National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Dry Tortugas National Park

Geologic Resources Inventory Report, Revised April 2014

Natural Resource Report NPS/NRSS/GRD/NRR—2014/809

ON THE COVER
Surrounded by patchy coral and a deep channel, Garden Key is home to the majority of the park's infrastructure, including Fort Jefferson, the largest masonry structure in the Americas. View toward the southwest. National Park Service photograph courtesy of the Submerged Resources Center.

THIS PAGE
Loggerhead Light on Loggerhead Key warns mariners of the keys and shallow carbonate banks fringed with coral reefs in Dry Tortugas National Park. View toward the northeast.
US Geological Survey photograph courtesy of Don Hickey.

Dry Tortugas National Park

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NOTE: The Dry Tortugas National Park Geologic Resources Inventory (GRI) report was original completed and distributed in early March 2014 as Port, R. 2014. Dry Tortugas National Park: Geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2014/771. National Park Service, Fort Collins, Colorado.

Shortly after publication, the GRI report team was contacted regarding report sections describing construction materials and subsidence of Fort Jefferson. Those sections of the report were based primarily upon the GRI scoping meeting summary, which was completed in 2005 (Thornberry-Ehrlich 2005). Since the writing of the scoping meeting summary, additional research was undertaken regarding subsidence of the fort.

This revised version of the report includes updated content and photographs in the "Geologic Materials Used in Fort Jefferson", "Sediment Erosion and Accretion", and "Subsidence" sections. The "List of Figures" and "Literature Cited" sections were also updated to reflect the new content.

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Executive Summary

The Geologic Resources Inventory is one of 12 inventories funded by the National Park Service Inventory and Monitoring Program. This report synthesizes discussions from a scoping meeting for Dry Tortugas National Park in Florida on 23–24 January 2005 and a follow-up conference call on 17 December 2012, which were held by the Geologic Resources Division to determine geologic resources, the status of geologic mapping, and geologic resource management issues and needs. It is a companion document to the previously completed Geologic Resources Inventory digital geologic map data.

This Geologic Resources Inventory report was written for Dry Tortugas National Park to assist with resource management and science-informed decision making. It may also be useful for interpretation. The report discusses distinctive geologic features and processes within the park, geologic issues facing resource managers at the park, and the geologic history leading to the park's present-day landscape.

Included with this report is a Benthic Map Graphic (in pocket) that illustrates the benthic map data and a Map Unit Properties Table (in pocket) that summarizes the main features, characteristics, and potential management issues for the units on the digital benthic map for the park. A glossary of geologic terms used in this report is also provided along with a geologic time scale.

Dry Tortugas National Park is a remote island park 113 km (70 mi) west of Key West between the Gulf of Mexico and the Straits of Florida. Its 262 km^2 (101 mi^2) is predominantly underwater with pristine coral reefs, sand banks and seagrass beds. Seven small, sand islands—Loggerhead, Garden, Bush, Long, Hospital, Middle, and East keys—emerge from the warm tropical waters. The islands were first named Las Tortugas, meaning "The Turtles," by Spanish explorer Ponce de Leon in 1513 because of the abundance of sea turtles. Shortly after "Dry" was added to indicate the lack of freshwater.

The coral reefs of the Dry Tortugas are home to an incredible array of marine life, including two species of threatened (proposed endangered) coral—elkhorn (*Acropora palmata*) and staghorn (*Acropora cervicornis*). Bush Key is famous for its nesting colony of sooty terns. Garden Key contains the 19th-century Fort Jefferson, the largest masonry structure in the Americas.

Geologic features and processes of particular significance for resource management at Dry Tortugas National Park include the following:

- Pleistocene Bedrock. Pleistocene limestone, consisting of two formations, underlies all of the Florida Keys, including Dry Tortugas National Park. The Upper Pleistocene Key Largo Limestone is a fossilized coral reef that forms the bedrock foundation directly beneath the Holocene sand banks, islands, and reefs of the park. Topographic variations in this formation are largely responsible for the location of the park's living reefs, modern sand banks, and islands. The Upper Pleistocene Miami Limestone is not present in the subsurface of Dry Tortugas National Park. However, it is closely related to the Key Largo Limestone and is important with respect to the geologic history of the Florida Keys. The Miami Limestone has two facies that represent different environmental/depositional settings. The oolitic facies, which was deposited at the same time as the Key Largo Limestone but in a different environment, was deposited in a shallow, wave affected, high energy, nearshore environment. The bryozoan facies of the Miami Limestone was deposited in a slightly deeper, calm lagoon behind (landward of) the oolitic facies.
- Holocene Coral Reefs. The living coral reefs in Dry Tortugas National Park draw tourists and researchers alike. The reefs have been growing for the past 11,700 years and in some places are more than 15 m (50 ft) thick. They are home to more than 50 coral species. The benthic map of the park separates the Holocene coral reef complex into five broad categories: linear reef (includes reef terrace and remnant), spur and groove, reef rubble, patch reef, and patchy coral and/or rock in unconsolidated sediment.
- Unconsolidated Sediments. More than half of the seafloor in the park is covered by recent, unconsolidated sediments. These sediments make up the shallow sand banks. Due to the lack of stabilizing vegetation and coral, unconsolidated sediments are easily transported by flowing water. Sand ripples are common features.
- Pavement. Pavement is a type of flat, low relief, hardbottom. Hardbottom is a mostly solid rock substrate which may be overlain by a thin veneer of sand. Hardbottom is composed of either exposed bedrock or lithified non-bedrock seafloor. The pavement mapped in the park is entirely of the latter variety. It formed when algae or inorganically precipitated calcium carbonate partially cemented granular marine sediments on the seafloor.
- Seagrass Beds. Seagrass beds play an important role in the process of sedimentation. They trap sediment that would otherwise cloud the water and inhibit coral growth. Seagrass beds also protect marine organisms and coastlines against the impacts of waves and currents, which is especially important during storms and hurricanes that often threaten Florida.

- Islands and Sediment Transport. Seven small highly dynamic islands currently exist within the park. The islands are composed of carbonate sand and smaller amounts of coral rubble, with the exception of Loggerhead Key which contains the most extensive occurrence of beachrock in southern Florida. Carbonate sands and to a lesser extent coral rubble are easily transported by wind and water, especially during tropical storms and hurricanes. The size, shape and location of the islands are constantly in flux.
- Paleontological Resources. Fossils are the primary constituent of the bedrock limestone, coral reefs, sand banks, and islands of the Dry Tortugas. From a management perspective, the fossil material exposed at the surface is the most important for preservation. Interpretive and educational opportunities exist in the form of paleoecology (the fossils can show how the environment has changed over time) and dating (fossil material can be radiometrically dated).
- Geologic Materials Used in Fort Jefferson. Fort Jefferson is the largest masonry structure in the Americas. It is composed of more than 16 million bricks. Geologic materials such as clay, sandstone, and coral rubble were used in its construction.

Geologic issues of particular significance for resource management at Dry Tortugas National Park were identified during a 2005 GRI scoping meeting and a 2012 follow-up conference call. They include the following:

- Sea Level Rise. Sea level rise will affect all of the natural and cultural resources in the park. The islands, along with Fort Jefferson, are at risk from inundation. Coral reefs and other marine life will be forced to respond to changing environmental conditions. Further research and monitoring will provide information to help park managers understand how park resources will respond to sea level fluctuations and make timely decisions about the future of natural and cultural resources as sea level rises.
- Hurricane and Storm Impacts. The park is frequently affected by tropical storms and hurricanes. In a four-month period in 2005, four hurricanes impacted the park. Hurricanes and storms change the shape of the islands, create and destroy channels between islands, and sometimes cause islands to disappear entirely. These changes affect the ecosystems in the park, facilities on the islands (specifically on Garden Key), and accessibility.
- Coral Reef Rehabilitation. Dry Tortugas National Park protects pristine and remote coral communities. Although the reefs in the park appear stunning compared to the more easily accessible reefs along the Florida Keys to the east, their health has been declining since at least the 1980s. Coral disease outbreaks and bleaching are on the rise. Coral reef rehabilitation is a primary concern of resource managers. More research is needed to determine the cause of decline in stony coral cover and how to encourage new growth on reefs.
- Recreation and Commercial Uses. Intensive snorkeling, SCUBA diving, and boating activities can negatively impact natural resources, including coral reefs, although these activities apparently are not responsible for the decline of reefs in the park. However, in 2007, a no-take, no-anchor Research Natural Area was established in the park to protect marine life and benthic habitats. Baseline data has recently been established and ongoing monitoring has determined the Research Natural Area is improving the condition of resources within its boundaries.
- Sediment Accretion and Erosion. The landscape of the Dry Tortugas is constantly changing, sometimes quite rapidly. Islands regularly change shape, location, and size. A sand bridge intermittently joins Garden Key and Long Key. Resource management concerns include understanding the effects of channel closures and island migration on the marine environment.
- Subsidence. Fort Jefferson on Garden Key is unevenly subsiding atop the unconsolidated sands and coral rubble that compose the island. Resource management concerns include what steps should be taken to rehabilitate Fort Jefferson.
- Groundwater Flow and Salinity. Contaminants and nutrients present on the islands—particularly Garden Key, which receives the most visitor use—may be carried into the ocean by flowing groundwater. Further research is needed to determine groundwater flow patterns and how patterns are affected when the islands change shape as a result of sediment transport processes.
- Benthic Habitat Mapping. At the time of the scoping meeting in 2005, participants identified the need for a large scale, comprehensive benthic habitat map to assist with resource management. Waara et al. (2011) completed a benthic map for use in park management, thus addressing the issue identified during GRI scoping.

Acknowledgements

The GRI is administered by the Geologic Resources Division of the Natural Resource Stewardship and Science Directorate.

The Geologic Resources Division relies on partnerships with institutions such as Colorado State University, the US Geological Survey, state geological surveys, local museums, and universities to develop GRI products.

The Geologic Resources Inventory team would like to extend their appreciation to the following people for their assistance with this report:

- The participants at the 2005 scoping meeting (see Appendix A);
- Trista Thornberry-Ehrlich (Colorado State University, research associate) for providing the scoping summary, photographs, graphics, and references;
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Introduction

This section briefly describes the National Park Service Geologic Resources Inventory Program and the regional geologic and historic setting of Dry Tortugas National Park.

Geologic Resources Inventory Program

The Geologic Resources Inventory (GRI) is one of 12 baseline natural resource 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.

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

The objectives of the GRI are to provide geologic map data and pertinent geologic information to support resource management and science-based decision making in more than 270 natural resource parks throughout the National Park System. To realize these objectives, the GRI team undertakes three tasks for each natural resource park: (1) conduct a scoping meeting and provide a scoping summary, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report. These products are designed and written for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps, develop a geologic mapping plan, and discuss geologic issues, features, and processes that should be included in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan into digital geologic map data in accordance with their data model. Refer to the "Geologic Map Data" section for additional map information. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the geologic report. This geologic report assists park managers in the use of the map, and provides an overview of the park geology, including geologic resource management issues, geologic features and process, and the geologic history leading to the park's present-day landscape.

For additional information regarding the GRI, including contact information, please refer to the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/). The current status and projected completion dates for GRI products are available on the GRI status website (http://www.nature.nps.gov/geology/GRI_DB/Scoping/Quick_Status.aspx).

Park Setting

Dry Tortugas National Park is approximately 113 km (70 mi) west of Key West between the Gulf of Mexico and the Atlantic Ocean. The park boasts colorful and pristine coral reefs surrounding a cluster of seven small islands and central lagoon, and is known for spectacular marine life, nesting bird colonies, military history, and legends of pirates and sunken treasure. Visitors can only access the park by boat or seaplane.

The park was initially designated "Fort Jefferson National Monument" by presidential proclamation in 1935. The monument was established for the purpose of preserving the Dry Tortugas group of islands within the original 1845 federal military reservation of islands, keys, and banks (National Park Service 2006). Fort Jefferson, located on Garden Key, is the largest masonry structure in the Americas. In 1992 Congress redesignated, expanded, and renamed the national monument "Dry Tortugas National Park."

Geologic Setting

Dry Tortugas National Park is located near the southwestern edge of the Florida Platform (fig. 1). This broad, flat, carbonate platform is only partially exposed above sea level as the Florida peninsula. The submerged portion of the platform extends to water depths of approximately 90 m (300 ft). Beyond this point the sea floor drops abruptly to more than 3,000 m (10,000 ft).

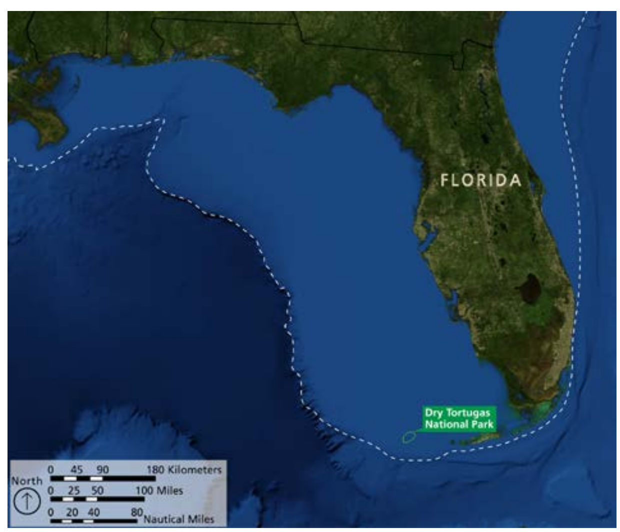

Figure 1. The Florida Platform. The white dashed line on the figure delineates the broad, flat, carbonate Florida Platform that is only partially exposed above sea level as the Florida peninsula. Dry Tortugas National Park is near the southern edge of the Florida Platform. Imagery from NASA Earth Observatory annotated by Rebecca Port (NPS Geologic Resources Division).

The Florida Platform has been accumulating sediments since the Atlantic Ocean basin began to form almost 200 million years ago. Carbonate rocks such as limestone and dolomite more than 5,000 m (15,000 ft) thick make up the platform and underlie Dry Tortugas National Park. These rocks continue to form on the submerged portion of the platform.

During the Pleistocene Epoch (2.6 million–11,700 years ago; fig. 2), sea level rose and fell repeatedly in response to advancing and retreating glaciers. During glacial periods, when a larger portion of Earth's water budget is stored as glacial ice, much of the platform was exposed and carbonate rocks were eroded. During interglacial periods the Florida Platform was largely submerged and coral reefs established themselves on the outside of the tiny Florida peninsula. As sea level dropped to its current location, the tops of these reefs were exposed and now make up the Florida Keys.

Today, coral reefs grow along the Florida Keys and at Dry Tortugas National Park. The Dry Tortugas are a complex of reefs, shallow sand banks, and low relief islands atop Pleistocene limestone bedrock of the Florida Platform (Multer 1977). The banks, reefs, and islands form a horseshoe shape around a central lagoon (fig. 3). Three channels connect the open ocean to the central lagoon.

