 2013 Mississippi geology. Mineral resources on-line spatial data. US Geological Survey, Reston, Virginia.

Velardo, B. 2005. Detailed geochronology of the Mississippi Sound during the late Holocene. Thesis. Louisiana State University, Baton Rouge, Louisiana.

Walters, D., L. J. Moore, O. Duran Vinent, S. Fagherazzi, and G. Mariotti. 2014. Interactions between barrier islands and backbarrier marshes affect island system response to sea level rise: insights from a coupled model. Journal of Geophysical Research: Earth Surface 119(9):2013–2031.

Walton, W. R. 1960. Diagnostic faunal characteristics on and near a barrier island, Horn Island, Mississippi. Gulf Coast Association of Geological Societies Transactions 10:7–24.

Wamsley, T. V., K. K. Hathaway, and M. Wutkowski. 2010. Hatteras Breach, North Carolina. Defense Technical Information Center (DTIC) accession number ADA530601. US Department of Defense, Fort Belvoir, Virginia.

Western Carolina University. 2016. Beach nourishment viewer. Online database. Western Carolina University, Program for the Study of Developed Shorelines, Cullowhee, North Carolina.

Wharton, B. R., J. R. Vogel, and M. K. Church. 2014. Archaeological investigations in support of the MC252 oil spill response at Gulf Islands National Seashore Florida and Mississippi. Draft final report. Southeast Archeological Center (SEAC) accession numbers SEAC-02539 (FL) and SEAC-02540 (MS). HDR, New Orleans, Louisiana.

Whitfield, P. E., W. J. Kenworthy, K. K. Hammerstrom, and M. S. Fonseca. 2002. The role of a hurricane in the expansion of disturbances initiated by motor vessels on seagrass banks. Journal of Coastal Research, Special Issue 37:86–99.

Wikel, G. L. 2008. Variability in geologic framework and shoreline change: Assateague and Wallops Islands, eastern shore of Virginia. Thesis. Virginia Institute of Marine Science, The College of William and Mary, Williamsburg, Virginia.

Williams, C. H. Jr. 1969. Cross section from Mississippi–Tennessee state line to Horn Island in Gulf of Mexico. Mississippi Geological Survey, Jackson, Mississippi.

Williams, S. J. 2013. Sea-level rise implications for coastal regions. Journal of Coastal Research, Special Issue 63:184–196.

Williams, S. J., J. Flocks, C. Jenkins, S. Khalil, and J. Moya. 2012. Offshore sediment character and sand resource assessment of the northern Gulf of Mexico, Florida to Texas. Journal of Coastal Research, Special Issue 60:30–44.

Wolfe, S. H., J. A. Reidenauer, and D. B. Means. 1988. An ecological characterization of the Florida Panhandle. Department of the Interior, Washington, DC; National Wetlands Research Center, Slidell, Louisiana; Minerals Management Service, New Orleans, Louisiana; Bureau of Ocean Energy Management, Gulf of Mexico Outer Continental Shelf (OCS) Regional Office, New Orleans, Louisiana.

Wolinsky, M. A., and A. B. Murray. 2009. A unifying framework for shoreline migration: 2. Application to wave-dominated coasts. Journal of Geophysical Research: Earth Surface 114, F01009, doi:10.1029/2007JF000856.

Young, R., and L. Norby. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado.

Yuill, B., D. Lavoie, and D. J. Reed. 2009. Understanding subsidence processes in coastal Louisiana. Journal of Coastal Research, Special Issue 54:23–36.

Additional References

These references, resources, and websites may be of use to resource managers. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources. Refer to Appendix C for URLs.

Geology of National Park Service Areas

- NPS Geologic Resources Division (Lakewood, Colorado) Energy and Minerals; Active Processes and Hazards; Geologic Heritage
- NPS Geologic Resources Division Education Website
- NPS Geologic Resources Inventory
- NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program
- Lillie, R. J. 1999. Gulf Islands National Seashore geology training manual: plate tectonics and formation of the northern Gulf of Mexico. Geoscientists-In-the-Parks document, 1999-GUIS. National Park Service, Denver, Colorado. (Contract NPS Geologic Resources Division to obtain a copy).

NPS Resource Management Guidance and Documents

- NPS Gulf Coast Inventory and Monitoring Network
- Management Policies 2006 (Chapter 4: Natural resource management)
- 1998 National parks omnibus management act
- NPS-75: Natural resource inventory and monitoring guideline (see DO 77).
- NPS Natural resource management reference manual #77(see DO 77).
- Geologic monitoring manual (Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado)
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents)

Climate Change Resources

- NPS Climate Change Response Program Resources
- US Global Change Research Program
- Intergovernmental Panel on Climate Change

Geological Surveys and Societies

- Mississippi Department of Environmental Quality, Office of Geology
- Florida Geological Survey
- US Geological Survey
- Geological Society of America
- American Geophysical Union
- American Geosciences Institute
- Association of American State Geologists

USGS Reference Tools

- USGS Coastal Change Hazards Portal (to view shoreline change, sea level rise projections, and coastal change forecasts)
- USGS involvement in the Mississippi Coastal Improvements Program (MsCIP)
- National Geologic Map Database (NGMDB)
- Geologic Names Lexicon (GEOLEX; geologic unit nomenclature and summary)
- Geographic Names Information System (GNIS; official listing of place names and geographic features)

- GeoPDFs (download PDFs of any topographic map in the United States; click on “Map Locator”)
- Publications Warehouse (many publications available online)
- Tapestry of Time and Terrain (descriptions of physiographic provinces)

State Coastal Management Agencies

- Florida Joint Coastal Permit Program
- Florida rules and procedures for application for coastal construction permits
- Mississippi Department of Marine Resources
- Mississippi comprehensive ecosystem restoration tool

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting, held on 12–15 September 2006, or the follow-up report writing conference call, held on 16 May 2006. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website. Refer to Appendix C for URLs.