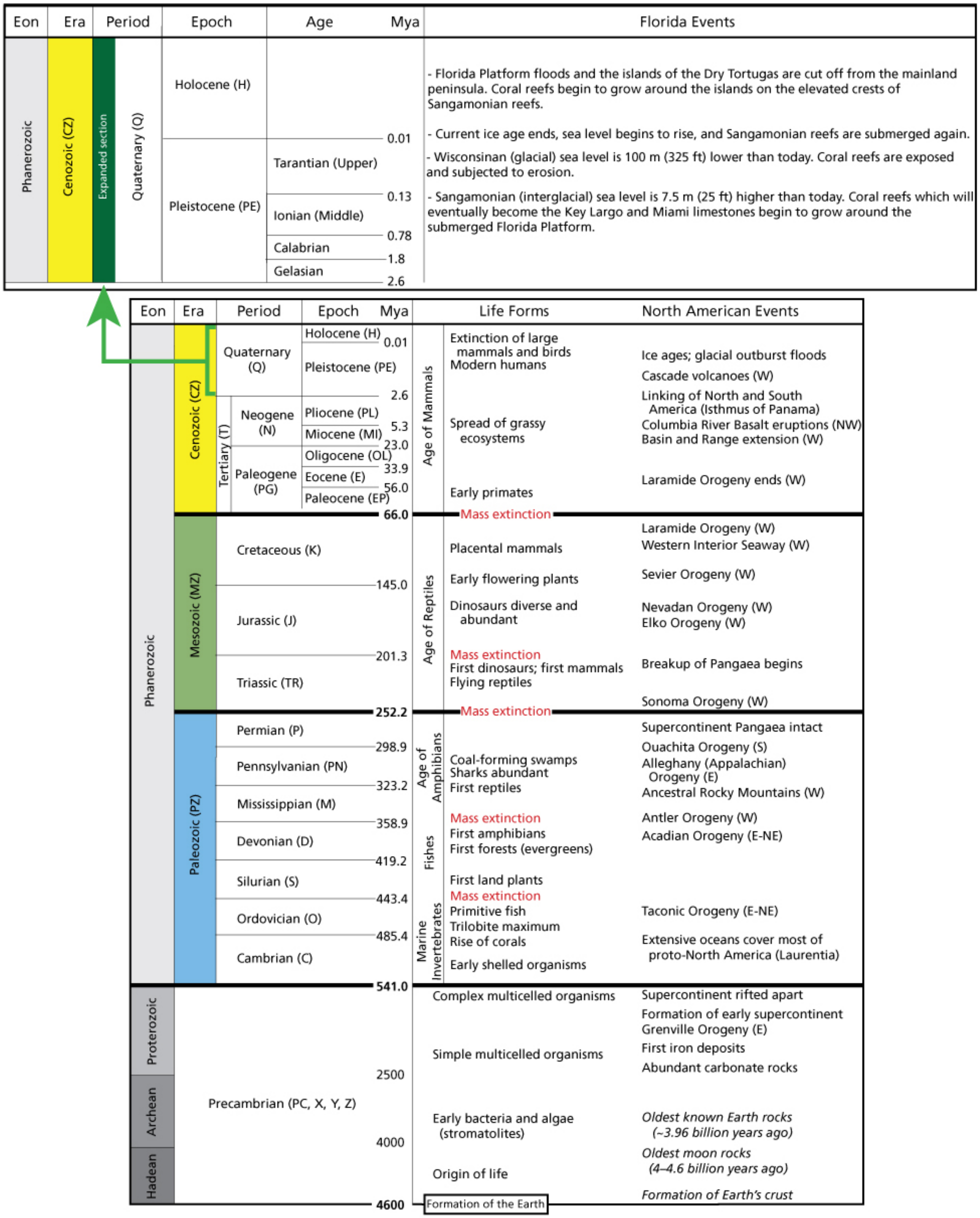

Figure 2. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest at the bottom and youngest at the top. GRI map abbreviations for each geologic time division are in parentheses. Boundary ages are in millions of years ago (Mya). Major North American and Florida life history and tectonic events are included. Compass directions in parentheses indicate the regional locations of events. Bold horizontal lines indicate major boundaries between eras. National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 10 January 2014).

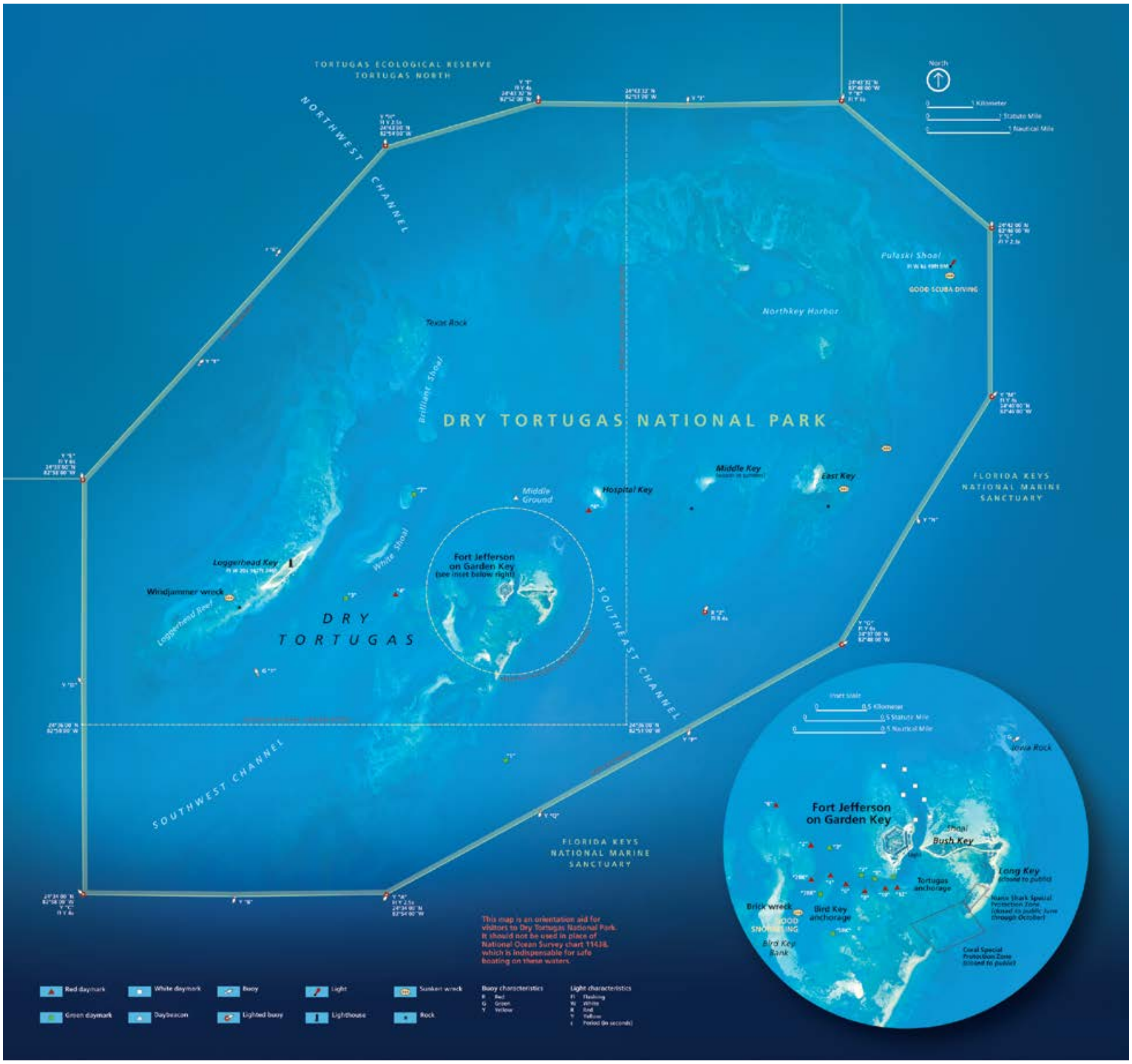

Figure 3. Location map of Dry Tortugas National Park. The green outline on the figure marks the boundary of Dry Tortugas National Park, which includes a complex of islands, reefs, and sand banks (shoals) encircling a central lagoon. The complex of features is roughly elliptical and is intersected by three channels. The white dashed lines inside the park indicate the boundary of the Research Natural Area (RNA). National Park Service graphic.

Geologic Features and Processes

Geologic resources underlie park ecosystems and geologic processes shape the landscape of every park. This section describes the most prominent and distinctive geologic features and processes in Dry Tortugas National Park.

Dry Tortugas National Park consists of slightly less than 262 km^2 (101 mi^2) of submerged lands and seven islands. The total area of the islands is about 0.4 km^2 (0.15 mi^2), although this figure fluctuates annually as a result of changes in sea level, hurricane and storm impacts, and sediment erosion and accretion. Together, the islands and shallow areas form a roughly elliptical shape around a deeper central lagoon (fig 2).

Geologic features in the park include the underlying bedrock, submerged lands, and seven islands. The bedrock is composed of Pleistocene coral reef limestone. The submerged lands contain a variety of benthic habitats, including Holocene coral reefs, seagrass beds, unconsolidated sediments, and pavement. The islands are made up of sand and reef rubble. The bedrock, submerged lands, and islands all contain the remains of prehistoric life and are therefore considered paleontological resources. In addition, the building materials that were brought to Garden Key for construction Fort Jefferson constitute a geologic feature.

This section of the report discusses these geologic features, their associated geologic processes, and their relationship to the benthic map GIS data (see attached CD) and map graphic (in pocket). The Pleistocene bedrock is not part of the benthic map GIS data because it is not exposed at the surface anywhere in the park. Similarly, the geologic material used in the construction of Fort Jefferson does not correspond to a unit in the benthic map GIS data.

The following geologic features are discussed in stratigraphic order; that is chronologically and vertically, starting with bedrock, and moving upward to submerged lands, islands, and anthropogenic structures:

- Pleistocene Bedrock
- Holocene Coral Reefs
- Seagrass Beds
- Unconsolidated Benthic Sediments
- Pavement
- Islands and Sediment Transport
- Paleontological Resources
- Geologic Materials Used in Fort Jefferson

All of the natural geologic features associated with the park have one thing in common—calcium carbonate ($CaCO_3$). The rock, reef, and sediments are all composed of materials that contain the carbonate ion (CO_3^{2-}). These may be minerals that have precipitated directly out of the sea water, such as calcite or aragonite, or they may be whole specimens or fragments of recent or fossil coral, mollusks, coralline algae, or foraminifera. Noncarbonate materials were transported to the site for construction of Fort Jefferson.

Pleistocene Bedrock

All of the Florida Keys, including Dry Tortugas National Park, is underlain by limestone. The limestone was deposited during the Pleistocene Epoch (2.6 million to 11,700 years ago; fig. 2). Two Pleistocene limestone formations, the Key Largo Limestone and the Miami Limestone underlie the Florida Keys. The two formations are, for the most part, contemporaneous (formed at the same time) (Bond 1986; Davis 1979; Harrison and Coniglio 1985).

The Key Largo Limestone underlies the upper and middle Florida Keys and occurs in the subsurface of Dry Tortugas National Park. The Miami Limestone is not known to occur beneath the park. It underlies the mainland in southeastern Florida and is exposed in the Lower Keys.

Key Largo Limestone

The Key Largo limestone is an exquisitely preserved fossilized coral reef (fig. 4). It is a white to light gray, moderately to well-cemented (Stanley 1966; Hoffmeister and Multer 1968) limestone with little to no siliciclastic (noncarbonate) sediment (Toscano et al. 2010). It consists primarily of intact coral heads embedded in a matrix of calcarenite, which is composed of sand-size carbonate grains (Hoffmeister and Multer 1968; Stanley 1966). The coral-head framework must have functioned as a trap for smaller fragments of coral, coralline algae, mollusk shells, and foraminifer tests.

Figure 4. Key Largo Limestone. Intact coral heads are visible in the Key Largo Limestone exposed at Windley Key Fossil Reef Geological State Park in Islamorada, Florida. Coral heads occur throughout the formation. Space between the coral heads has been filled with calcarenite (sand-size grains of other corals, mollusks, coralline algae, and foraminifera). Photograph by Johanna Gambrell (Boston University).

The framework corals are mainly boulder star coral (*Montastraea annularis*). Brain corals are also present. Nearly all of the coral species found in the Key Largo Limestone are extant in the modern reefs around southern Florida. *M. annularis* is currently the major component of patch reefs all over Florida (Shinn et al. 1989).

The Key Largo limestone formed in the Pleistocene Epoch during a warm period (interglacial) between ice ages when sea level was as much as 30 m (100 ft) higher than today. Mallinson et al. (1997) provided an age of 107,000 years before present (BP) for the top of the Key Largo Limestone in Dry Tortugas National Park. Age ranges between 144,000 to 120,000 years BP have been consistently calculated using radiometric dating of coral and mollusk fossils from other Key Largo Limestone locations outside of the park (Broecker and Thurber 1965; Osmond et al. 1965; Mitterer 1975; Muhs et al. 1992; Fruijtier et al. 2000).

The Key Largo Limestone crops out in the Upper and Middle keys, but is not exposed at the surface in the park or anywhere in the Lower Keys (fig. 5). In the park, the Key Largo Limestone underlies the living reefs and recent sediments. Sediment cores have verified its presence at various depths within the park and surrounding areas (fig. 6). For example in 1968, drilling as a part of geologic exploration intersected the limestone at 10 m (33 ft) below sea level in the westernmost Dry Tortugas (Hoffmeister and Multer 1968). Multer et al. (2003) provided a corrected chronology and stratigraphy for these data that showed the Key Largo Limestone occurring 16–17 m (52–-56 ft) below mean sea level. Cores drilled near the Marquesas Keys, east of the park, revealed Key Largo Limestone 8 m (26 ft) beneath modern reefs (Davis 1979). In all likelihood the upper surface of the Key Largo Limestone is not flat but has great topographical variation similar to a living reef.

Topography controlled by reef growth would explain why the Key Largo Limestone is encountered at various depths throughout the park and nearby locations. The variation may also be a result of erosion that occurred during the most recent glacial maximum when sea level was lower and the reef was exposed. Multer (1977) noted that the bedrock beneath Garden Key was found at an elevation considerably higher than the bottom of the channels between the keys of the Tortugas group of islands. This suggests that the relief of the Key Largo Limestone may be one of the factors controlling the present day location of the living reefs and islands within the park (Multer 1977).

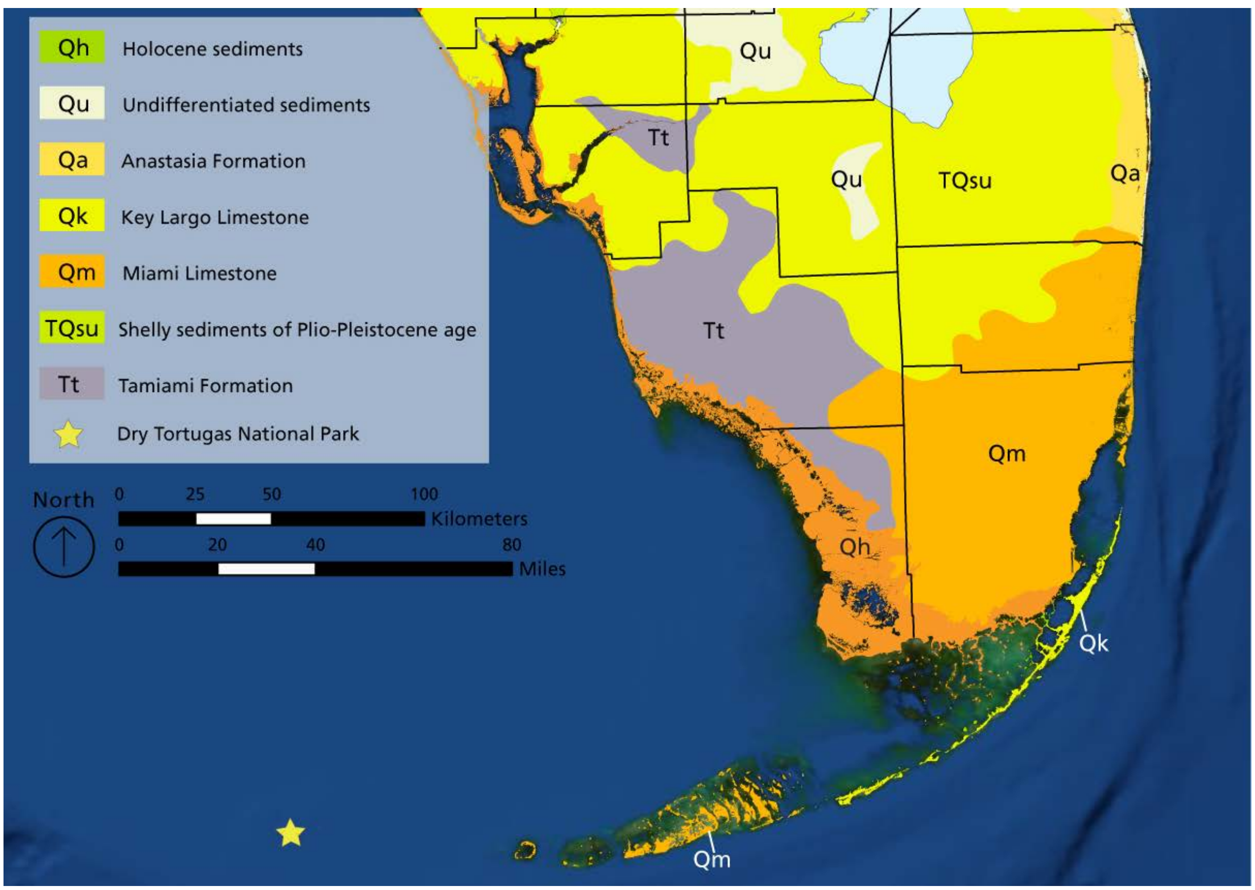

Figure 5. Geologic map of South Florida. This simplified map of South Florida shows the distribution of the Key Largo and Miami limestones. The Key Largo Limestone underlies the living reefs and recent sediments in Dry Tortugas National Park. Graphic compiled by Rebecca Port (NPS Geologic Resources Division) using geologic data produced by the Florida Geological Survey in cooperation with the Florida Department of Environmental Protection (Scott et al. 2001). Imagery from NASA Earth Observatory, available at http://earthobservatory.nasa.gov/ (accessed 17 September 2013).