2006 Scoping Meeting Participants

Name	Affiliation	Position
John Baehr	US Army Corps of Engineers	Land geologist
Rebecca Beavers	NPS Geologic Resources Division	Coastal geologist
Greg Carter	University of Southern Mississippi, Gulf Coast Geospatial Center	Chief scientist
Rick Clark	NPS Gulf Islands National Seashore	Chief of Science and Resources Management
Tim Connors	NPS Geologic Resources Division	Geologist
Sid Covington	NPS Geologic Resources Division	Geologist
Monette Dalal	Kent State University	MS student (geology)
Jim Flocks	US Geological Survey	Coastal geologist
Ron Hoenstine	Florida Geological Survey	Director (coastal research)
Riley Hoggard	NPS Gulf Islands National Seashore	Natural resource specialist
Gary Hopkins	NPS Gulf Islands National Seashore	Biologist
Chris Houser	University of West Florida	Assistant professor (coastal geomorphology)
Katie KellerLynn	Colorado State University	Research associate/geologist
Klaus Meyer-Arendt	University of West Florida	Professor and department chair
Andrew Moore	Kent State University	Assistant professor (geology)
Mark Nicholas	NPS Gulf Islands National Seashore	Biologist
Martha Segura	NPS Gulf Coast Network	Network coordinator
Barbara Yassin	Mississippi Department of Environmental Quality	GIS Specialist
Linda York	NPS Southeast Regional Office	Coastal geologist

2016 Conference Call Participants

Name	Affiliation	Position
Rebecca Beavers	NPS Climate Change Response Program	Climate change adaptation coordinator
Lynda Bell	NPS Ocean and Coastal Resources Branch	Sea level rise specialist
Jeff Bracewell	NPS Gulf Coast Inventory & Monitoring Network	GIS specialist
Cass Bromley	NPS Gulf Islands National Seashore	Chief, Resources Management Division
Chris Houser	Texas A&M University	Professor (geology)
Jason Kenworthy	NPS Geologic Resources Division	GRI report team lead
Hal Pranger	NPS Geologic Resources Division	Chief, Geologic Systems Branch
Courtney Schupp	NPS Geologic Resources Division	Coastal geologist/GRI report author
Martha Segura	NPS Gulf Coast Inventory & Monitoring Network	Program manager
Jolene Williams	NPS Gulf Islands National Seashore	Environmental protection specialist
Linda York	NPS Southeast Regional Office	Coastal geologist

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to NPS 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 December 2018. Contact the NPS Geologic Resources Division for detailed guidance

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 CFR § 2.1** prohibits possessing/destroying/disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.
Paleontology	**National Parks Omnibus Management Act of 1998, 54 USC § 100701** 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. **43 CFR Part 49** (in development) will contain the DOI regulations implementing the Paleontological Resources Preservation Act.	**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.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Recreational Collection of Rocks Minerals	**NPS Organic Act, 54 USC. § 100101 et seq.** directs the NPS to conserve all resources in parks (which includes 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 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units. **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and 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.
Geothermal	**Geothermal Steam Act of 1970, 30 USC. § 1001 et seq. as amended in 1988**, states ● No geothermal leasing is allowed in parks. ● "Significant" thermal features exist in 16 park units (the features listed by the NPS at **52 Fed. Reg. 28793-28800** (August 3, 1987), plus the thermal features in Crater Lake, Big Bend, and Lake Mead). ● NPS is required to monitor those features. ● Based on scientific evidence, Secretary of Interior must protect significant NPS thermal features from leasing effects. **Geothermal Steam Act Amendments of 1988, Public Law 100--443** prohibits geothermal leasing in the Island Park known geothermal resource area near Yellowstone and outside 16 designated NPS units if subsequent geothermal development would significantly adversely affect identified thermal features.	None applicable.	**Section 4.8.2.3** requires NPS to ● Preserve/maintain integrity of all thermal resources in parks. ● Work closely with outside agencies. ● Monitor significant thermal features.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Mining Claims (Locatable Minerals)	**Mining in the Parks Act of 1976, 54 USC § 100731 et seq.** authorizes NPS to regulate all activities resulting from exercise of mineral rights, on patented and unpatented mining claims in all areas of the System, in order to preserve and manage those areas. **General Mining Law of 1872, 30 USC § 21 et seq.** allows US citizens to locate mining claims on Federal lands. Imposes administrative and economic validity requirements for "unpatented" claims (the right to extract Federally-owned locatable minerals). Imposes additional requirements for the processing of "patenting" claims (claimant owns surface and subsurface). Use of patented mining claims may be limited in Wild and Scenic Rivers and OLYM, GLBA, CORO, ORPI, and DEVA. **Surface Uses Resources Act of 1955, 30 USC § 612** restricts surface use of unpatented mining claims to mineral activities.	**36 CFR § 5.14** prohibits prospecting, mining, and the location of mining claims under the general mining laws in park areas except as authorized by law. **36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart A** requires the owners/operators of mining claims to demonstrate bona fide title to mining claim; submit a plan of operations to NPS describing where, when, and how; prepare/ submit a reclamation plan; and submit a bond to cover reclamation and potential liability. **43 CFR Part 36** governs access to mining claims located in, or adjacent to, National Park System units in Alaska.	**Section 6.4.9** requires NPS to seek to remove or extinguish valid mining claims in wilderness through authorized processes, including purchasing valid rights. Where rights are left outstanding, NPS policy is to manage mineral-related activities in NPS wilderness in accordance with the regulations at **36 CFR Parts 6 and 9A**. **Section 8.7.1** prohibits location of new mining claims in parks; requires validity examination prior to operations on unpatented claims; and confines operations to claim boundaries.
Nonfederal Oil and Gas	**NPS Organic Act, 54 USC § 100751 et seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). Individual Park Enabling Statutes: • **16 USC § 230a** (Jean Lafitte NHP & Pres.) • **16 USC § 450kk** (Fort Union NM), • **16 USC § 459d-3** (Padre Island NS), • **16 USC § 459h-3** (Gulf Islands NS), • **16 USC § 460ee** (Big South Fork NRRA), • **16 USC § 460cc-2(i)** (Gateway NRA), • **16 USC § 460m** (Ozark NSR), • **16 USC § 698c** (Big Thicket N Pres.), • **16 USC § 698f** (Big Cypress N Pres.)	**36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart B** requires the owners/operators of nonfederally owned oil and gas rights outside of Alaska to • demonstrate bona fide title to mineral rights; • submit an Operations Permit Application to NPS describing where, when, how they intend to conduct operations; • prepare/submit a reclamation plan; and • submit a bond to cover reclamation and potential liability. **43 CFR Part 36** governs access to nonfederal oil and gas rights located in, or adjacent to, National Park System units in Alaska.	**Section 8.7.3** requires operators to comply with 9B regulations.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Federal Mineral Leasing (Oil, Gas, and Solid Minerals)	**The Mineral Leasing Act, 30 USC § 181 et seq., and the Mineral Leasing Act for Acquired Lands, 30 USC § 351 et seq.** do not authorize the BLM to lease federally owned minerals in NPS units. **Combined Hydrocarbon Leasing Act, 30 USC §181**, allowed owners of oil and gas leases or placer oil claims in Special Tar Sand Areas (STSA) to convert those leases or claims to combined hydrocarbon leases, and allowed for competitive tar sands leasing. This act did not modify the general prohibition on leasing in park units but did allow for lease conversion in GLCA, which is the only park unit that contains a STSA. **Exceptions: Glen Canyon NRA (16 USC § 460dd et seq.), Lake Mead NRA (16 USC § 460n et seq.), and Whiskeytown-Shasta-Trinity NRA (16 USC § 460q et seq.)** authorizes the BLM to issue federal mineral leases in these units provided that the BLM obtains NPS consent. Such consent must be predicated on an NPS finding of no significant adverse effect on park resources and/or administration. American Indian Lands Within NPS Boundaries Under the **Indian Allottee Leasing Act of 1909, 25 USC §396, and the Indian Leasing Act of 1938, 25 USC §396a, §398 and §399, and Indian Mineral Development Act of 1982, 25 USCS §§2101-2108**, all minerals on American Indian trust lands within NPS units are subject to leasing. **Federal Coal Leasing Amendments Act of 1975, 30 USC § 201** prohibits coal leasing in National Park System units.	**36 CFR § 5.14** states prospecting, mining, and…leasing under the mineral leasing laws [is] prohibited in park areas except as authorized by law. **BLM regulations at 43 CFR Parts 3100, 3400, and 3500** govern Federal mineral leasing. **43 CFR Part 3160** governs onshore oil and gas operations, which are overseen by the BLM. Regulations re: Native American Lands within NPS Units: • **25 CFR Part 211** governs leasing of tribal lands for mineral development. • **25 CFR Part 212** governs leasing of allotted lands for mineral development. • **25 CFR Part 216** governs surface exploration, mining, and reclamation of lands during mineral development. • **25 CFR Part 224** governs tribal energy resource agreements. • **25 CFR Part 225** governs mineral agreements for the development of Indian-owned minerals entered into pursuant to the **Indian Mineral Development Act of 1982, Pub. L. No. 97-382, 96 Stat. 1938** (codified at **25 USC §§ 2101-2108**). • **30 CFR §§ 1202.100-1202.101** governs royalties on oil produced from Indian leases. • **30 CFR §§ 1202.550-1202.558** governs royalties on gas production from Indian leases. • **30 CFR §§ 1206.50-1206.62 and §§ 1206.170-1206.176** governs product valuation for mineral resources produced from Indian oil and gas leases. • **30 CFR § 1206.450** governs the valuation coal from Indian Tribal and Allotted leases. • **43 CFR Part 3160** governs onshore oil and gas operations, which are overseen by the BLM.	**Section 8.7.2** states that all NPS units are closed to new federal mineral leasing except Glen Canyon, Lake Mead and Whiskeytown-Shasta-Trinity NRAs.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Nonfederal minerals other than oil and gas	**NPS Organic Act, 54 USC §§ 100101 and 100751**	NPS regulations at **36 CFR Parts 1, 5, and 6** require the owners/ operators of other types of mineral rights to obtain a special use permit from the NPS as a **§ 5.3** business operation, and **§ 5.7 – Construction of buildings or other facilities**, and to comply with the solid waste regulations at **Part 6**.	**Section 8.7.3** states that operators exercising rights in a park unit must comply with **36 CFR Parts 1 and 5**.
Coal	**Surface Mining Control and Reclamation Act of 1977, 30 USC § 1201 et. seq.** prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights.	**SMCRA Regulations at 30 CFR Chapter VII** govern surface mining operations on Federal lands and Indian lands by requiring permits, bonding, insurance, reclamation, and employee protection. **Part 7** of the regulations states that National Park System lands are unsuitable for surface mining.	None applicable.
Uranium	**Atomic Energy Act of 1954** Allows Secretary of Energy to issue leases or permits for uranium on BLM lands; may issue leases or permits in NPS areas only if president declares a national emergency.	None applicable.	None applicable.
Common Variety Mineral Materials (Sand, Gravel, Pumice, etc.)	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Reclamation Act of 1939, 43 USC §387**, authorizes removal of common variety mineral materials from federal lands in federal reclamation projects. This act is cited in the enabling statutes for Glen Canyon and Whiskeytown National Recreation Areas, which provide that the Secretary of the Interior may permit the removal of federally owned nonleasable minerals such as sand, gravel, and building materials from the NRAs under appropriate regulations. Because regulations have not yet been promulgated, the National Park Service may not permit removal of these materials from these National Recreation Areas. **16 USC §90c-1(b)** authorizes sand, rock and gravel to be available for sale to the residents of Stehekin from the non-wilderness portion of Lake Chelan National Recreation Area, for local use as long as the 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, 54 USC § 100751 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. *See also "Climate Change"*	**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. *See also "Climate Change"*	**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 new developments in areas subject to natural shoreline processes unless certain factors are present. *See also "Climate Change"*