Figure 6. Sediment cores. Drilling and resultant sediment cores revealed the Key Largo Limestone at various depths beneath islands and modern coral reefs within the park. The upper surface of the Key Largo Limestone is not flat; it shows great topographical variation, similar to a living reef. This variation may exert control on the locations of the islands and reefs within the park today. US Geological Survey photograph.

Miami Limestone

The Miami Limestone is a white to orangish gray, sandy, limestone of Upper Pleistocene age, about 125,000 to 100,000 years old. It is exposed in the southeastern region of the Florida mainland and in the southern part of the Florida Keys (fig. 5) (Scott et al. 2001). The Miami Limestone does not extend to Dry Tortugas National Park. The formation consists of two facies—an upper, cross-bedded, oolitic facies and a lower, bryozoan facies—that reflect deposition in two different environments (Hoffmeister et al. 1967).

The oolitic facies of the Miami Limestone is composed of ooids, named because of their resemblance to small eggs. Ooids are small, spheroidal grains, less than 2 mm (0.08 in) in diameter, that contain a nucleus, perhaps a shell fragment or quartz grain, which has been coated in one or more layers of fine calcite or aragonite crystals. Ooids are not considered fossils, even if their nucleus is a fossil, such as a shell fragment. Ooids typically form on shallow banks where warm, calcium–carbonate saturated water is driven toward the shore by tidal currents (Boggs 2001). The agitated water rocks the nucleii back and forth allowing the grains to become evenly coated in calcium carbonate which readily precipitates from the supersaturated water (Boggs 2001).

Rocks formed mainly of ooids, like the Miami Limestone, are called oolites. The ooids in the Miami Limestone are cemented together by calcite. Below the water table, ooids dissolve, leaving behind spherical and ellipsoidal cavities in a matrix of calcite cement (Hoffmeister et al. 1967). Above the water table, the ooids remain intact (fig. 7).

Cross-bedding in the oolitic facies of the Miami Limestone is further evidence of deposition in a high energy setting, such as a nearshore environment affected by waves and tides. Cross-beds appear in the rocks as nearly horizontal layers made up of internally inclined layers (fig. 8). The dip of the cross-beds varies throughout the sequence and represents changes in the direction and intensity of sediment transport similar to modern ooid shoal settings in the Bahamas (Hoffmeister et al. 1967; Bond 1986).

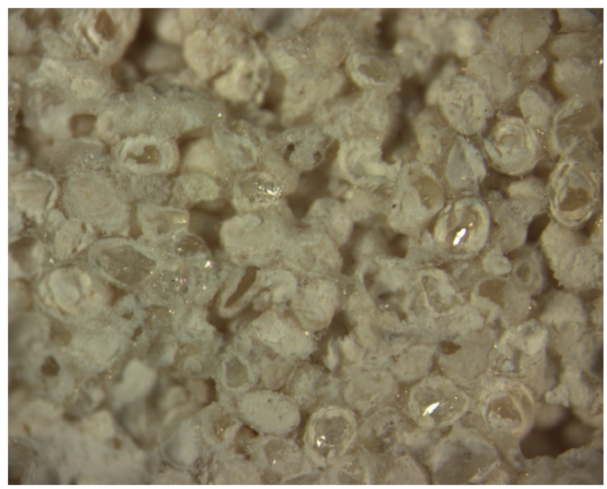

Figure 7. Ooids of the Miami Limestone. An outcrop at Victoria Park in downtown Fort Lauderdale displays ooids of the Miami Limestone. This outcrop is above the water table, therefore the ooids have not dissolved. Photograph by Anton Oleinik (Florida Atlantic University).

The bryozoan facies of the Miami Limestone is beneath the oolitic facies (fig. 9). This deposit is one of the most extensive bryozoan limestones in the country (Hoffmeister et al. 1967). Massive compound colonies of the bryozoan species *Schizoporella floridana* are the main constituent of this facies (Hoffmeister et al. 1967). Bryozoans are aquatic, invertebrate, filter feeders. They are animals, although they superficially resemble some plants and are often called "moss animals."
The bryozoan facies formed in calmer and slightly deeper water than the oolitic facies, most likely in a shallow lagoon similar to those in the Bahamas where living bryozoans thrive (Bond 1986; Hoffmeister et al. 1967).

Figure 8. Cross-bedding in the Miami Limestone. Cross-bedding is a signature of deposition in a high energy environment, such as a coast affected by waves and tides. Thin layers of bioturbated (disturbed by organisms) sediment separate the cross-bedded units. Preservation of bioturbated layers indicates that sediments accumulated in a calm environment. The alteration of bioturbated and cross-bedded layers indicates the environment must have changed back and forth from a deep to more shallow coastal setting. On the figure, the solid white lines bound nearly horizontal units. The red lines show the inclination of the internal ooid layers; inclination indicates flow direction (orange arrows). Photographs by Erin Fogarty-Kellis (Florida Atlantic University).

Today, in the Bahamas, ooids forming in the shoals are encroaching over bryozoan mounds as the lagoon fills in with sediment. A similar transition may have occurred in the Pleistocene which would explain the bryozoan facies location beneath the oolitic facies in the Miami Limestone.

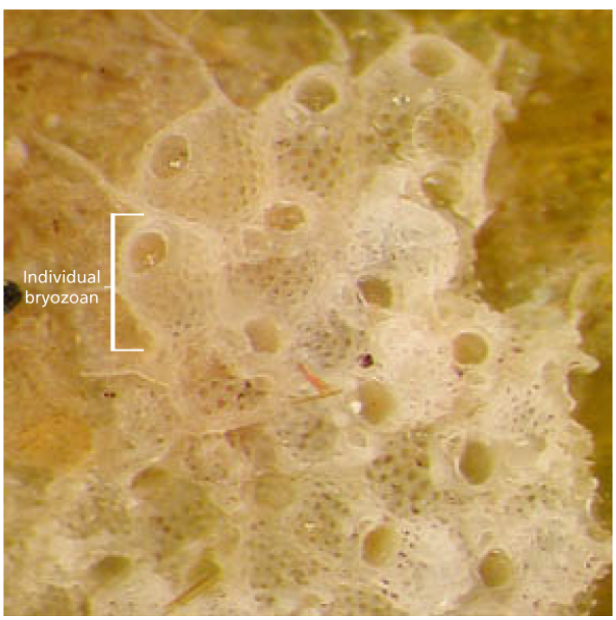

Figure 9. Bryozoan facies of the Miami Limestone. The bryozoan *Schizoporella floridana* is the main constituent of the bryozoan facies of the Miami Limestone. No scale is available for the photograph. However, individual bryozoans typically measure an average of 0.5 by 0.25 mm (0.02 by 0.01 in). Photograph courtesy of K. Hill (Smithsonian Marine Station).

Holocene Coral Reefs

The Holocene Epoch is the current period of geologic time. It began 11,700 years ago after the most recent ice age, and continues today. Throughout this period of time, the typically clear, warm waters of the Dry Tortugas have provided habitat for coral, which form reefs in the shallow waters along the edges of the islands and sand banks. Three major reef regions in the park are easily distinguished on aerial photographs; they are Pulaski Shoal to the northeast, Loggerhead Shoal to the west, and Southeast Reef (also referred to as Long Key/Bird Key Shoal) to the southeast (fig. 10).

The Holocene coral reef system of Dry Tortugas National Park forms an atoll-like rim around all seven islands, which in turn surround a central lagoon. However, the Dry Tortugas is not a true atoll. True atolls are nearly circular (in map view), enclose a lagoon, and are surrounded by deep oceanic water. Atolls typically form around submerged volcanic vents and are therefore common in the western and central Pacific Ocean. Because the reefs of Dry Tortugas National Park form a more elliptical shape than true atolls, and are located on the shallow Florida Platform, rather than in the deep ocean, they are more accurately called a "bank atoll" (Meeder 1979).

The overall atoll-like shape of the Holocene reef system at Dry Tortugas is the result of the preexisting topography formed by Pleistocene coral reefs (Multer 1977; Shinn et al. 1977). Holocene reefs developed on areas of elevated Pleistocene reef rock, rather than nearby shallow depressions, because this foundation was less likely to contain a veneer of fine, loose sediment, which interferes with coral development (Stone 1993). The shape of the modern reef system is probably very similar to the reefs of the Pleistocene Epoch. Comparisons to the Marquesas Keys east of the park show a very similar shape and separation of the reef into three regions (fig. 10). This distribution is most likely a result of prevailing currents and wind patterns.

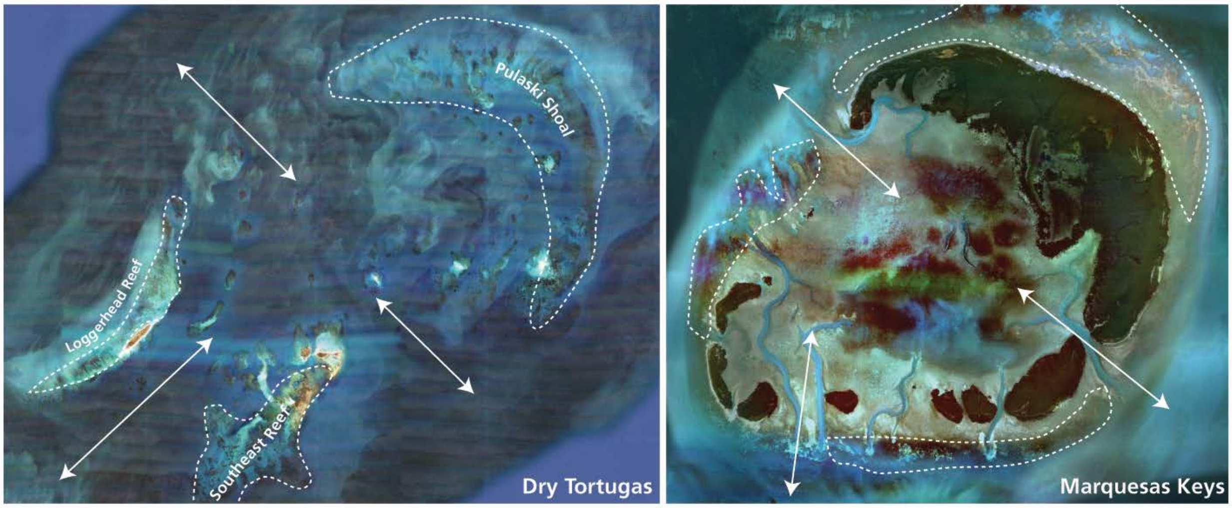

Figure 10. Major reef regions of Dry Tortugas and the Marquesas Keys. Both Dry Tortugas and Marquesas Keys have three major reef regions (outlined in dashed lines) intersected by channels (solid lines with arrows). The distribution of reefs and channels is similar in both locations and is most likely a result of prevailing currents and wind patterns. The Marquesas Keys are about 50 km (30 mi) west of Key West and 60 km (37 mi) east of Dry Tortugas. North is to the top of the images. Imagery from NASA Earth Observatory annotated by Rebecca Port (NPS Geologic Resources Division).

The reefs in the park are built from the skeletons of coral. Corals are animals belonging to the phylum Cnidaria, the same group as jellyfish and anemones. The coral animal is made of a group of polyps; each polyp resembles an upside-down jellyfish. Most corals form colonies from several to hundreds of polyps. Polyps of stony corals secrete a hard skeleton of calcium carbonate. The reefs are composed of layer upon layer of calcium carbonate secreted by coral polyps.

The Holocene coral reefs in the park are quite thick. Shinn et al. (1989) reported Holocene reefs as thick as 17 m (55 ft). Southeast Reef is the most continuous coral reef in the park with the best developed reef profile (fig.10 and 11). The reef beneath the ridge crest is 14 m (45 ft) thick.

More than 50 species of coral have been reported in Dry Tortugas National Park (Meeder 1979; Wheaton et al. 2006), where reefs have been constructed by the same stony coral assemblage as the underlying Key Largo Limestone. The dominant reef-building corals in the park today belong to the genera *Diplora*, *Montastraea*, and *Siderastraea*. These stony corals create the rigid framework upon and within which a variety of soft corals and algae thrive. Additionally, reefs support a wide variety of marine life including sponges, urchins, spiny lobsters, sea stars, clams, scallops, snails, fish, sharks, and sea turtles.

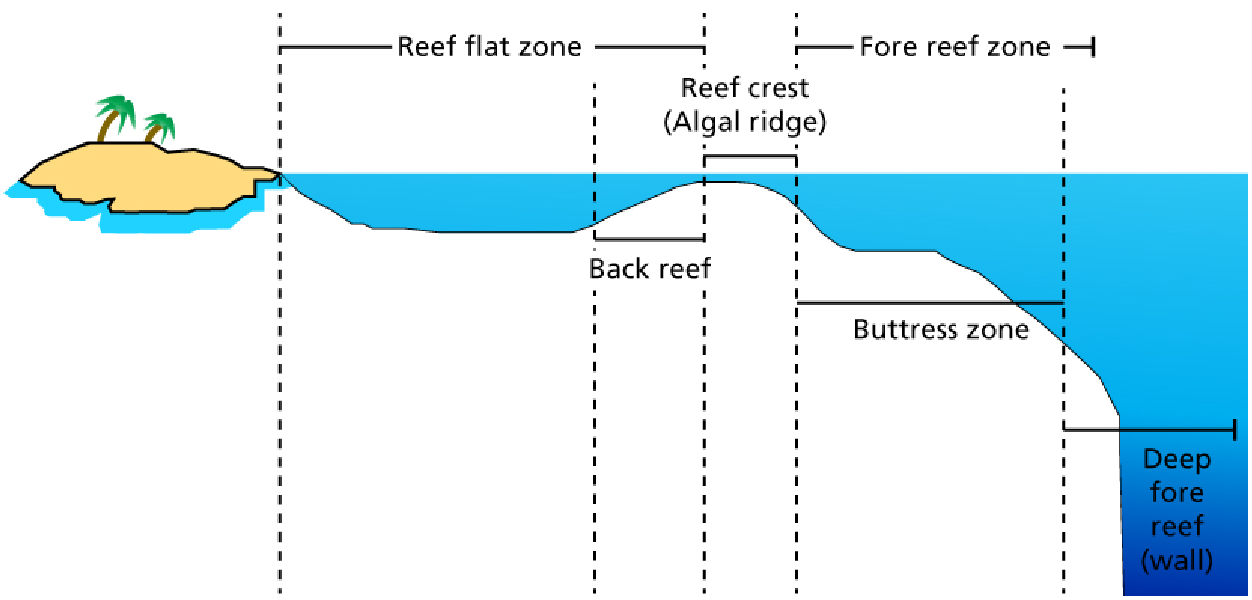

Figure 11. Cross section of a coral reef. The figure illustrates the typical zones in a reef complex. Linear coral reefs occupy the back reef, reef crest, and fore reef zones. Original graphic by Kyle Carothers (Cayman Islands Twilight Zone 2007 Exploration), modified by Rebecca Port (NPS Geologic Resources Division), available from NOAA Ocean Explorer Gallery at http://oceanexplorer.noaa.gov/explorations/07twilightzone/background/plan/media/reef_diagram.html (accessed 17 September 2013).

Two other coral species, although not dominant in the park, are important because of their past reef-building significance and current listing as "threatened" under the Endangered Species Act. The role and condition of elkhorn coral (*Acropora palmata*) (fig. 12) and staghorn coral (*Acropora cervicornis*) (fig. 13) are discussed in more detail in the "Geologic Issues" section.

Figure 12. Elkhorn coral (Acropora palmata). *A. palmata* is a threatened (proposed endangered) species under the Endangered Species Act. It is rare in the park, but can be found forming the spurs in spur and groove habitats within the Research Natural Area. Photograph courtesy of the Florida Fish and Wildlife Conservation Commission.

Figure 13. Staghorn coral (Acropora cervicornis). *A. cervicornis* is a threatened (proposed endangered) species under the Endangered Species Act found in the park. Photograph courtesy of the Florida Fish and Wildlife Conservation Commission.