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

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. *2006 Management Policies, continued:* **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.	**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. ***continued in Regulations column***

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).

Appendix C: List of URLs

Websites used in the GRI report for Gulf Islands National Seashore.

Page, figure, or table	Description of link	URL
Inside cover	USGS photograph of Fort Massachusetts (JPG file)	https://pubs.usgs.gov/ds/0988/downloads/photos/photogroup01/2012_0902_195440d.jpg
p. ii	Geologic Resources Inventory publications page	http://go.nps.gov/gripubs
p. ii	Natural Resources Publications series page	https://www.nps.gov/im/publication-series.htm
p. xiii	Geologic Resources Inventory page	http://go.nps.gov/gri
figs. 2-4	NPS Harpers Ferry Center cartography website (download park maps)	https://www.nps.gov/carto/app/#!/parks
figs. 5 and 6	NOAA National Centers for Environmental Information website (coastal elevation models)	https://www.ngdc.noaa.gov/mgg/coastal/coastal.html
p. 9	NPS Geologic Resources Division Coastal Geology website	https://go.nps.gov/grd_coastal
fig. 14	USGS online publications directory (JPG files)	https://pubs.usgs.gov/ds/0988/html/contactsheets/thumbnails/
fig. 20	NPS and University of Maryland Center for Environmental Science (2012, online figure)	http://www.teachoceanscience.net/teaching_resources/education_modules/barrier_islands_and_sea_level_rise/learn/
p. 26	NPS Fossils and Paleontology website	https://www.nps.gov/subjects/fossils/index.htm
p. 27	NPS Reference Manual #39-1: Ocean and Coastal Park Jurisdiction	http://www.nps.gov/applications/npspolicy/DOrders.cfm
p. 28	Mississippi Department of Marine Resources	http://www.dmr.state.ms.us/
p.28	Florida Department of Environmental Protection	https://floridadep.gov/water/beaches#JCP
p. 28	NPS Sea Level Rise Online Viewer	https://maps.nps.gov/slr/
p. 29	NPS Water Resources Division, Ocean and Coastal Resources Branch website	https://www.nps.gov/orgs/1439/ocrb.htm
p. 29	NPS Ocean and Coastal Parks website	https://www.nps.gov/subjects/oceans/ocean-and-coastal-parks.htm
p. 31	USGS Coastal Change Hazards Portal	https://marine.usgs.gov/coastalchangehazardsportal/
p. 31	USGS Digital Shoreline Analysis System website	https://woodshole.er.usgs.gov/project-pages/DSAS/
p. 33	NPS Sea Level Rise Online Viewer	https://maps.nps.gov/slr/
p. 33	USGS Coastal Change Hazards Portal	https://marine.usgs.gov/coastalchangehazardsportal/
Table 8	National Hurricane Center website	http://www.nhc.noaa.gov/aboutsshws.php
p. 46	US Army Corps of Engineers Program and Project Management page	http://www.sam.usace.army.mil/Missions/Program-and-Project-Management/MsCIP-Program/
fig. 32	National Weather Service Riptide Currents page	https://www.weather.gov/mdl/ripcurrent
p. 51	NPS AML website	http://go.nps.gov/grd_aml
p. 52	DOI Deepwater Horizon website	https://www.doi.gov/deepwaterhorizon
Table 10 and 11	International Commission on Stratigraphy international chronostratigraphic chart page	http://www.stratigraphy.org/index.php/ics-chart-timescale
p. 77	GRI publications website	http://go.nps.gov/gripubs
p. 77	American Geosciences Institute website	http://www.americangeosciences.org/environment/publications/mapping
p. 77	Geomorphology and depositional subenvironments of Gulf Islands National Seashore	https://pubs.er.usgs.gov/publication/ofr20091250