The benthic habitat map by Waara et al. (2011) shows more extensive coral cover, approximately 34%,than earlier benthic maps completed for the park (figs. 14 and 15). For example, according to Davis (1979), coral reefs made up less than 4% of the sea floor shallower than 18 m (60 ft). The discrepancy in these figures is probably due to more inclusive criteria used in more recent mapping.

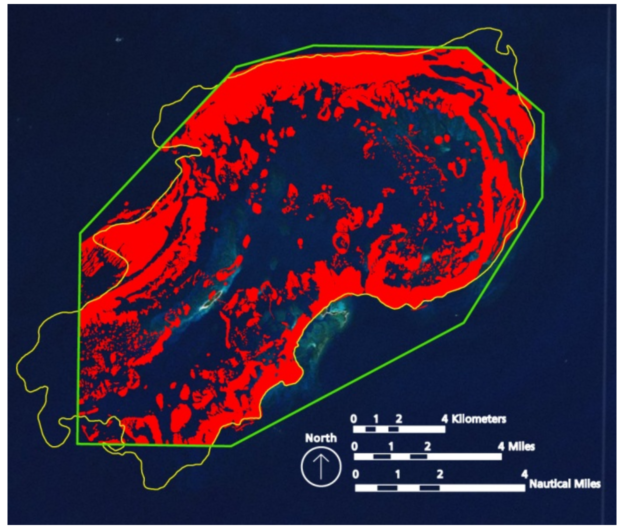

Figure 14. Coral cover in Dry Tortugas National Park. Waara et al. (2011) mapped coral cover (shown here in red) in the park. The yellow line is the 60 foot bathymetric contour, and the green line is the park boundary. Coral cover data courtesy of Waara et al. (2011) and bathymetry data courtesy of Mullins (1995). Graphic compiled by Rebecca Port (NPS Geologic Resources Division). Imagery from NASA Earth Observatory, available at http://earthobservatory.nasa.gov/ (accessed 17 September 2013).

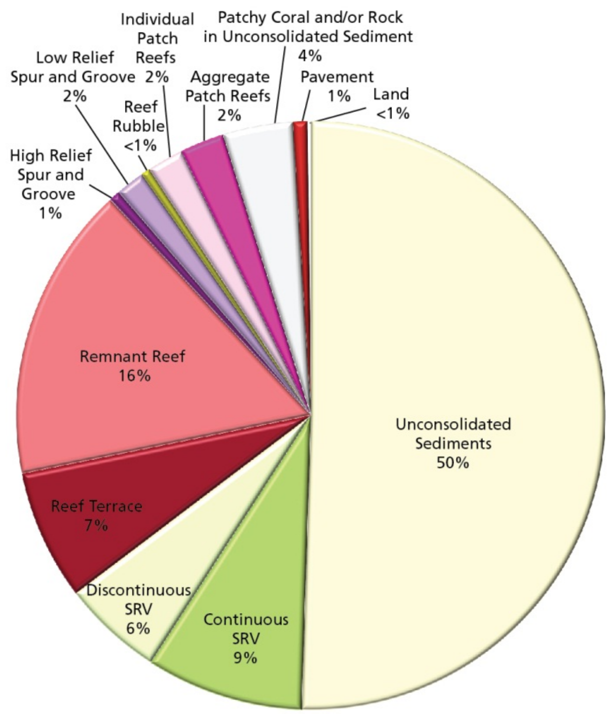

Figure 15. Percent cover of benthic units within Dry Tortugas National Park. The benthic habitat map for Dry Tortugas National Park by Waara et al. (2011) delineated 13 units (see also Benthic Map Graphic, in pocket). Graphic compiled by Rebecca Port (NPS Geologic Resources Division).

The 2011 benthic map divides coral cover into five broad categories: (1) linear reef (includes reef terrace and remnant), (2) spur and groove, (3) reef rubble, (4) patch reef, and (5) patchy coral and/or rock in unconsolidated bottom (Waara et al. 2011). The following subsections highlight these categories, and the Benthic Map Graphic (in pocket) illustrates the distribution of these categories

Figure 16. Reef terraces. Linear reefs with high complexity and high relief, greater than 2 m (7 ft), are called "reef terraces." They are often more mature and have a more developed reef profile than remnant reefs (see fig. 17). Photograph courtesy of NPS Submerged Resources Center.

Linear Coral Reefs

Linear reefs (also called "bank reefs" and "fringing reefs") are quasi-continuous bands of reef formations that include the back reef, reef crest, and fore reef zone (fig. 11). Based on relief, two types of linear reef are distinguished on the benthic map: Reef terrace (RT) is a category of linear reef with greater than 2 m (7 ft) relief (fig. 16). Remnant reef (RM) is a category of linear reef with less than 2 m (7 ft) of relief (fig. 17).

Figure 17. Remnant reefs. Linear reefs that lack distinctive spur and groove characteristics and have less than 2m (7 ft) of relief are called "remnant reefs." They are often found growing parallel to reef terraces. National Park Service photograph by Rob Waara.

Linear reefs are typically found in conjunction with spur and groove and reef rubble habitats. Spur and groove may develop on the fore reef side of linear reefs, whereas reef rubble often accumulates in the back reef zone. This distribution develops primarily in response to the impact of waves.

Spurs and Grooves

Spur and groove topography is common along the edges of modern and ancient linear reefs and usually occurs in the fore reef zone (fig. 11). Spurs are finger-like projections of the reef emanating seaward, perpendicular to the length of the reef crest (fig. 18). Spurs are separated by channels called grooves.

Spurs and grooves develop on the seaward side of linear reefs in response to wave impacts. They serve as breakwaters to dampen the energy of incoming waves (Shinn et al. 1989). Their presence is probably vital to the survival of the less wave resistant coral in the back reef zone.

Most spurs in the Caribbean and Florida are constructed of the relatively fast growing elkhorn coral (*A. palmata*) (Shinn et al. 1989). This species is rare in Dry Tortugas National Park and less than 4% of the benthic environment can be classified as spur and groove. Branches of coral that grow into the grooves break off during storms (Shinn 1963). Elkhorn coral reproduces by fragmentation, allowing it to regrow rapidly following storms. However, this ability is hindered if the coral has been affected by disease (see "Geologic Issues" section).

Two types of spur and groove topography are mapped in the park—high relief (map unit HRSG), which is 1.5 to 4 m (5 to 13 ft) (fig. 19), and low relief (LRSG), which is less than 1.5 m (5 ft). Bands of spur and groove exist in the park roughly paralleling linear reefs and forming a discontinuous ring. Low relief spurs occupy the northwestern perimeter of the park where wave energy is less intense. High relief spurs and grooves are prominent in the southeast where wave energy is higher.

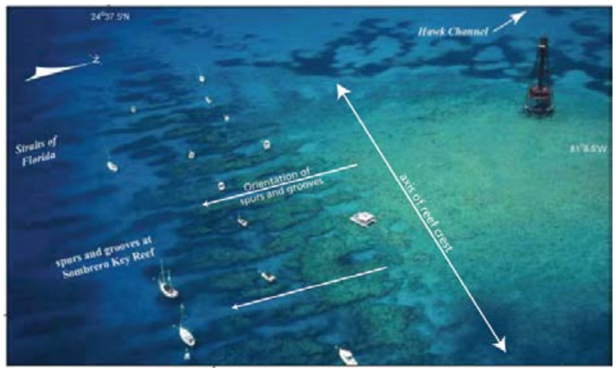

Figure 18. Spurs and grooves. These spurs and grooves are at Sombrero Key, approximately 160 km (100 mi) east of the Dry Tortugas. Spurs project seaward perpendicular to the axis of the linear reef crest. Note boats for scale. US Geological Survey photograph, annotated by US Geological Survey and Rebecca Port (NPS Geologic Resources Division).

Figure 19. High relief spur and groove topography. High relief spur and grooves develop seaward of linear reef crests in response to high wave energy. Spurs are dominated by fast growing coral, such as elkhorn coral, which can keep pace with the debris buildup produced by waves and storms. National Park Service photograph by Rob Waara.

Reef Rubble

Reef rubble is dead, unstable coral that usually occurs landward of linear reefs (fig. 20). Waves sweep fragments of storm damaged coral over the reef crest and toward land. Only a small portion of the benthic environment in the park is mapped as reef rubble (map unit RR) (fig. 15). The largest area of reef rubble occurs on the lagoon side of Southeast Reef. In addition, a small area of reef rubble occurs north of Bush Key and another along the eastern coast of Loggerhead Key.

Figure 20. Reef rubble. Dead, unstable coral rubble, called "reef rubble," is an outcome of storms and disease. Reef rubble often occurs landward of linear reefs where it has been swept by waves. National Park Service photograph by Rob Waara.

Patch Reefs

Patch reefs are irregularly shaped reef communities separated by non-reef habitat such as unconsolidated sediments and seagrass beds (fig. 21). Patch reefs may be surrounded by bare substrate, which is created by foraging reef species.

The patch reefs in the park are mostly located on the lagoon side of the islands and linear reefs. At the 1:2,000 scale of the benthic map, patch reefs are shown as either aggregated patch reefs (APR) or individual patch reefs (IPR). Aggregate patch reefs are clusters of patch reefs too small or close together to map separately. This type is concentrated in the far southwestern region of the lagoon. Individual patch reefs are more common in the northeastern part.

Figure 21. Patch reefs. Patch reefs are irregularly shaped reef communities separated by non-reef (often "bare") habitat. National Park Service photograph.

Patchy Coral and/or Rock in Unconsolidated Bottom

This category contains areas of sand, seagrass, low relief coral, and rock covered with a thin layer of sand (fig. 22). Only minor patches of coral are present, if at all. Such areas are commonly found adjacent to spurs and grooves as a result of sediments produced from the impact of waves on spurs. The largest area of patchy coral and/or rock bottom in unconsolidated sediment (map unit PCRUB) parallels high relief spurs and grooves in the southeastern region of the park.

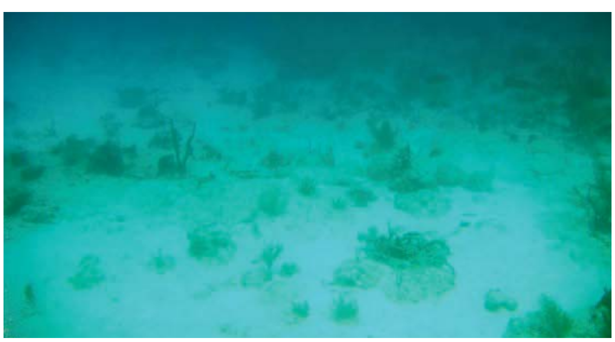

Figure 22. Patchy coral and/or rock in unconsolidated bottom. This map unit (PCRUB) covers 4% of Dry Tortugas National Park. Note the low relief and sparse coral patches, all of which is covered in a thin layer of sand. National Park Service photograph.

Seagrass Beds

Although seagrass is not a geologic feature, it plays an important role in the geologic process of sedimentation. Seagrasses increase sedimentation by trapping sands and other fine particles which would otherwise be carried away by wave activity or ocean currents. Seagrass roots and rhizomes also stabilize the seabed. Once established, seagrass beds provide protection to reef communities and shorelines against waves and coastal erosion.

Many varieties of marine life depend on seagrass. High sedimentation rates in seagrass beds increase water clarity, which is beneficial for coral growth. Small organisms find protection from predators and fast-moving currents in seagrass beds and associated sediment accumulations. Seagrass beds can serve as nurseries for juvenile reef fish species, which are commonly exploited by predators and overfishing (Kuffner et al. 2012). Seagrass also provides a source of food for foraging marine animals. The large—up to 30 cm (12 in) across—marine gastropod, queen conch (*Strombus gigas*) is common in the seagrass beds throughout the park (fig. 23). Queen conch is an Endangered Species Act candidate species. Collection is prohibited in Florida and adjacent federal waters.

Figure 23. Sparse continuous submersed rooted vascular plants. Queen conchs (*Strombus gigas*) forage in a sparsely vegetated area of seagrass and oligohaline grasses that compose continuous submersed rooted vascular (CSRV) plants. National Park Service photograph by Rob Waara.

Between 15% and 30% of the seafloor in Dry Tortugas National Park is covered by seagrass communities mapped as submersed rooted vascular plants (Davis 1979; Waara et al. 2011). These plant communities are classified as either continuous (map unit CSRV) (figs. 23 and 24) or discontinuous (DSRV) (fig. 25). The density of plants may be high or low in either category; the distinguishing feature is the amount of bare sediment. Continuous beds with minimal areas of bare sediment are typically located parallel to the linear reefs on the lagoon side. A large continuous bed is also present in the north-central region of the lagoon. Discontinuous seagrass separated by bare sediment is present in smaller spots adjacent to linear reefs.

Figure 24. Continuous submersed rooted vascular plants. This map unit (CSRV) covers 9% of Dry Tortugas National Park. This photograph was taken off the northwestern coast of Loggerhead Key. Note diver for scale. Photograph courtesy of NPS Submerged Resources Center.

Several seagrass species grow in the park. Turtle grass (*Thalassia testudinum*) dominates the shallow flats (< 2 m). The deeper grass beds are a mixture of turtle and manatee grass (*Syringodium filiforme*) stands with manatee grass gradually replacing turtle grass (Davis 1979) as depth increases, such as southwest of Pulaski Shoal. The very deepest parts of the lagoon are occupied by tape grass (*Halophila*) (Davis 1979).

Figure 25. Discontinuous submersed rooted vascular plants. This map unit (DSRV) may consist of seagrass and oligohaline grasses (shown here). The unit covers 6% of the park. National Park Service photograph.

Unconsolidated Benthic Sediments

More than half of the seafloor in the park is covered by unconsolidated sediments (map unit US) (fig. 15), specifically calcareous sand with less than 10% colonization by submersed vegetation or coral (Davis 1979; Waara et al. 2011) (fig. 26). Accumulations have been cored, dated, and assigned a Holocene age (Shinn et al. 1977; Mallinson et al. 1997; Multer et al. 2002). Unconsolidated sediments are easily transported by flowing water due to the lack of stabilizing vegetation or coral. Sand ripples are common features.

Sand grains that make up the unconsolidated sediments are from the same species as those typically found in the underlying older Key Largo Limestone. The unconsolidated calcareous sands consist primarily of particles of calcified algae of the genus *Halimeda*, along with varying quantities of fragmented coral, mollusk, and foraminifera. Sediment size varies. Gravel and sand are common in storm degraded shoals, whereas sand and silt are common in the lagoon (Jindrich 1972). Muddy carbonate sediments are found in the deepest areas of the lagoon (Shinn et al. 1989).

Figure 26. Unconsolidated sediments. This map unit (US) covers 50% of the park. Note the ripples in the sand formed by flowing water. National Park Service photograph.

Figure 27. Pavement. The unit (PVT) covers less than 1% of the benthic environment in the park. The pavement in the park was created when recent sediments cemented together during deposition (syndepositional cementation). National Park Service photograph.

Pavement

Pavement is a type of flat, low relief, mostly solid rock substrate (hardbottom). It may be overlain by a very thin layer of unconsolidated sediment (fig. 27). Pavement (map unit PVT) makes up a very small portion of the benthic environment (fig. 15). The largest area of pavement is located southwest of Loggerheard Key. Communities of soft corals, such as octocorals, are established on some portions of pavement in the park (Davis 1979).

Pavement may be exposed bedrock. However, the Key Largo Limestone bedrock does not crop out anywhere in the park. The pavement mapped in the park is actually a type of lithified, non-bedrock seafloor which forms where algae or inorganically precipitated calcium carbonate partially cement granular marine sediments (Stone 1993). This process is called syndepositional sedimentation (cementation that occurs during deposition). These recent sediments could be mistaken for ancient bedrock in remote sensing. However, confusion is much less likely in physical examination.

Islands and Sediment Transport

Presently, seven islands, called “keys,” exist in Dry Tortugas National Park (fig. 2). In order of decreasing size they are Loggerhead, Garden, Bush, East, Long, Middle, and Hospital. Key is the name given specifically to coral and sand islets or barrier islands off the southern coast of Florida.

Excepting Loggerhead Key, all of the islands consist of thick accumulations of unconsolidated Holocene sediments, more than 15 m (50 ft) thick in some cases. Sediments range from cobble-sized rubble to silt, and are composed of coralline algae (Halimeda sp.), coral and mollusk grains, and minor amounts of foraminifera (Jindrich 1972). Beach sediments show a high degree of sorting in all grain sizes (Jindrich 1972).