Page, figure, or table	Description of link	URL
p. 77	Geomorphology and depositional subenvironments of Gulf Islands National Seashore, Perdido Key and Santa Rosa Island, Florida	https://pubs.er.usgs.gov/publication/ofr20101330
p. 78	GRI GIS data website	http://go.nps.gov/gridatamodel
p. 78	GRI publications website	http://go.nps.gov/gripubs
p. 78	NPS Integrated Resource Management Applications (IRMA) portal	https://irma.nps.gov/Portal
p. 81	Cross-shore suspended sediment transport in the surf zone: a field-based parameterization	http://www.sciencedirect.com/science/article/pii/S0025322702001937
p. 81	The use of aerial RGB imagery and LiDAR in comparing ecological habitats and geomorphic features on a natural versus man-made barrier island. Remote Sensing	http://www.mdpi.com/2072-4292/8/7/602
p. 81	Variable response of coastal environments of the northwestern Gulf of Mexico to sea-level rise and climate change: implications for future change	http://linkinghub.elsevier.com/retrieve/pii/S0025322713002636
p. 81	Recycling sediments between source and sink during a eustatic cycle: systems of late Quaternary northwestern Gulf of Mexico basin	http://linkinghub.elsevier.com/retrieve/pii/S001282521530060X
p. 81	Dune and shoreline evolution of western Santa Rosa Island, Florida, 1973–2013	http://diginole.lib.fsu.edu/islandora/object/fsu%3A254419
p. 81	Influence of antecedent geology on stratigraphic preservation potential and evolution of Delaware's barrier systems	http://www.sciencedirect.com/science/article/pii/0025322785900854
p. 81	Monitoring shoreline position at Gulf Coast Network parks: protocol implementation plan. Natural Resource Report	https://irma.nps.gov/DataStore/Reference/Profile/2243713
p. 81	Monitoring coastal topography at Gulf Coast Network parks: protocol implementation plan. Natural Resource Report	https://irma.nps.gov/DataStore/Reference/Profile/2244086
p. 81	Monitoring and comparison to predictive models of the Perdido Key beach nourishment project, Florida, USA	http://www.sciencedirect.com/science/article/pii/S0378383999000575
p. 81	Case study 19: establishing alternative transportation to Fort Pickens to supplement vulnerable road access, Gulf Islands National Seashore, Florida	https://www.nps.gov/subjects/climatechange/coastaladaptationstrategies.htm
p. 82	Unauthorized fossil collecting from National Park Service shorelines: servicewide policy and perspectives	http://www.georgewright.org/proceedings2009
p. 82	Abandoned mineral lands in the National Park System: comprehensive inventory and assessment. Natural Resource Technical Report	http://go.nps.gov/aml_publications
p. 82	Coastal features and processes	http://go.nps.gov/geomonitoring
p. 82	Historical bathymetry and bathymetric change in the Mississippi–Alabama coastal region, 1847–2009	https://pubs.usgs.gov/sim/3154/
p. 82	Channel dredging and geomorphic response at and adjacent to Mobile Pass, Alabama	http://www.dtic.mil/docs/citations/ADA536622
p. 82	Littoral sediment budget for the Mississippi Sound barrier islands	http://www.dtic.mil/docs/citations/ADA572117

Page, figure, or table	Description of link	URL
p. 82	Historical sediment transport pathways and quantities for determining an operational sediment budget: Mississippi Sound barrier islands	http://www.bioone.org/doi/abs/10.2112/SI63-014.1
p. 82	Sea level and storm trends, Gulf Islands National Seashore	https://irma.nps.gov/DataStore/Reference/Profile/2224654
p. 82	Sea level rise and storm surge projections for the National Park Service	https://irma.nps.gov/DataStore/Reference/Profile/2253283
p. 82	Relationships among marsh surface topography, hydroperiod, and soil accretion in a deteriorating Louisiana salt marsh	http://journals.fcla.edu/jcr/article/view/79548
p. 82	Ability of beach users to identify rip currents at Pensacola Beach, Florida	https://link.springer.com/article/10.1007%2Fs11069-013-0673-3
p. 82	Seagrass—Gulf Islands National Seashore—2011/10/04	https://irma.nps.gov/DataStore/Reference/Profile/2194913
p. 82	Catastrophic storm impact and gradual recovery on the Mississippi-Alabama barrier islands, 2005–2010: Changes in vegetated and total land area, and relationships of post-storm ecological communities with surface elevation	https://doi.org/10.1016/j.geomorph.2018.08.020
p. 82	Climate change impacts in the United States: the third national climate assessment	https://www.globalchange.gov/
p. 83	Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change	http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml
p. 83	Net longshore sediment transport and textural changes in beach sediments along the southwest Alabama and Mississippi barrier islands, USA	http://www.jstor.org/stable/4300195
p. 83	Effect of Hurricane Ivan on coastal dunes of Santa Rosa barrier island, Florida: characterized on the basis of pre- and post-storm LiDAR surveys	http://www.jstor.org/stable/40605476
p. 83	Shoreline length and water area in the ocean, coastal and Great Lakes parks: updated statistics for shoreline miles and water acres (rev1b)	https://irma.nps.gov/App/Reference/Profile/2180595/
p. 83	Sedimentation from 2005 Hurricane Katrina on the Mississippi and Alabama Gulf Coast barrier islands	https://gsa.confex.com/gsa/2006AM/finalprogram/abstract_112485.htm
p. 83	National Park Service beach nourishment guidance	https://irma.nps.gov/App/Reference/Profile/2185115
p. 83	Beach nourishment: a guide for local government officials	http://www.csc.noaa.gov/beachnourishment/html/geo/scitech.htm
p. 83	The Outer Banks of North Carolina	https://pubs.er.usgs.gov/publication/pp1177B
p. 83	Beach erosion and deposition on Dauphin Island, Alabama, USA	http://www.jstor.org/stable/4298218
p. 84	The sedimentological characteristics and geochronology of the marshes of Dauphin Island, Alabama	https://doi.org/10.3133/ofr20171165
p. 84	Critical bifurcation of shallow microtidal landforms in tidal flats and salt marshes	http://www.pnas.org/content/103/22/8337.shor
p. 84	A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation	http://www.nature.com/nature/journal/v342/n6250/abs/342637a0.html
p. 84	Is the detection of accelerated sea level rise imminent?	https://www.nature.com/articles/srep31245

Page, figure, or table	Description of link	URL
p. 84	Pitfalls of shoreline stabilization: selected case studies	http://dx.doi.org/10.1007/978-94-007-4123-2_3
p. 84	Sediment distribution on the Mississippi-Alabama Shelf, northern Gulf of Mexico	https://pubs.er.usgs.gov/publication/ofr20101002
p. 84	Offshore sand-shoal development and evolution of Petit Bois Pass, Mississippi–Alabama barrier islands, Mississippi, USA	https://www.worldscientific.com/worldscibooks/10.1142/8190#t=toc
p. 84	Near-surface stratigraphy and morphology, Mississippi inner shelf, northern Gulf of Mexico	https://pubs.er.usgs.gov/publication/ofr20151014
p. 84	Climate change and sea-level rise in Florida: an update of the effects of climate change on Florida's ocean and coastal resources	www.floridaoceanscouncil.org
p. 85	Recent deltaic deposits of the Mississippi River: their development and chronology	http://archives.datapages.com/data/browse/gcags-transactions/
p. 85	Numerical simulation of vertical marsh growth and adjustment to accelerated sea-level rise, North Norfolk, UK	http://onlinelibrary.wiley.com/doi/10.1002/esp.3290180105/abstract
p. 85	Hurricane Katrina storm surge distribution and field observations on the Mississippi barrier islands	http://linkinghub.elsevier.com/retrieve/pii/S0272771407000868
p. 85	Hurricane Katrina storm surge reconnaissance	http://ascelibrary.org/doi/10.1061/%28ASCE%291090-0241%282008%29134%3A5%28644%29
p. 85	Macroclimatic change expected to transform coastal wetland ecosystems this century	https://www.nature.com/articles/nclimate3203
p. 85	NPS continues to remove asphalt chunks from Gulf Islands National Seashore	http://www.pnj.com/story/news/local/pensacola/beaches/2017/12/11/gulf-islands-national-seashore-asphalt-project-cleanup/941125001/
p. 85	Multibeam mapping of the Pinnacles region, Gulf of Mexico	https://pubs.er.usgs.gov/publication/ofr026
p. 85	Neogene and Quaternary geology of a stratigraphic test hole on Horn Island, Mississippi Sound	https://pubs.er.usgs.gov/publication/ofr9620A
p. 85	Stability and bistability in a one-dimensional model of coastal foredune height: A 1-D model of coastal foredune height	http://doi.wiley.com/10.1002/2015JF003783
p. 85	Deep Water: the Gulf oil disaster and the future of offshore drilling, report to the president, January 2011	https://digital.library.unt.edu/ark:/67531/metadc123527/
p. 85	Potential for shoreline changes due to sea-level rise along the US Mid-Atlantic region	https://cmgds.marine.usgs.gov/publications/of2007-1278/
p. 85	Coastal sensitivity to sea-level rise: a focus on the mid-Atlantic region. A report by the US Climate Change Science Program and the Subcommittee on Global Change Research	http://papers.risingsea.net/coastal-sensitivity-to-sea-level-rise-3-ocean-coasts.html
p. 85	Long-term and storm-related shoreline change trends in the Florida Gulf Islands National Seashore	https://pubs.er.usgs.gov/publication/ofr20071392
p. 85	Natural resource condition assessment for Gulf Islands National Seashore	https://irma.nps.gov/DataStore/Reference/Profile/2227467
p. 86	Geomorphological controls on road damage during Hurricanes Ivan and Dennis	http://www.bioone.org/doi/abs/10.2112/07-0923.1
p. 86	Feedback between ridge and swale bathymetry and barrier island storm response and transgression	http://linkinghub.elsevier.com/retrieve/pii/S0169555X12002589

Page, figure, or table	Description of link	URL
p. 86	Alongshore variation in the rip current hazard at Pensacola Beach, Florida	http://link.springer.com/10.1007/s11069-010-9636-0
p. 86	Onshore Migration of a swash bar during a storm	http://www.jcronline.org/doi/abs/10.2112/03-0135.1
p. 86	Sensitivity of post-hurricane beach and dune recovery to event frequency	http://doi.wiley.com/10.1002/esp.1730
p. 86	EOF analysis of morphological response to Hurricane Ivan	https://ascelibrary.org/doi/book/10.1061/9780784409268
p. 86	Controls on coastal dune morphology, shoreline erosion and barrier island response to extreme storms	http://linkinghub.elsevier.com/retrieve/pii/S0169555X08000020
p. 86	Posthurricane airflow and sediment transport over a recovering dune	http://www.bioone.org/doi/abs/10.2112/06-0767.1
p. 86	Alongshore correspondence of beach users and rip channels at Pensacola Beach, Florida	http://link.springer.com/10.1007/s11069-015-1804-9
p. 86	Post-storm beach and dune recovery: Implications for barrier island resilience	http://linkinghub.elsevier.com/retrieve/pii/S0169555X1500029X
p. 86	Scale dependent behavior of the foredune: implications for barrier island response to storms and sea level rise	https://agu.confex.com/agu/fm15/webprogram/Paper58744.html
p. 86	Verification of the Gulf of Mexico hindcast wave information. Wave Information Studies of US Coastlines	https://apps.dtic.mil/dtic/tr/fulltext/u2/a259413.pdf
p. 86	Vulnerability of Louisiana's coastal wetlands to present-day rates of relative sea-level rise	http://www.nature.com/doifinder/10.1038/ncomms14792
p. 86	Global climate change impacts in the United States	https://www.globalchange.gov/browse/reports/global-climate-change-impacts-united-states
p. 86	Exploring high-end scenarios for local sea level rise to develop flood protection strategies for a low-lying delta—The Netherlands as an example	http://link.springer.com/10.1007/s10584-011-0037-5
p. 86	Aqueous geochemistry of the sand-and-gravel aquifer, northwest Florida	http://onlinelibrary.wiley.com/doi/10.1111/j.1745-6584.1991.tb00496.x/abstract
p. 87	Seismic stratigraphy of the Mississippi–Alabama shelf and upper continental slope	https://doi.org/10.1016/0025-3227(88)90053-9
p. 87	Rapid wetland expansion during European settlement and its implication for marsh survival under modern sediment delivery rates	http://geology.gsapubs.org/content/39/5/507
p. 87	Coastal response to storms and sea-level rise: Santa Rosa Island, northwest Florida, USA	http://www.bioone.org/doi/abs/10.2112/SI63-012.1
p. 87	An evaluation of subsidence rates and sea-level variability in the northern Gulf of Mexico	https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2011GL049458
p. 87	Benthic substrate classification map: Gulf Islands National Seashore	https://pubs.usgs.gov/of/2012/1051/
p. 87	Gulf of Mexico Cenozoic biostratigraphic, lithostratigraphic, and sequence stratigraphic event chronology	http://archives.datapages.com/data/browse/gcags-transactions/
p. 87	Geologic framework influences on the geomorphology of an anthropogenically modified barrier island: assessment of dune/beach changes at Fire Island, New York	http://linkinghub.elsevier.com/retrieve/pii/S0169555X10004708
p. 87	Understanding the science of climate change: talking points—impacts of the Gulf Coast	http://www.treesearch.fs.fed.us/pubs/35939