Because the islands are composed of recent, unconsolidated sand and coral rubble, not Pleistocene reef rock, they are dynamic in nature rather than stable relict features. Furthermore, wind, waves, and currents control the shape of individual islands. Because the islands are located between the Atlantic Ocean and the Gulf of Mexico, they are subjected to wind and waves on all sides. Their size, shape, and even existence are constantly changing. These changes can occur slowly (gradual net movement of sediment), rapidly (hurricanes and storms), or seasonally (storm, wind, and current patterns).

Gradual changes occur as a result of constant, average wave activity. Waves in Dry Tortugas are typically small, with heights averaging between 0.5 and 0.8 m (1.5 to 2.5 ft) (Pendleton et al. 2004). Sediment transport by average waves generated from prevailing winds tends to occur gradually. Prevailing easterly winds and waves run along the shelf and reef axis at the park and along the lower Florida Keys, causing a net westward movement of carbonate sand (Shinn et al. 1990). For example, North and Northeast keys, formerly adjacent to East Key, became submerged as they gradually migrated into the deep, central lagoon (O'Neill 1976).

Rapid and dramatic changes in island morphology are a result of hurricanes and storms. These changes can occur in as little as a few hours. Bird Key (formerly south of Long Key) was submerged following hurricanes in 1910 and again in 1919 (Davis 1982).

Seasonal effects of wave energies and shifting currents create recurring patterns of sediment transport (Brooks 1962; O'Neill 1976; Davis 1982). For example, Middle Key is typically awash in the summer.

The following sections describe features and processes of the seven islands located within the park.

Loggerhead Key

Loggerhead Key is the largest island in Dry Tortugas National Park. It is approximately 1,430 m (4,690 ft) long by 200 m (650 ft) wide and its highest point is 3 m (10 ft) above sea level on the northeastern tip of the island (Ginsburg 1953). Loggerhead Key is a 14-m- (45-ft-) thick accumulation of coarse and medium size calcium carbonate sand.

Beachrock

Loggerhead Key is unique among the islands of the park because it is the only one with outcrops of beachrock (fig. 28). Loggerhead Key contains the most extensive beachrock deposit in southern Florida (Davis 1979).

Beachrock is a sedimentary rock that forms underneath a thin layer of unconsolidated sediments along some shorelines. It lithifies relatively quickly, often in only a few years, as shallowly buried beach sediment is cemented by calcite or aragonite remaining from the evaporation of salt water during low tide (Multer 1977). Beachrock typically occurs in fractured blocks inclined toward the sea. As coasts erode beachrock may become exposed. Because beachrock forms more or less at sea level, exposed beachrock is an excellent indicator of past sea levels.

On Loggerhead Key the beachrock surface is pitted and jointed and is composed mainly of mollusk shells, coralline algae, coral, and encrusting algal debris (Multer 1977). The degree of cementation varies throughout, so the beachrock is friable in some places and very hard in others (Multer 1977). The beachrock on Loggerhead Key dips between 5° and 15° (Multer 1977).

Loggerhead Key is one of the more stable islands in the park. Erosion is minimal due to the protection afforded by the extensive beachrock deposits. The central portion of the island has remained virtually unchanged since at least 1922 (Pendleton et al. 2004) (figs. 29 and 30). Accretion and erosion of sediments primarily occurs at the northeastern and southwestern tips of the island where unconsolidated sand dominates.

Figure 28. Beachrock. Well-cemented, carbonate sand and gravel form beachrock on Loggerhead Key in the park. Beachrock reinforces the island and limits erosion. Photograph courtesy of NPS Submerged Resources Center.

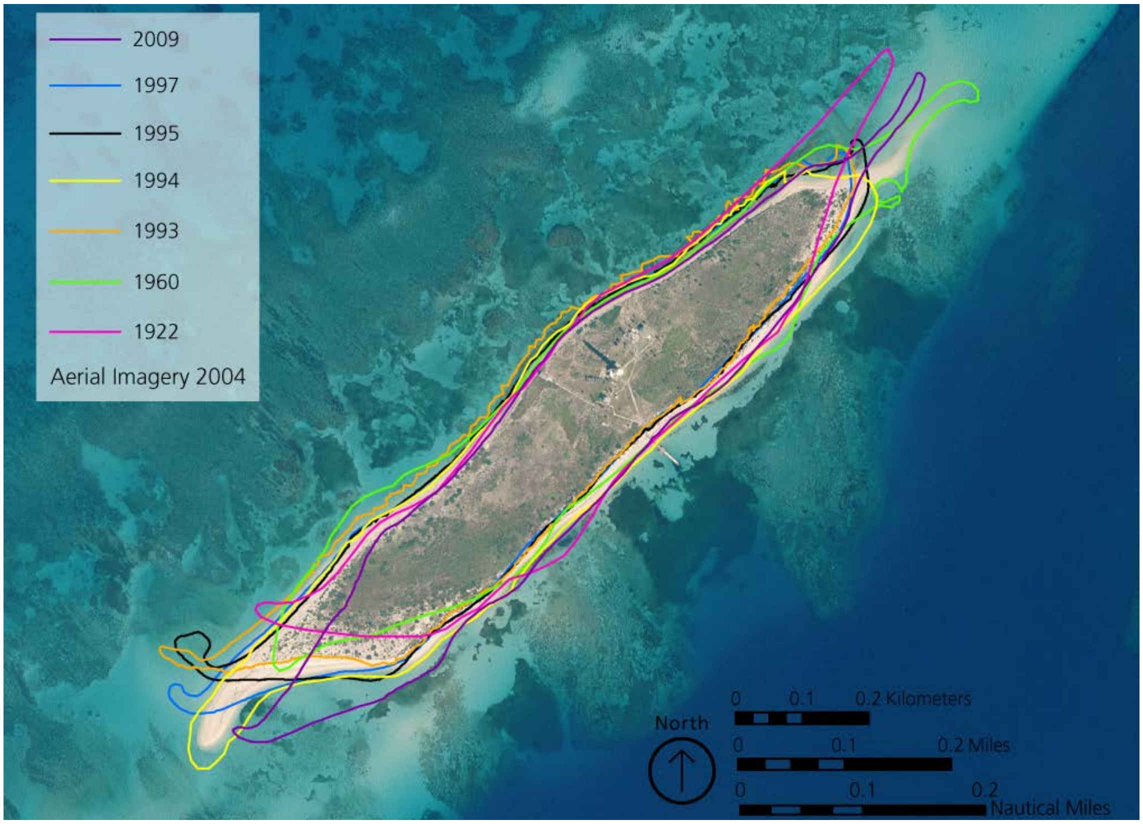

Figure 29. Shoreline change on Loggerhead Key. Shoreline change on Loggerhead Key has been minimal in large part due to the presence of extensive outcrops of beachrock. Note that the most change occurred at the northeastern and southwestern tips of the island which lack stabilizing vegetation or beachrock deposits. The central part of the island has remained relatively stable since surveying began in 1922. Graphic compiled by Rebecca Port (NPS Geologic Resources Division) with data from Mullins (1993b 1995, 1997), Pendleton et al. (2004), and Patterson (unpublished data). US Geological Survey imagery, taken in 2004.

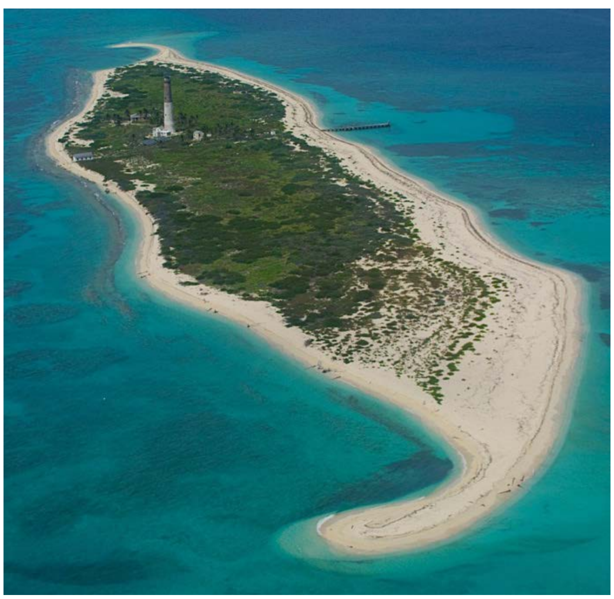

Figure 30. Aerial photograph of Loggerhead Key. The sand spits at each end of the island are frequently reshaped by storms and waves while the center of the island has remained relatively stable for at least the last 100 years. This photograph was taken on 14 July 2010. As of 7 March 2013 the spits at the end of the island are not nearly as curved. North is to the top left corner of the image. Photograph courtesy of NPS Submerged Resources Center.

Garden Key

Garden Key is approximately 0.09 km^2 (0.02 mi^2) with a diameter of about 325 m (1,070 ft). It consists of unconsolidated Holocene calcareous sediments, with an age of 9,330 years ago BP (Multer et al. 2002). Cores taken on Garden Key show these sediments extending to 16 m (52 ft) beneath the surface, beyond which lies the Pleistocene Key Largo Limestone (Multer et al. 2002).

Garden Key is almost entirely occupied by Fort Jefferson. Because of the fort, the island appears hexagonal in map view (fig. 31). A moat surrounds the main part of the island where the fort is located. A strip of land is present on the outside of the moat to the east. Ruins of a north and south coaling dock as well as an active dock and slip occupy this strip. Refer to the “Geologic Materials Used in the Construction of Fort Jefferson” section for additional information about the fort. Resource management issues associated with the structure are described in the “Geologic Issues” section.

Sediment transport processes have not proceeded at a natural rate on Garden Key since the construction of the fort which began in 1846. The fort has stabilized the main part of the island. However, erosion and accretion of sediment has occurred along the narrow strip of land on the east side of the key. Resource management issues associated with the erosion of this area are described in the “Geologic Issues” section.

Figure 31. Aerial photograph of Garden Key. Fort Jefferson stabilizes the main part of the island. The sandy stretch of land along the eastern coast of Garden Key experiences erosion and accretion of sediments. This photograph was taken on 14 July 2011. North is to the top of the photo. Photograph courtesy of NPS Submerged Resources Center.

Bush and Long Keys

Bush and Long keys are to the east of Garden Key. Bush Key is elongated in an east–west orientation. It is approximately 760 m (2,500 ft) long and ranges from 25 to 185 m (80 to 610 ft) wide. Long Key is oriented perpendicular to and east of Bush Key. It spans approximately 400 m (1,310 ft) in a north–south direction and is about 35 m (115 ft) wide.

As of September 2013, the two keys connect at the eastern end of Bush Key and the northern end of Long Key via a sand bridge. This sand bridge fluctuates in thickness and at times may disappear completely. The park's brochure published in 1994 shows no connection between Bush Key and Long Key (fig. 32). However, aerial images show the sand bridge started to build as early as 1995 and has been increasing in thickness. The sand bridge is presently about 30 m (100 ft) wide.

Long Key has changed shape dramatically over the last 100 years (fig. 33). Long Key is small, has little stabilizing vegetation, and its orientation subjects a good part of the island to incoming waves from the east.

Bush Key is slightly more stable than Long Key, but like Long Key has changed shape considerably over the last 100 years (fig. 33). Bush Key is famous for its colony of sooty terns (*Onychoprion fuscatus*) nesting on the island every year from April to September. Because sooty terns nest directly in the sand, changes to the island size and shape are monitored regularly by NPS staff.

Figure 32. Location map of Dry Tortugas National Park. This 1994 map of the park shows a small channel (red arrow) between the eastern end of Bush Key and the northern end of Long Key. Based on aerial images, this channel began to close sometime after 1995 and has remained closed through September 2013. National Park Service graphic.

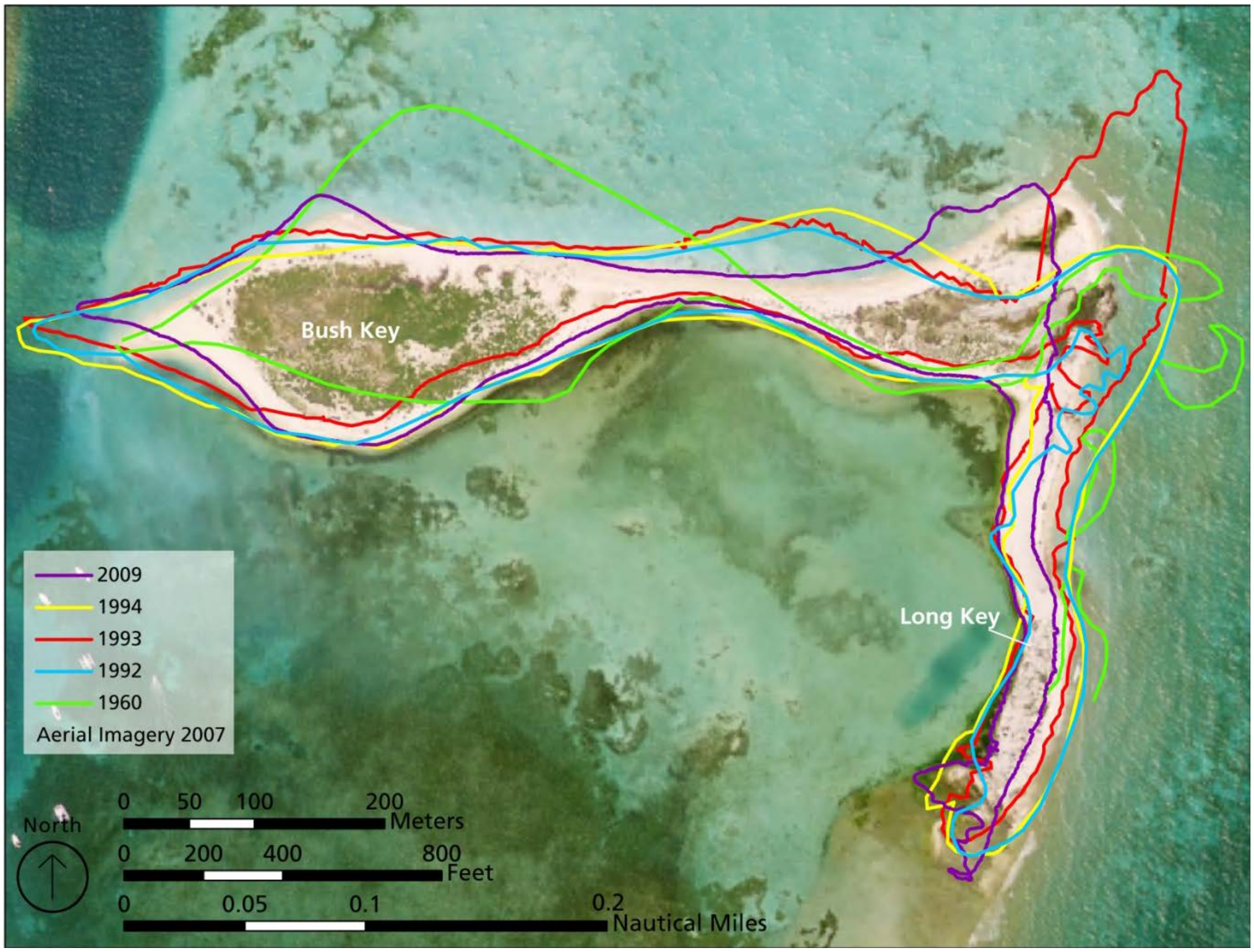

Figure 33. Shoreline change on Bush and Long keys. Long Key has changed dramatically, whereas Bush Key is slightly more stable. Graphic compiled by Rebecca Port (NPS) using data by Mullins (1992, 1993a), Pendleton et al. (2004), and Patterson (unpublished data). Imagery from the National Agriculture Imagery Program, taken in 2007.

Today, Bush Key is elongated east–west, with a wider western end. However, 60 to 70 years ago Bush Key was much rounder. The island has been building to the west and moving toward Garden Key (Bob Howard, manager assistant, Dry Tortugas National Park, conference call, 13 March 2001). An emerging concern among park biologists has been a speedy erosion of the eastern end and other sections on the northern side. Between 2009 and 2012, about 1.2 ha (3 ac) of the island was lost to erosion. Mangroves that anchored the eastern side have been lost entirely (Judd Patterson, GIS specialist, NPS South Florida/Caribbean Network, personal communication, 6 September 2013). In 2005, Hurricane Katrina dramatically affected the contours and shape of the island (see “Geologic Issues” section).