Page, figure, or table	Description of link	URL
p. 87	Change in distribution and composition of vegetated habitats on Horn Island, Mississippi, northern Gulf of Mexico, in the initial five years following Hurricane Katrina	http://linkinghub.elsevier.com/retrieve/pii/S0169555X12005302
p. 87	Geologic characteristics and spatial distribution of paleo-inlet channels beneath the outer banks barrier islands, North Carolina, USA	http://linkinghub.elsevier.com/retrieve/pii/S0272771410001319
p. 87	Influence of storm surges and sea level on shallow tidal basin erosive processes	http://onlinelibrary.wiley.com/doi/10.1029/2009JC005892/full
p. 88	Application of a barrier island translation model to the millennial-scale evolution of Sand Key, Florida	http://www.sciencedirect.com/science/article/pii/S0278434308000812
p. 88	Effects of sea-level rise on barrier island groundwater system dynamics—ecohydrological implications	http://onlinelibrary.wiley.com/doi/10.1002/eco.1442/abstract
p. 88	The Pliocene Citronelle Formation of the Gulf coastal plain	https://pubs.er.usgs.gov/publication/pp98L
p. 88	Surficial sediments and morphology of the southwestern Alabama/western Florida Panhandle coast and shelf	http://archives.datapages.com/data/browse/gcags-transactions/
p. 88	Protecting infrastructure: costs and impacts	https://www.nps.gov/subjects/climatechange/coastalhandbook.htm
p. 88	Refining the link between the Holocene development of the Mississippi River Delta and the geologic evolution of Cat Island, MS: implications for delta-associated barrier islands	http://www.sciencedirect.com/science/article/pii/S0025322714001789
p. 88	Mississippi Sound and the Gulf Islands	https://pubs.usgs.gov/sir/2006/5287/
p. 88	Statewide summary of Mississippi	https://pubs.usgs.gov/sir/2006/5287/
p. 89	Modeling barrier island response to sea-level rise in the Outer Banks, North Carolina	http://ascelibrary.org/doi/abs/10.1061/40926(239)89
p. 89	Complexities in barrier island response to sea level rise: insights from numerical model experiments, North Carolina Outer Banks	http://onlinelibrary.wiley.com/doi/10.1029/2009JF001299/full
p. 89	Inlet migration and hydraulic processes at East Pass, Florida	http://www.jstor.org/stable/4297989
p. 89	Gulf of Mexico regional sediment budget	http://www.bioone.org/doi/abs/10.2112/SI_60_3
p. 89	Coastal change during Hurricane Isabel 2003	https://pubs.usgs.gov/fs/2009/3025/
p. 89	Baseline coastal oblique aerial photographs collected from Navarre Beach, Florida, to Breton Island, Louisiana, September 1, 2014	https://dx.doi.org/10.3133/ds952
p. 89	Baseline coastal oblique aerial photographs collected from Navarre Beach, Florida, to Breton Island, Louisiana, September 18–19, 2015	https://dx.doi.org/10.3133/ds1008
p. 89	Responses of coastal wetlands to rising sea level	http://www.esajournals.org/doi/full/10.1890/0012-9658(2002)083%5B2869:ROCWTR%5D2.0.CO;2
p. 89	Historical changes in the Mississippi–Alabama barrier islands and the roles of extreme storms, sea level, and human activities	http://pubs.usgs.gov/of/2007/1161/
p. 89	First-order controls of extreme-storm impacts on the Mississippi–Alabama barrier-island chain	http://dx.doi.org/10.2112/08-1152.1

Page, figure, or table	Description of link	URL
p. 89	The national assessment of shoreline change: part 1–historic shoreline change and associated coastal land loss along the US Gulf of Mexico	https://pubs.usgs.gov/of/2004/1043/
p. 89	Geomorphology and depositional subenvironments of Gulf Islands National Seashore, Perdido Key and Santa Rosa Island, Florida	https://pubs.er.usgs.gov/publication/ofr20101330
p. 89	Wetland subsidence, fault reactivation, and hydrocarbon production in the US Gulf Coast region	https://pubs.usgs.gov/fs/fs091-01/
p. 89	Geomorphology and depositional subenvironments of Gulf Islands National Seashore	https://pubs.er.usgs.gov/publication/ofr20091250
p. 89	The life and death of salt marshes in response to anthropogenic disturbance of sediment supply	http://geology.gsapubs.org/content/39/5/511.full
p. 89	How does vegetation affect sedimentation on tidal marshes? Investigating particle capture and hydrodynamic controls on biologically mediated sedimentation	http://onlinelibrary.wiley.com/doi/10.1029/2009JF001566/full
p. 89	A climatology of tropical storm and hurricane strikes to enhance vulnerability prediction for the southeast US coast	http://www.jstor.org/stable/4300254
p. 90	Rip current science	http://www.ripcurrents.noaa.gov/science.shtml
p. 90	Tides & currents: sea level trends	http://tidesandcurrents.noaa.gov/sltrends/sltrends.html
p. 90	Datums for 8745557, Gulfport Harbor MS. 1983–2001 tidal epoch	https://tidesandcurrents.noaa.gov/datums.html?id=8745557
p. 90	Gulf Islands National Seashore geologic resource evaluation scoping summary	http://go.nps.gov/gripubs
p. 90	Final general management plan / environmental impact statement (July 2014)	https://parkplanning.nps.gov/document.cfm?parkID=384&projectID=11318&documentID=60389
p. 90	Record of decision for the general management plan: Gulf Islands National Seashore, Florida and Mississippi	https://federalregister.gov/a/2015-00047
p. 90	US Department of Interior, National Park Service, record of decision: Mississippi Coastal Improvements Program, comprehensive barrier island restoration, August 2016	https://parkplanning.nps.gov/document.cfm?documentID=75385
p. 90	Operating hours & seasons. Gulf Islands National Seashore	https://www.nps.gov/guis/planyourvisit/hours.htm
p. 90	Barrier islands and sea level rise. Teach Ocean Science online module	http://www.teachoceanscience.net/teaching_resources/education_modules/barrier_islands_and_sea_level_rise/learn/
p. 90	Late Pleistocene transgressive unit (Biloxi Formation), northern Gulf Coast: geologic notes	http://archives.datapages.com/data/bulletns/1974-76/data/pg/0059/0001/0100/0148.htm
p. 90	New Orleans—South Hancock Holocene barrier trends and origins of Lake Pontchartrain	http://archives.datapages.com/data/browse/gcags-transactions/
p. 90	Barrier island formation through nearshore aggradation: stratigraphic and field evidence	http://www.sciencedirect.com/science/article/pii/002532278190181X
p. 91	Coastal geology of Mississippi, Alabama and adjacent Louisiana areas	http://archives.datapages.com/data/nogs/data/005/005027/i.htm
p. 91	Coastal evolution—Louisiana to northwest Florida	http://archives.datapages.com/data/nogs/data/006/006018/i.htm
p. 91	Pliocene age of coastal units, northeastern Gulf of Mexico	http://archives.datapages.com/data/browse/gcags-transactions/