A notable feature of Bush Key is the channel which separates it from Garden Key. This channel has opened and closed repeatedly, a process that has created resource management issues. For more information about the history of the channel and associated management issues refer to the “Geologic Issues” section.

East Key

East Key is atop a shallow bank and elongated roughly north–south. It consists of coarse sand and fine gravel, and currently lacks beach rock, though beachrock was once reported by the US Army (Manucy 1961). Storm processes produced high sand ridges on the eastern side of the island. Of the three smallest islands, East Key is the only key that has consistently been vegetated; records extend back as far as 1904 (Judd Patterson, personal communication, 6 September 2013). Due to vegetation, the island’s central part is the most stable, with significant changes occurring in the northern and southern regions (fig. 34).

East Key is one of the most dynamic islands in the park. It displays long term and seasonal changes in shape, size and location (Davis and O’Neill 1979). Since the turn of the 20th century, the area of the island has decreased significantly. Bowman (1918) reported a size of 533 m (1750 ft) by 267 m (875 ft), Davis (1942) measured 364 m (1194 ft)by 181 m (594 ft), and O’Neill (1976) surveyed 262 m (860 ft) by 120 m (394 ft). The entire island has been migrating to the southeast; between 1898 and 1960 the island moved nearly 200 m (656 ft) (O’Neill 1976) (fig. 34).

Additionally, notable seasonal changes take place on East Key. During the spring and summer, waves pushed by the dominantly southerly winds erode the southern part of the island and accrete sand on the north. During the winter, northerly winds (stronger, but for shorter duration than the spring and summer winds) dominate and cause the opposite effect. This documented cycle does not account for hurricanes (Davis and O'Neill 1979).

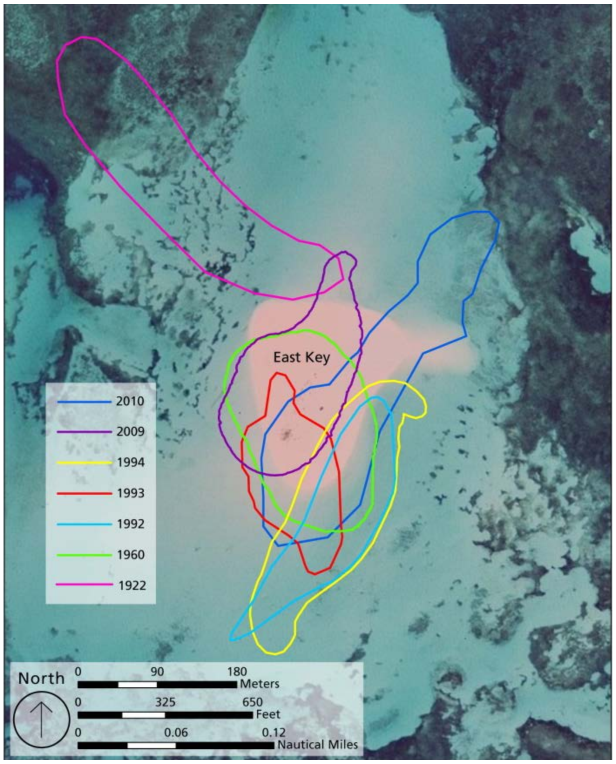

Figure 34. Shoreline changes to East Key. East Key is one of the most dynamic islands in the park. Vegetation helps to stabilize the central part. Graphic compiled by Rebecca Port (NPS Geologic Resources Division) using data by Mullins (1992, 1993a), Pendleton et al. (2004), Waara et al. (2011), and Patterson (unpublished data). Imagery from the National Agriculture Imagery Program, taken in 2010.

Middle and Hospital Keys

Middle and Hospital keys are sand islands that have been present for more than 50 years. Middle Key is typically awash in the summer but reemerges annually. These are the smallest keys within the park, both averaging less than 0.5 ha (1.2 ac).

Paleontological Resources

Paleontological resources are any remains of past life preserved in a geologic context, including body fossils such as the calcium carbonate skeletons of corals, shells of mollusks, and remains of coralline algae. All of the geologic materials within the park, from the surficial Holocene reefs and island sediments down to the underlying Pleistocene limestone rock, contain fossils. From a management and preservation perspective, the paleontological resources of primary concern are those that are immediately accessible such as the substrate of the islands and the carbonate material of the shallow marine areas in the park (Toscano et al. 2010). Fossils within these units include corals, mollusks, invertebrates, microfauna, and calcareous algal remains (Toscano et al. 2010).

Geologic Materials Used in Fort Jefferson

Clay

Fort Jefferson, located on Garden Key in Dry Tortugas National Park, is composed of more than 16 million bricks. It is the largest masonry structure in the Americas. All of the bricks were transported from hundreds of kilometers away (fig. 35). They can be grouped into two general categories—"Southern bricks" and "Northern bricks." Southern bricks were manufactured from clay along Escambia Bay located in the far western panhandle of Florida, near Pensacola (Anderson 1988). Southern bricks were used when construction on the fort began in 1846. However, as the country advanced toward the Civil War, southern brickyards became reluctant to supply bricks for the construction of a federal fort. Thus Northern bricks began to be shipped great distances to the Tortugas. The Northern bricks came from brickyards in Danvers, Massachusetts, and Brewer, Maine. These bricks are darker in color than the Southern bricks and somewhat more resistant to erosion.

Granite

Stone was also used in fort construction where larger and stronger materials were required. Steps, lintel stones, and traverse circles in gun emplacements are composed of granite from New York and Vermont (Murphy 1993) (fig. 35). Granite is an intrusive igneous rock, which means it formed from magma that cooled deep beneath Earth's surface. Granite is exposed at the surface today where erosion has removed overlying material. Granite is a popular building stone throughout the world.

Sandstone

Sandstone, referred to as "bluestone slate" by Anderson (1988), was used as flooring in casemates (the structure from which guns were fired from inside the fort) and for manhole covers (fig. 36). Geologically, "bluestone slate" is not technically slate, but refers to a group of sandstones classified as feldspathic greywacke. This type of rock contains angular grains in a fine, clay matrix. It typically appears bluish gray in color. Bluestone slate was quarried extensively in Pennsylvania and New York (fig. 35). The sand-size grains now constituting the rock are eroded material from the Acadian Mountains (ancestral Appalachians) which were deposited in the Catskill Delta during the Middle to Upper Devonian Period, some 380 million years ago.

Local Materials

Coral rubble from outlying reefs and local sand was used to make the concrete infill that comprises the bulk of the fort walls. Mortars for laying brick consisted of local sand, natural cement (mined from Rosendale, New York), and sometimes lime. Concretes and mortars were mixed on site using local materials such as sand, coral, and water (K. Clark, Dry Tortugas NP, written communication, 9 April 2014).

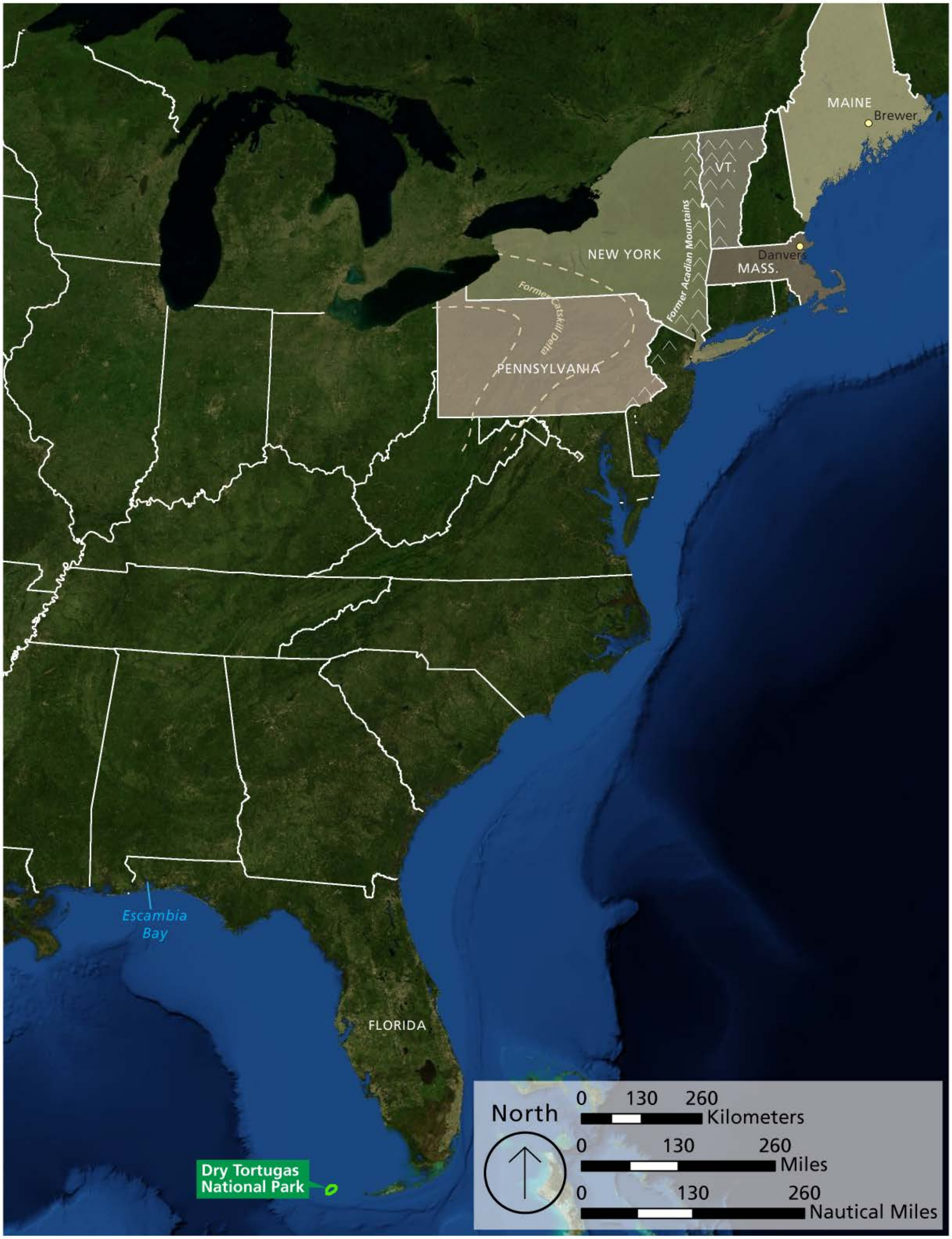

Figure 35. Origins of building materials. Materials used in the construction of Fort Jefferson were transported great distances. Initially, bricks were shipped from manufacturers in the Florida panhandle using clay from Escambia Bay. Later, bricks were shipped from Danvers, Massachusetts, and Brewer, Maine. Granite was quarried throughout New York and Vermont. Sandstone, referred to as "bluestone slate," was sourced from New York and Pennsylvania where it was deposited 380 million years ago in the Devonian Catskill Delta as the ancestral Appalachians eroded. Graphic by Rebecca Port (NPS Geologic Resources Division).

Figure 36. Interior of Fort Jefferson. More than 16 million bricks make up Fort Jefferson. The floors of the casements were constructed with "bluestone slate," which is actually a sandstone quarried in Pennsylvania and New York. National Park Service photographs.

Geologic Issues

Geologic issues described in this section may impact park resources or visitor safety and could require attention from resource managers. Contact the Geologic Resources Division for technical and policy assistance.

During the 2005 scoping meeting and 2012 conference call, the following geologic resource management issues were identified:

- Sea Level Rise
- Hurricanes and Storms
- Coral Reef Rehabilitation
- Recreation and Commercial Uses
- Sediment Erosion and Accretion
- Subsidence
- Groundwater Flow and Salinity
- Benthic Habitat Mapping

Sea Level Rise

Nearly all of the land area at Dry Tortugas National Park is at or within 3 m (10 ft) of sea level. Almost half of the park's coastlines are highly vulnerable to the physical effects of sea level rise (Pendleton et al. 2004) (fig. 37). Sea level rise will impact low-elevation areas and threaten land-based cultural resources and infrastructure via inundation and increased erosion. Moreover, sea level rise will affect coral reef communities.

The slope, or steepness, of a coast dictates how quickly the ocean will inundate the land under rising sea level conditions (Pilkey and Davis 1987). The coastal slope of islands in Dry Tortugas National Park is between 0.3% and 0.6% (Pendleton et al. 2004). Because of the very gentle slope, inundation will be rapid as sea level rises.

Within the past 16,000 years, sea level has risen rapidly (Intergovernmental Panel on Climate Change 2007). Sea level at Key West has been rising at an average rate of 2.24 mm (0.09 in) per year based on data collected by the National Ocean and Atmospheric Administration (NOAA) from 1971 to 2006. If sea level continues to rise

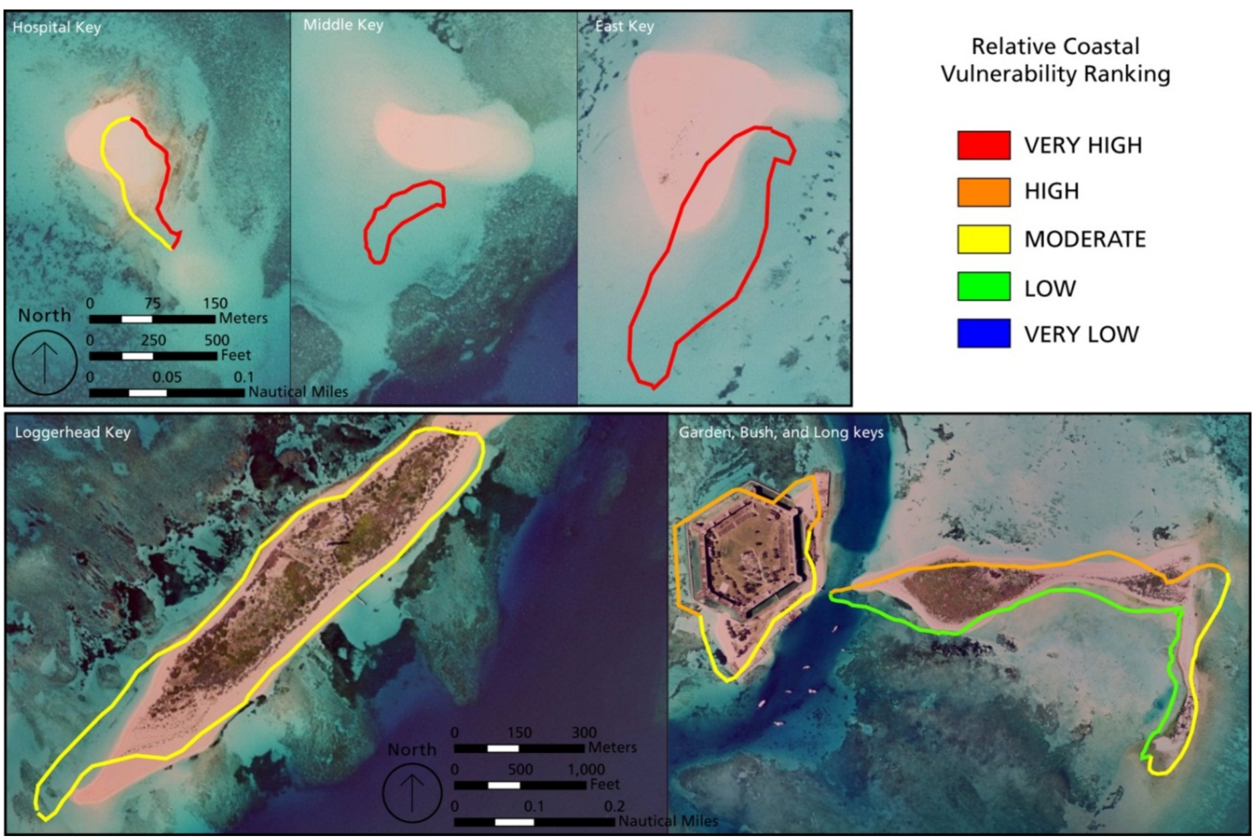

Figure 37. Relative coastal vulnerability ranking. Pendleton et al. (2004) provided a coastal vulnerability assessment for the islands of Dry Tortugas National Park. The coastlines of Hospital, Middle, and East keys were ranked most vulnerable. Note that the 2004 data do not line up with the aerial image taken in 2010, demonstrating that a great deal of change has occurred in a short amount of time. Graphic compiled by Rebecca Port (NPS Geologic Resources Division) with data from Pendleton et al. (2004). Imagery from the National Agriculture Imagery Program, taken in 2010.

as projected by the Intergovernmental Panel on Climate Change (2007), the islands of Dry Tortugas National Park along with the Florida Keys and large parts of the mainland will become submerged, which will, in turn, affect coral reef communities, ocean currents, and weather patterns (Davis 1997).

The coral reefs of Dry Tortugas may survive rising sea level if their upward growth rate is fast enough to offset the rising sea, thus keeping the coral within its preferred water depth, generally shallower than about 18 m (60 ft) in this area. If the corals cannot keep pace with rising sea level, they will eventually become drowned beneath their critical growth depth. The major reef builders *Montastraea annularis* and *Acropora palmata* should be able to keep pace with rising sea level (Lewis et al. 1968; Hudson 1981). However, growth rates alone will not determine the longevity of these reefs. Changes in water temperature, salinity, chemistry, and sediment content, which may accompany sea level rise, will have deleterious effects on the reefs.

If sea level continues to rise at its current rate, sedimentation will also continue. The Florida Keys reef track would eventually become buried thus exposing Florida Bay to much stronger wave action. The sediments of Florida Bay would shift from largely lime-mud dominated to sand and the bay itself would migrate inland across the Everglades and toward Lake Okeechobee (Davis 1997).

If sea level were to stabilize, the entire Florida Keys reef tract, including the Dry Tortugas, would eventually fill with sediments and become land. Based on accumulation rates calculated by Shinn et al. (1989), under constant sea level conditions very little land will remain along the reef tract in as little as 18,000 years. The reefs would be forced to accrete outward and away from the platform and into the Straits of Florida. Sediments would begin creating larger beach environments behind the reefs. The area in the center of the Dry Tortugas atoll-like feature would shift from a lagoonal environment dominated by seagrass to a peat-forming swamp where water is pooled with restricted outlets, then to a more arid evaporitic tidal flat environment (Shinn et al. 1989).

Because 18,000 years into the future is beyond the scope of "normal" park planning, the impacts of stabilized sea level are not a principal concern for resource management. Rather, the impacts of rising sea level—which will be felt much sooner, perhaps in only a few years—are critical. Therefore, an understanding by resource managers of how the islands in the park will respond to sea level rise is necessary to determine possible means for preserving coastal resources. Further research and monitoring of coral growth rates and rates of sedimentation are needed to determine how the environments at Dry Tortugas National Park will respond to sea level rise.

Hurricanes and Storms

Hurricanes and storms have had serious impacts at Dry Tortugas National Park, striking the islands about once every five or six years over the past 100 years. During the early 2000s, hurricanes impacted the islands much more frequently. In 2004, Hurricane Charley passed directly over the park. Within a four-month period in 2005, four hurricanes (Dennis, Katrina, Wilma, and Rita) impacted the park. This occurrence was unprecedented in the history of the park. The park also sees regularly occurring summer storms. In the summer months afternoon thunderstorms are the norm.

Hurricanes and storms affect island morphology, submarine sediment distribution, coral reef communities, park infrastructure, and cultural resources. Island surveys, coral reef monitoring, and facilities assessments are necessary to understand and mitigate the impacts of these events.

Hurricanes and storms can alter island morphology drastically, eroding large sections of beach and moving large quantities of sediment in a few hours. The larger and more powerful the wave, the larger the sediment size it is able to transport. Boulder size coral rubble can be moved by hurricane generated waves. For example, Hurricane Katrina shifted huge mounds of coral westward, reducing the lagoon to the south of Bush Key by two-thirds (Michael Ryan, chief of Operations, NPS Dry Tortugas National Park, conference call, date not known). The northeastern tip of Bush Key now extends northward approximately 30 m (100 ft) where it did not exist prior to Hurricane Katrina (Michael Ryan, conference call, date not known). This extension was still present as of September 2013.

Most hurricanes approach Florida from the southeast. Because hurricanes rotate counterclockwise in the northern hemisphere, the first and strongest winds to hit the Lower Keys blow offshore from the northeast. During storms, sediment transport direction may vary, although the primary direction is to the west due to prevailing hurricane winds (Ball et al. 1967).

Living reefs in the park are survivors of intense and frequent storm activity (Multer 1977). Reef crests and shoals typically bear the brunt of the damage from storms, with branching corals such as elkhorn and staghorn sustaining the most damage (Jindrich 1972). Rocky truncated surfaces, abundant reef rubble, erosion of spurs, and development of intertidal reef rubble flats are common storm impacts (Jindrich 1972). Regeneration of reefs following a storm is a slow process and often a different assemblage of reef organisms develops. This is a normal component of reef succession. In the park, storm-resistant coralline algae and fire coral species (*Millepora* sp.) are taking over habitat previously occupied by branching corals (*A. palmata* and *A. cervicornis*) (Jindrich 1972; Multer 1977; Reynolds and Steinmetz 1983).

As of May 2007, 19.7 ha (48.7 ac) of seagrass meadows had been destroyed around Loggerhead and Bush Keys due to the 2004–2005 hurricanes and subsequent winter and tropical storms (Morrison 2010). This loss is equivalent to nearly half of the land area in the park. Additional loss occurred in 2009 during Hurricane Ike.

Hurricanes and storms have damaged or even destroyed many buildings within the park. Fort Jefferson has remained standing, yet damaged, through many hurricanes. A 1947 hurricane destroyed buildings of the Dry Tortugas Laboratory of the Carnegie Institution (built in 1904). Hospital Key once supported a small hospital for treating yellow fever patients, but it too was destroyed during a hurricane sometime after 1870.

Coral Reef Rehabilitation

Caribbean coral populations have been in decline since the 1980s. Dry Tortugas protects a remote reef community home to protected coral species. Coral reef rehabilitation is a primary goal of the park as outlined in its enabling legislation. This section of the report highlights threats such as ocean chemistry, freezing, bleaching, and disease, which may impact reef communities.

Ocean Chemistry

Healthy reefs are associated with clear, nutrient-poor waters. Increased pollution and sewage discharge adds intolerable nutrients to the water, increasing algal growth and deterring coral growth. Rising sea level creates lagoons where there was once dry land. These newly formed lagoons serve as a pathway for the release of nitrates and other nutrients to the oceans. Many reef building coral species cannot tolerate increased nitrate levels (Hallock and Schlager 1987).

Temperature Fluctuations

A sudden drop in ocean temperature can have devastating effects on coral populations. A "freeze" in January 1977 killed hundreds of acres of staghorn coral within the park at White Shoal and Middle Ground (Davis 1982; Porter et al. 1982; Kuffner et al. 2012). Transplanted elkhorn coral was also killed (Porter et al. 1982). Some of the hardier coral species such as boulder star coral (*M. annularis*) were killed in 1977 when water temperatures off the Middle Keys dropped to 9°C (48°F) for four hours (Hudson 1981).

Elevated water temperature can be equally detrimental to coral, causing loss of zooxanthellae (symbiotic algae), which leads to "bleaching" and death (Shinn 1966). Coral at Dry Tortugas may be more tolerant to high water temperatures. Daily average temperatures regularly exceed the theoretical 30.5°C (87°F) threshold for zooxanthellae survival, with no apparent widespread bleaching (Miller et al. 2012). Bleaching may be more of a concern as water temperatures rise in response to continued climate change.

Disease

Black-band disease is a serious issue in the Florida Keys. The disease is caused by a bacterial mat which appears as a dark line migrating across coral heads separating healthy coral from coral skeleton. Decline in sea urchin (*Diadema*) populations may be related to an increase in the number of cases of black-band disease. *Diadema* are known to feed on algae that inhabit disease affected areas of coral, thus potentially controlling the spread of black-band disease. However, more data are necessary to confirm if *Diadema* mortality played a role in the coral decline at Dry Tortugas National Park that began in the 1980s. Recent increases in *Diadema* may help coral rehabilitation (Kuffner et al. 2006; Paul et al. 2011).

In the summer of 2008 an outbreak of the coral disease white plague was observed by NPS South Florida/Caribbean Network (SFCN) staff (Miller et al. 2012). White plague appears as an abrupt line on the coral head separating living tissue from algal-colonized skeleton. The disease typically begins at the base of a coral head and spreads upward and out.

Threatened Species

In May 2006, two species of coral—staghorn coral (*A. cervicornis*) and elkhorn coral (*A. palmata*)—that inhabit the park were listed as threatened under the Endangered Species Act. A species listed as threatened is defined as "any species which is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range." The act requires that critical habitat is designated and recovery plans are developed and implemented for species listed as threatened or endangered. Critical habitat for these corals in Florida extends from Palm Beach County to Key West, which includes the Dry Tortugas (fig. 38).

Both of these species were once dominant in shallow reef-crest habitats throughout the Florida Keys and the

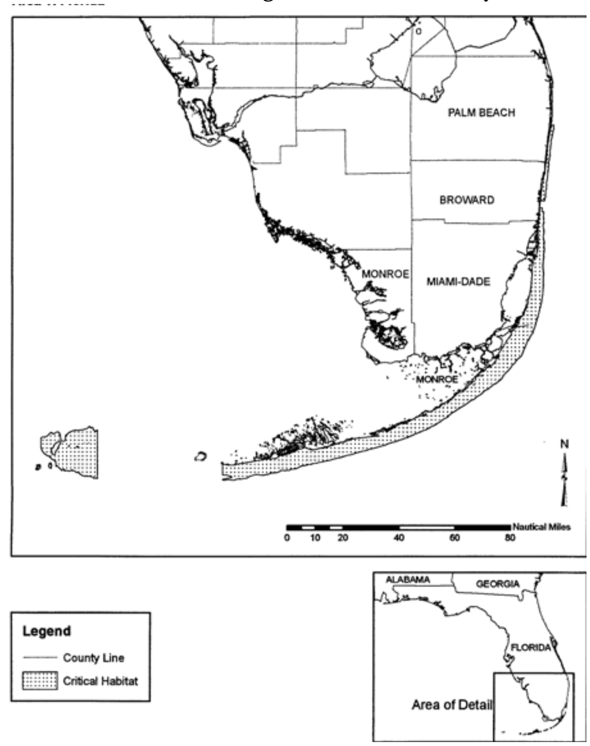

Figure 38. Critical habitat for elkhorn and staghorn corals. Critical habitat for *A. palmata and A. cervicornis* extends into Dry Tortugas National Park. Graphic from National Oceanic and Atmospheric Administration (2008).

Dry Tortugas, but in the last 30 years populations have declined drastically. Coral disease is the primary cause of their demise. Staghorn coral sites have shown a steady decline due to bleaching and diseases (Beaver et al. 2005). Elkhorn coral is not as common in the park, and a lack of known sites makes this species more difficult to monitor. The condition of these species in the park is an indication of overall reef health.

Most of the staghorn coral thickets that once thrived at Dry Tortugas are now dead (Shinn et al. 1989). Prior to a freeze in January of 1977 their coverage in the park was vast. Extensive areas were covered with dense stands. Northwest of Loggerhead Key the staghorn coral reef formed east-west oriented ridges 2 to 3 m (6.5 to 10 ft) high and 7 to 8 m (23 to 26 ft) wide, separated by sand-bottomed ravines 3 to 10 m (10 to 33 ft) wide (Davis 1982). In other areas this species blanketed slopes on the edges of channels or occupied large patches of hardbottom (Davis 1982). This species has still not fully recovered (Kuffner et al. 2012).

Monitoring

Monitoring is a critical component of comprehensive natural resource management at the park but has many inherent challenges. Coral reef monitoring at Dry Tortugas has been conducted by federal, state, and university institutions. According to Waara et al. (2011) some of the issues with collaborative monitoring efforts include re-sampling or over sampling of the same sites, a variety of data collection methods, and lack of data sharing and coordination.

Despite challenges in methodology and coordination, Miller et al. (2012) concluded that the decline in coral cover may be part of an overall trend. For example, a study by Jaap et al. (1989), with field work conducted in 1975, measured much more extensive coral cover than present at Bird Key Reef (south of Long Key). A 1999 to 2008 study reported a significant decrease in coral cover in the Long and Bird Key Reef areas (Ruzicka et al. 2009). The NPS South Florida/Caribbean Network began coral reef monitoring in 2004 at Bird Key Reef. From 2004 through 2011 a significant decrease in stony coral cover occurred in this reef, with the bulk of loss occurring between 2004 and 2007 (Miller et al. 2012). Octocoral cover declined again at Bird Key Reef in 2007 followed by an increase in 2011 (Miller et al. 2012). Staghorn coral are also monitored by network staff. Radial plots for monitoring were established in 2011. The plots will be surveyed a minimum of three times annually (Miller et al. 2012).

In 2007, a Research Natural Area (RNA) was established within the park to facilitate rehabilitation of coral reefs (see “Recreation and Commercial Uses” section). Baseline conditions were established in 2010 and monitoring will be ongoing to determine whether the RNA is helping to reverse the decline of coral (Miller et al. 2010 and Miller et al. 2012). Notably, baseline data show no significant preexisting differences between coral sites within and outside the RNA (Kuffner et al. 2012).

Recreation and Commercial Uses

Despite the park’s remote location and limited accessibility (all visitors must arrive via boat or seaplane), visitation to the Dry Tortugas increased nearly 300% since its designation as a national park in 1992. Another factor for visitation is that South Florida’s population is projected to increase. Consequently, pressure on natural resources from recreational and commercial activities at Dry Tortugas is likely to continue to increase.

In 2007, in response to increased pressure on resources and in order to comply with a statutory mandate to manage and protect park resources, the National Park Service established a Research Natural Area (RNA) in the northwestern part of the park. The RNA is a no-take marine reserve encompassing 119 km^2 (46 mi^2), which translates to more than 46% of Dry Tortugas National Park (fig. 2). Extractive activities, including fishing, are prohibited, and boats are allowed to attach to mooring buoys only. Snorkeling and SCUBA diving are permitted.

Studies are currently underway to assess whether the RNA is successfully reducing pressure on natural resources from recreational and commercial activities (Miller et al. 2012, Morrison 2010, Morrison et al. 2010, and Ruzicka et al. 2012).

Snorkeling and SCUBA Diving

With anchoring not permitted within the RNA, snorkeling and SCUBA diving activities are concentrated around mooring buoys. Intensive snorkeling and diving at these locations poses a concern for park managers because inadvertent (or intentional) physical contact with coral, stirring up of sediments, littering, and water pollution are associated with these activities.

Researchers are studying the effects of snorkeling and SCUBA diving on coral reefs in the park, both within and outside the RNA (Miller et al. 2010; Morrison et al. 2010; Ruzicka et al. 2012). For example, Morrison et al. (2010) used underwater video to assess the effects on corals from diving and snorkeling at RNA mooring buoys. Preliminary results showed a significant decline in stony corals and octocorals at Bird Key reef (Miller et al. 2010).

Baseline conditions have been established for sites within and outside the RNA, making future assessment possible (Ruzicka et al. 2012).

Boating

Boat anchoring damage to resources is not a major concern at the park. Anchoring is prohibited in the RNA, and mooring buoys are provided in many other locations. However, boat anchors can damage coral reefs, seagrass communities, and hardbottom habitat, so park managers monitor these areas for impacts from boats. Researchers are monitoring changes in seagrass bed abundance within the RNA, making comparisons to areas in the park where anchoring is permitted (Morrison 2010). Preliminary results showed no anchor damage within the RNA over a five year period from 2005 through 2009.

Sediment Erosion and Accretion

Six of the seven islands within Dry Tortugas National Park are very highly vulnerable to erosion (Pendleton et al. 2004). Loggerhead Key is the exception because its shoreline consists of beachrock (fig. 28), which affords protection against erosion (see “Loggerhead Key” section).

Coastal researchers have calculated rates of erosion in excess of 2 m (6.5 ft) per year within the park (Pendleton et al. 2004). Erosion threatens infrastructure as well as cultural resources.

In addition, accretion (the addition of sediment onto a land mass) is occurring and presents some problems of its own. Accretion can close channels thus affecting the circulation and flow of water, movement of marine life, and navigability around the islands. It can also fill in docks preventing boat access.

Erosion and accretion have created issues of particular management concern at Garden Key and the channel between Garden and Bush keys.

Garden Key

Garden Key is home to Fort Jefferson and nearly all other park infrastructure. The majority of the island is stabilized by the fort. However, a strip of land on the eastern side of the island lies outside the protection of the fort. Shoreline changes have resulted in a land deficit (erosion) near the seaplane ramp, and a surplus (accretion) around the supply pier and dock which impedes park operations (figs. 39 and 40).