Page, figure, or table	Description of link	URL
p. 91	Mississippi's revised Neogene stratigraphy in northern Gulf context	http://archives.datapages.com/data/browse/gcags-transactions/
p. 91	Multiple Pliocene–Quaternary marine highstands, northeast Gulf coastal plain: fallacies and facts	http://www.jstor.org/stable/4298405
p. 91	Citronelle Formation, northeastern Gulf coastal plain: Pliocene stratigraphic framework and age issues	http://archives.datapages.com/data/browse/gcags-transactions/
p. 91	Mississippi coast: stratigraphy and Quaternary evolution in the northern Gulf coastal plain framework	https://pubs.usgs.gov/of/2001/of01-415/
p. 91	Prospects for interregional correlations using Wisconsin and Holocene aridity episodes, northern Gulf of Mexico coastal plain	http://linkinghub.elsevier.com/retrieve/pii/S0033589403001418
p. 91	Numerical chronology of the late Quaternary Gulf coastal plain: barrier evolution and an updated Holocene sea-level curve	http://archives.datapages.com/data/browse/gcags-transactions/
p. 91	Coastal barriers, Gulf of Mexico: Holocene evolution and chronology	https://www.jstor.org/stable/25736980?seq=1#page_scan_tab_contents
p. 91	Numerical chronology of Pleistocene coastal plain and valley development: extensive aggradation during glacial low sea-levels	http://linkinghub.elsevier.com/retrieve/pii/S1040618204002198
p. 91	Pleistocene Gulf coastal plain: regional stratigraphic and geomorphic contrasts. Intensive erosion related to sea-level decline and hinterland uplift	http://archives.datapages.com/data/browse/gcags-transactions/
p. 91	The last interglacial stage: definitions and marine highstand, North America and Eurasia	http://linkinghub.elsevier.com/retrieve/pii/S1040618214003061
p. 91	Last interglacial, Gulf shorelines during last eustatic cycle; barrier island formation and development; and barrier island preservation and destruction	https://link.springer.com/referencework/10.1007/978-3-319-48657-4#introduction
p. 91	Hurricane degradation—barrier development cycles, northeastern Gulf of Mexico: landform evolution and island chain history	http://www.bioone.org/doi/abs/10.2112/06-0820.1
p. 91	Regressive and transgressive barrier islands on the north-central Gulf Coast—contrasts in evolution, sediment delivery, and island vulnerability	http://linkinghub.elsevier.com/retrieve/pii/S0169555X13002900
p. 91	Interlinked barrier chain and delta lobe development, northern Gulf of Mexico	http://linkinghub.elsevier.com/retrieve/pii/S0037073804001381
p. 91	Coastal vulnerability assessment of Gulf Islands National Seashore (GUIS) to sea-level rise	http://pubs.usgs.gov/of/2003/of03-108/
p. 92	Navarre Beach renourishment done early, under budget	http://www.pnj.com/story/news/local/pensacola/beaches/2016/05/02/beach-renourishment-update-sand-being-pumped-onto-beach/83817880/
p. 92	Seagrasses in the Mississippi and Chandeleur Sounds and problems associated with decadal-scale change detection	http://goms.disl.org/assets/goms_disl/uploads/toc/2011_2030/03-goms-32-01-07-3Pham.pdf
p. 92	The apparent growth of Gulf Beach, extreme west Florida	http://archives.datapages.com/data/gcags/data/025/025001/0369.htm
p. 92	A semi-empirical approach to projecting future sea-level rise	http://science.sciencemag.org/content/315/5810/368.short
p. 92	Case study 14: large-scale restoration of barrier island systems and cultural resource protection through sediment placement, Gulf Islands National Seashore, Mississippi	https://www.nps.gov/subjects/climatechange/coastaladaptationstrategies.htm

Page, figure, or table	Description of link	URL
p. 92	Effect of storms on barrier island dynamics, Core Banks, Cape Lookout National Seashore, North Carolina, 1960–2001	https://pubs.usgs.gov/sir/2006/5309/
p. 92	Eye of a human hurricane: Pea Island, Oregon Inlet, and Bodie Island, northern Outer Banks, North Carolina	http://specialpapers.gsapubs.org/content/460/43.abstract
p. 92	Influence of inherited geologic framework on barrier shoreface morphology and dynamics	http://www.sciencedirect.com/science/article/pii/002532279500079E
p. 92	Cultural resources climate change strategy	https://www.nps.gov/subjects/climatechange/culturalresourcesstrategy.htm
p. 92	Recent morphologic changes at Dog Keys Pass, Mississippi: the formation and disappearance of the Isle of Caprice	http://archives.datapages.com/data/browse/gcags-transactions/
p. 92	Barrier island evolution and reworking by inlet migration along the Mississippi–Alabama Gulf Coast	http://archives.datapages.com/data/browse/gcags-transactions/
p. 93	Florida state summary. Technical Report NESDIS 149-FL	https://statesummaries.ncics.org/FL
p. 93	Storm impact scale for barrier islands	http://www.jstor.org/stable/4300099
p. 93	Quantifying the effects of increased storminess and sea-level change on the morphology of sandy barrier islands along the northwestern and Atlantic coasts of Florida	http://diginole.lib.fsu.edu/islandora/object/fsu%3A253032
p. 93	Monitoring in situ paleontological resources	http://go.nps.gov/geomonitoring
p. 93	Turn down the heat: why a 4°C warmer world must be avoided	http://library.wur.nl/WebQuery/wurpubs/reports/445744
p. 93	Inner–shelf hardbottom areas, northeastern Gulf of Mexico	http://archives.datapages.com/data/gcags/data/038/038001/0535.htm
p. 93	Coastal adaptation strategies: case studies	https://www.nps.gov/subjects/climatechange/coastaladaptationstrategies.htm
p. 93	Strategy for enhanced monitoring of natural resource condition in North Atlantic coastal parks to address the effects of rapid climate change	https://irma.nps.gov/DataStore/Reference/Profile/2166645
p. 93	A simple model for the spatially-variable coastal response to hurricanes	http://linkinghub.elsevier.com/retrieve/pii/S0025322706003355
p. 93	The importance of extratropical and tropical cyclones on the short-term evolution of barrier islands along the northern Gulf of Mexico, USA	http://www.sciencedirect.com/science/article/pii/S0025322704001306
p. 93	Multiple sediment sources and a cellular, non-integrated, longshore drift system: northwest Florida and southeast Alabama coast, USA	http://www.sciencedirect.com/science/article/pii/002532279290186L
p. 93	A nearshore sediment transport model for the northeast Gulf of Mexico coast, USA	http://www.jstor.org/stable/4298524
p. 93	Process-response modeling of wave-dominated coastal systems: simulating evolution and stratigraphy on geologic timescales	http://jsedres.sepmonline.org/content/72/2/226.short
p. 93	Climate science special report: fourth national climate assessment, volume I	https://science2017.globalchange.gov/chapter/12/
p. 93	Stratigraphic framework of a late Pleistocene shelf edge delta, northeast Gulf of Mexico	http://archives.datapages.com/data/bulletns/1994-96/data/pg/0078/0008/1250/1276.htm
p. 94	Modelling sea level rise impacts on storm surges along US coasts	http://iopscience.iop.org/article/10.1088/1748-9326/7/1/014032/meta

Page, figure, or table	Description of link	URL
p. 94	Digital Shoreline Analysis System (DSAS) version 4.0—an ArcGIS extension for calculating shoreline change (ver. 4.4, July 2017)	https://pubs.er.usgs.gov/publication/ofr20081278
p. 94	Geologic controls on regional and local erosion rates of three northern Gulf of Mexico barrier-island systems	http://www.bioone.org/doi/abs/10.2112/SI63-004.1
p. 94	The shallow stratigraphy and sand resources offshore of the Mississippi Barrier Islands	https://pubs.er.usgs.gov/publication/ofr20111173
p. 94	Mineral resources on-line spatial data	http://mrdata.usgs.gov/sgmc/ms.html
p. 94	Interactions between barrier islands and backbarrier marshes affect island system response to sea level rise: insights from a coupled model	http://doi.wiley.com/10.1002/2014JF003091
p. 94	Diagnostic faunal characteristics on and near a barrier island, Horn Island, Mississippi	http://archives.datapages.com/data/gcags/data/010/010001/0007.htm
p. 94	Hatteras Breach, North Carolina. Defense Technical Information Center (DTIC) accession number ADA530601	http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA530601
p. 94	Beach nourishment viewer	http://beachnourishment.wcu.edu/
p. 95	Sea-level rise implications for coastal regions	http://www.jcronline.org/doi/abs/10.2112/SI63-015.1
p. 95	Offshore sediment character and sand resource assessment of the northern Gulf of Mexico, Florida to Texas	http://www.jcronline.org/doi/abs/10.2112/SI_60_4
p. 95	An ecological characterization of the Florida Panhandle	http://www.osti.gov/scitech/biblio/6692895
p. 95	A unifying framework for shoreline migration: 2. Application to wave-dominated coasts	http://onlinelibrary.wiley.com/doi/10.1029/2007JF000856/full
p. 95	NPS Geological monitoring page	http://go.nps.gov/geomonitoring
p. 95	Understanding subsidence processes in coastal Louisiana	http://www.bioone.org/doi/abs/10.2112/SI54-012.1
p. 97	NPS Geologic Resources Division Geology website	http://go.nps.gov/geology
p. 97	NPS Geologic Resources Division Education website	http://go.nps.gov/geoeducation
p. 97	NPS Geologic Resources Inventory website	http://go.nps.gov/gri
p. 97	NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program website	http://go.nps.gov/gip
p. 97	NPS Gulf Coast Inventory and Monitoring Network website	https://www.nps.gov/im/guln/index.htm
p. 97	Management Policies 2006 (Chapter 4: Natural resource management)	http://www.nps.gov/policy/mp/policies.html
p. 97	1998 National parks omnibus management act pdf	http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
p. 97	NPS-75: Natural resource inventory and monitoring guideline (see DO 77)	https://www.nps.gov/applications/npspolicy/DOrders.cfm
p. 97	NPS Natural resource management reference manual #77 (see DO 77)	https://www.nps.gov/applications/npspolicy/DOrders.cfm
p. 97	NPS Geologic monitoring manual page	http://go.nps.gov/geomonitoring
p. 97	NPS Technical Information Center page	https://www.nps.gov/orgs/1804/dsctic.htm
p. 97	NPS Climate Change Response Program Resources page	http://www.nps.gov/subjects/climatechange/resources.htm
p. 97	US Global Change Research Program website	http://www.globalchange.gov/home
p. 97	Intergovernmental Panel on Climate Change website	http://www.ipcc.ch/

Page, figure, or table	Description of link	URL
p. 97	Mississippi Department of Environmental Quality, Office of Geology page	http://www.deq.state.ms.us/MDEQ.nsf/page/Geology_home
p. 97	Florida Geological Survey website	http://www.dep.state.fl.us/geology/
p. 97	US Geological Survey website	http://www.usgs.gov/
p. 97	Geological Society of America website	http://www.geosociety.org/
p. 97	American Geophysical Union website	http://sites.agu.org/
p. 97	American Geosciences Institute website	http://www.americangeosciences.org/
p. 97	Association of American State Geologists website	http://www.stategeologists.org/
p. 97	USGS Coastal Change Hazards Portal	https://marine.usgs.gov/coastalchangehazardsportal/
p. 97	USGS involvement in the Mississippi Coastal Improvements Program page	https://gom.usgs.gov/web/Projects/View/4
p. 97	National Geologic Map Database	http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
p. 97	Geologic Names Lexicon (geologic unit nomenclature and summary website)	http://ngmdb.usgs.gov/Geolex/search
p. 97	Geographic Names Information System website	http://gnis.usgs.gov/
p. 97	GeoPDFs (download PDFs of any topographic map in the United States; click on "Map Locator")	http://store.usgs.gov
p. 97	Publications Warehouse website	http://pubs.er.usgs.gov
p. 97	Tapestry of Time and Terrain (USGS geologic map)	http://pubs.usgs.gov/imap/i2720/
p. 97	Florida Joint Coastal Permit Program website	http://www.dep.state.fl.us/beaches/programs/envpermt.htm#JCP
p. 97	Florida rules and procedures for application for coastal construction permits page	https://www.flrules.org/gateway/ChapterHome.asp?Chapter=62B-41
p. 97	Mississippi Department of Marine Resources website	http://www.dmr.state.ms.us/
p. 97	Mississippi comprehensive ecosystem restoration tool	http://msrestoreteam.com/MCERTExplorer/
p. 99	GRI Publications website	http://go.nps.gov/gripubs

NPS 635/160210, August 2019

National Park Service
U.S. Department of the Interior

Natural Resources Stewardship and Science
1201 Oak Ridge Drive, Suite 150
Fort Collins, Colorado 80525

https://www.nps.gov/nature/index.htm