Figure 39. Accretion on Garden Key. Accretion at the supply pier and dock on the southeastern side of Garden Key caused an NPS ranger boat to become grounded, impeding park operations. National Park Service photograph, date unknown.

A NPS project proposes to dredge sand from under the dock and at two moat locations and use this material to fill an eroded shoreline area between the seaplane ramp and the north coaling dock (fig. 39). The beach on either side of the south coaling dock ruins has been eroding since at least 1960. Park facilities located behind a cement wall near the dock are being threatened where erosion has exposed the wall to incoming waves, causing it to crumble (fig. 41).

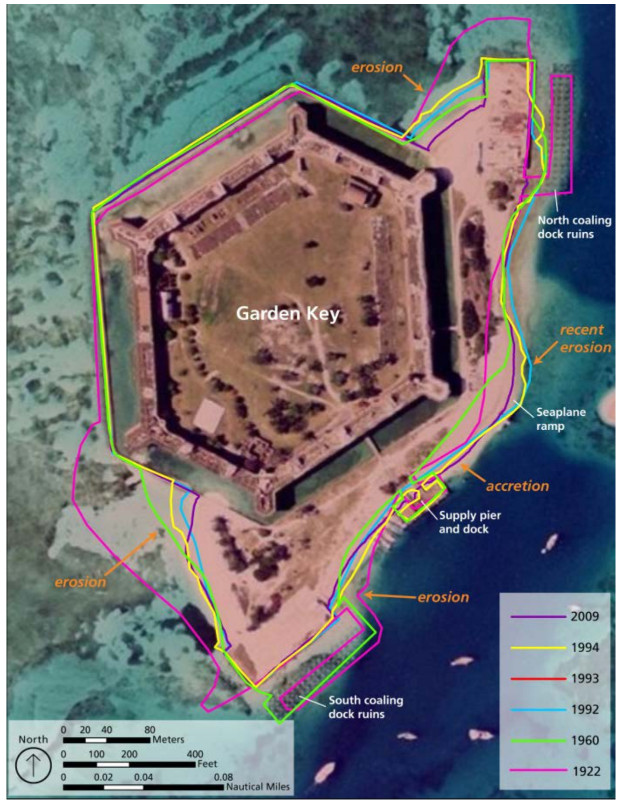

Figure 40. Shoreline change on Garden Key. Shoreline changes have resulted in a land deficit (erosion) near the seaplane ramp, and a surplus (accretion) around the supply pier and dock. Accretion at the dock impedes park operations. Graphic compiled by Rebecca Port (NPS Geologic Resources Division) with data from Mullins (1992, 1993), Pendleton et al. (2004), and Patterson (unpublished data). Imagery from the National Agriculture Imagery Program, taken in 2010.

Figure 41. Erosion of Garden Key. Erosion (black dashed line) on the northern side of the south coaling dock ruins has reduced the area of the beach and exposed the cement wall to waves. The wall is crumbling (inset photo) and shoreline encroachment is threatening facilities (e.g., white building and generator on the dock). National Park Service photographs, taken 25 June 2009.

Channel between Garden and Bush Keys

The area between Bush and Garden keys has a long and complex history of erosion and accretion. Only some of this history can be reconstructed with historic photos and personal accounts. Since at least the early 1900s, under the combined influence of regular sediment transport patterns and sporadic storms and hurricanes, the area has fluctuated between a channel of varying depths and a land bridge. In general, sediment transport is to the west and Bush Key has been slowly migrating closer to Garden Key. However, storms and hurricanes have interrupted this overall trend. Based on available data, the channel has been open the majority of the time since the early 1900s. As of report publication (February 2014), the channel was closed.

The channel was dredged at least once, around 1905, to approximately 9 m (30 ft) deep (coastal geologist, NPS Geologic Resources Division, site assessment memo, 22 June 2001). Since that time, the channel has closed twice. First, it closed in December 2000 as a result of a storm (Robert Brock, supervisory marine biologist, Everglades and Dry Tortugas national parks, email, 23 January 2001). A land bridge approximately 9 m (30 ft) wide at low tide formed between the two keys (fig. 42). During the 2004–2005 hurricane season, five hurricanes impacted the park and reopened a shallow channel between the two keys. By February 2012, the channel closed the second time (Judd Patterson, personal communication, 6 September 2013) (fig. 42). As of 7 March 2013, the channel was closed (based on satellite imagery). For a detailed reconstruction of events see table 1.

Figure 42. Area between Bush and Garden keys. Since at least the early 1900s, the area between Bush and Garden keys has fluctuated from a land bridge to a channel of varying depths. North is to the left in this photograph. In general, sediment transport is to the west and Bush Key has been slowly migrating closer to Garden Key. However, storms and hurricanes have interrupted this overall trend. The lower photo shows the land bridge less than 2 hours after low tide. The narrowest point across the land bridge was 9 m (29 ft). National Park Service photographs. Lower photograph courtesy of Naomi Blinick (NPS Submerged Resources Center).

Channel closure has caused three primary resource management concerns: water quality, access to Bush Key, and accretion near the supply pier and dock (Robert Brock, conference call, 9 March 2001). Water quality is a concern because boats empty their bilges (lowest compartments that are below the waterline) in the anchorage and flushing will be decreased following channel closure. Access to Bush Key is an issue because sooty terns nest in the sand there and the land bridge will give access to rats and potentially humans from Garden Key that would disturb the birds. Accretion near the supply pier and dock is expected to increase because the land bridge will prohibit sediment transport. Accretion in these areas will disrupt normal park operations.

In 2001, NPS Geologic Resources Division staff recommended not reestablishing the channel via dredging (staff, coastal geologist, NPS Geologic Resources Division, site assessment memo, 22 June 2001). The costs and maintenance associated with dredging do not outweigh its resource management benefits. According to Joseph Boyer (professor, Florida International University, email, 25 January 2001), the southeastern channel should provide enough water exchange to maintain water quality in the anchorage even in the presence of a land bridge between the two keys. Signs are posted to prohibit foot traffic from Garden to Bush key and resource managers continue to monitor the sooty terns.

Subsidence

Fort Jefferson is built on Garden Key which, like the other keys, is not underlain by solid, in-situ coral reef, but rather by coral rubble and carbonate sand. The unconsolidated and heterogeneous nature of the sediments causes them to compact unevenly which led to subsidence of the fort, first noted and reported in 1850-1851 (Bearss 1983). At that time modifications were made to the design of the fort foundation and piers to curb the subsidence. Settling was again reported in 1857-1858 (Manucy et al. 1942) and by the mid 1860s many of the cisterns under the first tier had cracked and rendered the collected water non-potable. The effects of settlement at the fort can be seen through cracks in the masonry as well as at the sloped water line around the base of the fort (fig. 43).

Figure 43. Water line around Fort Jefferson. Subsidence of the fort was noted during the original construction period beginning in the 1850s. Today, this uneven settlement is visible as observed at the sloped waterline around the fort. National Park Service photograph.

In 2012 an updated structural analysis was completed for the National Park Service and the current findings from that investigation indicate that the scarp wall and casemates as a whole system are stable in their present condition. As analyzed, the difference between the behavior of the structure in its original as-built condition and present deteriorated condition is very small, although the mechanisms for on-going deterioration are not completely known (Sillman and Associates 2012). With that, the NPS has installed updated crack monitors and strain gauges to collect data that may provide updated information as to whether the fort structure is continuing to settle (fig. 44).

Figure 44. Modern strain gauge. Modern strain gauges and crack monitors were installed in various locations in 2013 as part of the on-going efforts to monitor the fort and collect data that will be analyzed for determinations of the fort's current structural stability. National Park Service Photograph.

Groundwater Flow and Salinity

Nutrients from septic waste enter the marine environment via groundwater flow and surface runoff, and may have deleterious effects on marine organisms and habitats. However, the relationship between groundwater flow dynamics and overall marine quality has not been quantitatively determined (Thornberry-Ehrlich 2005), and a few studies have been conducted on groundwater flow dynamics on the islands in the park. During the GRI scoping meeting, participants suggested that research focus on determining the number of wells needed to delineate flow and how to account sediment transport effects on flow patterns (Thornberry-Ehrlich 2005).

Groundwater salinity under Loggerhead Key is low at the center of the island and increases gradually toward the shore (Halley and Steinen 1979). This is typical for groundwater on small islands and is most likely true for the other islands within the park. None of the groundwater has low enough salinity to be potable.

Benthic Habitat Mapping

During the 2005 scoping meeting the need for a large-scale benthic habitat map was discussed in order to help improve the monitoring and management of marine resources in Dry Tortugas National Park (Thornberry-Ehrlich 2005).

Previous benthic maps by Agassiz (1882) and Davis (1979) are important historic records but deemed inadequate for modern resource management. A contractor, Avineon, Inc., compiled a more recent map in 2008. The NPS South Florida/Caribbean Network updated the 2008 map in 2010 using new high resolution side scan sonar data combined with aerial and satellite imagery, bathymetry data, and field observations (Waara et al. 2011). Those revisions to the 2008 map improved the accuracy of hardbottom habitat locations as well as patch reefs and soft and hardbottom interfaces (Waara et al. 2011).

As of 2013, the 2010 benthic habitat map fulfilled resource management needs at the park by characterizing marine habitats and providing the ability to track whether management actions are effectively protecting the environment and associated resources. Park managers have no immediate need or plan to remap the entire park. Site-specific monitoring can be compared to the benthic map to gauge changes in habitat distribution.

The 2010 benthic habitat map is the source map for the GIS data and benthic map provided with this report (see "Geologic Map Data" section).

Table 1. History of the channel between Bush and Garden keys

Date	Channel Status	Details
~1905	Open	Channel dredged to approximately 9 m (30 ft)
1935	Open	Aerial photographs show Bush Key is more rounded and a substantial distance from the fort (Bob Howard, Manager Assistant, Dry Tortugas National Park, personal communication, 14 March 2001)
1990	Open	Channel is 8.5 m (28 ft) deep (Bob Howard, personal communication, 14 March 2001)
1995	Open	Channel appears to be deep on USGS National Aerial Photography Program (NAPP) imagery
1998	Open	Vessels with a 1.2 m (4 ft) draft can transit the channel (Bob Howard, conference call, 13 March 2001)
1999	Open	National Park Service photographs show seagoing vessel transiting the inlet
2000 / Fall	Open	Vessels with a 0.3 to 0.4 m (1 to 1.5 ft) draft can transit the channel (Bob Howard, conference call, 13 March 2001)
2000 / December	Closed	Channel closes rapidly in a storm and the land bridge that forms is approximately 9 m (30 ft) wide at low tide (Robert Brock, conference call, 9 March 2001)
2001 / June	Closed	Land bridge continues to accrete sediment and is being colonized by vegetation (Sesuvium) (staff, coastal geologist, NPS Geologic Resources Division, site assessment memo, 22 June 2001)
2004/2005	Open	Channel opens during 2004–2005hurricane season (Judd Patterson, GIS specialist, NPS South Florida/Caribbean Network, personal communication, 6 September 2013)
2006	Open	Channel appears shallow on IKONOS satellite imagery and confirmed open by NPS employee (Judd Patterson, personal communication, 6 September 2013)
2007	Open	Channel appears shallow on NAIP aerial imagery
2011	Open	Channel is open and appears narrow (fig. 38) with only small boats able to pass through (Judd Patterson, personal communication, 6 September 2013)
2012 / February	Closed	NPS boat captain confirms channel is closed (Judd Patterson, personal communication, 6 September 2013)
2012 / May	Closed	Channel is closed by a 10 m (30 ft) wide land bridge (Judd Patterson, personal communication, 6 September 2013)
2013 / March	Closed	Google Earth satellite imagery taken on 7 March 2013 shows a land bridge approximately 29 m (95 ft) wide

Geologic History

This section describes the environment in which the units that appear on the digital benthic map of Dry Tortugas National Park were deposited and the timing of geologic events that formed the present benthic environment and landscape.

Introduction

The natural history of Dry Tortugas National Park is rooted in geologically recent events. The geologic history of Florida can be traced all the way back to the Precambrian Era, more than 541 million years ago (figs. 2 and 45). Igneous rocks of Precambrian and Cambrian age lie thousands of meters below the carbonate platform, and. They form the "basement" of Florida. Sedimentary rocks of Ordovician, Silurian, and Devonian age are above, and are thus younger than, the basement rocks. These rocks were originally deposited in a basin formed by the then-rising Appalachian Mountains, as the supercontinent Pangaea was assembling. By 300 million years ago, the world's continents had assembled to form Pangaea. What is now Florida was originally part of the ancient landmass of Africa and Australia called "Gondwana" (fig. 45).

The narrative of Dry Tortugas starts when the Florida platform began to accumulate some 200 million years ago with the opening of the "modern" Atlantic Ocean and the breakup of Pangaea.

Mesozoic Era: Birth of the Atlantic Ocean

About 200 million years ago, Pangaea began to break apart. Landmasses that are now North America and Africa began to pull away from each other, stretching Earth's crust. This extension created a deep rift and many down-dropped basins along the edges of both continents. As the landmasses continued to spread away from each other, the rift widened and eventually formed the basin now occupied by the Atlantic Ocean. Florida separated from its ancestral "homeland," remaining attached to North America.

The Atlantic Ocean basin continues to widen today at the Mid-Atlantic Ridge where molten material rises through fractures in Earth's crust, cools, and becomes new seafloor (basalt). As more molten material rises, cooled seafloor is pushed towards the continents on both sides of the ridge, steadily widening the Atlantic Ocean. Over time sediments settle to the seafloor, deeply burying and concealing the basalt.

Cenozoic Era: Layers of Limestone

The expanding Atlantic Ocean basin has been collecting sediments since it began to form. Carbonate rocks such as limestone and dolomite have long been deposited in what is now Florida. The long—and continuing—duration of deposition is manifested as extremely thick layers of carbonate rocks. More than 5,000 m (15,000 ft) of limestone and dolomite, dating back to the Cretaceous Period, were measured in wells near Marquesas Key (Shinn et al. 1989). Presumably these ancient rocks are also buried deep beneath the Pleistocene limestone that directly underlies Dry Tortugas National Park.

Pleistocene Epoch: Glaciations, Sea-Level Fluctuations, Reef Development, and the Emergence of the Florida Keys

In Pleistocene Epoch (2.6 million to 11,700 years ago), continental scale glaciers repeatedly advanced and retreated during ice ages or "glacial periods" and "interglacial periods." Although glaciers never reached Florida (their southern extent was in what is now Pennsylvania), the effects of sea level rise and fall associated with interglacial and glacial periods, respectively, certainly did.

Sea level is relatively high during interglacial periods, including the present-day interglacial. 130,000 years ago, during the previous interglacial (called the "Sangamonian"), sea level was approximately 7.5 m (25 ft) higher than modern sea level. At that time, coral reefs grew around the then-submerged Florida platform. Those reefs are now preserved as the Key Largo Limestone that underlies the park and makes up much of the Upper and Middle Florida Keys (figs. 4 and 5).

Sea level is relatively low during glacial periods, when massive amount of water are frozen in ice sheets. By 15,000 years ago during the most recent glacial period (called the "Wisconsinan"), sea level had dropped to approximately 100 m (325 ft) below present sea level (fig. 46).

When sea level dropped, the Sangamonian reef was left high and dry and was heavily eroded. Although calcium carbonate, which makes up the coral, is stable in seawater, it is readily dissolved by rainwater when exposed.

As glaciers retreated back toward the poles during the end of the Pleistocene Epoch about 12,000 years ago, sea level began to rise rapidly as previously frozen water was released back into the oceans.

Holocene Epoch: Living Coral Reefs

Approximately 6,000 years ago sea level was high enough to flood the southern Florida platform (Robbin 1984). The lowest lying areas flooded first, including the area east of the park, thereby cutting off the Dry Tortugas islands from the mainland early in the transgression. Sea level continued to rise during the Holocene Epoch, submerging the continental shelf to its current extent (fig. 1) and leaving only a small fraction of the keys above water.

As sea level stabilized, modern coral reefs established themselves on the elevated foundation of preexisting Pleistocene reefs (Key Largo Limestone) (Murphy 1993; Davis 1997; Toscano et al. 2010). Wave action, exposure, and biological weathering (breakdown by organisms) of the reefs generated large amounts of carbonate sand, which settled in the deeper areas around the elevated Pleistocene foundation. Seagrass and other submersed vegetation colonized some of the calmer sandy areas behind the reefs. Gradually the Dry Tortugas complex that is recognizable today began to emerge.

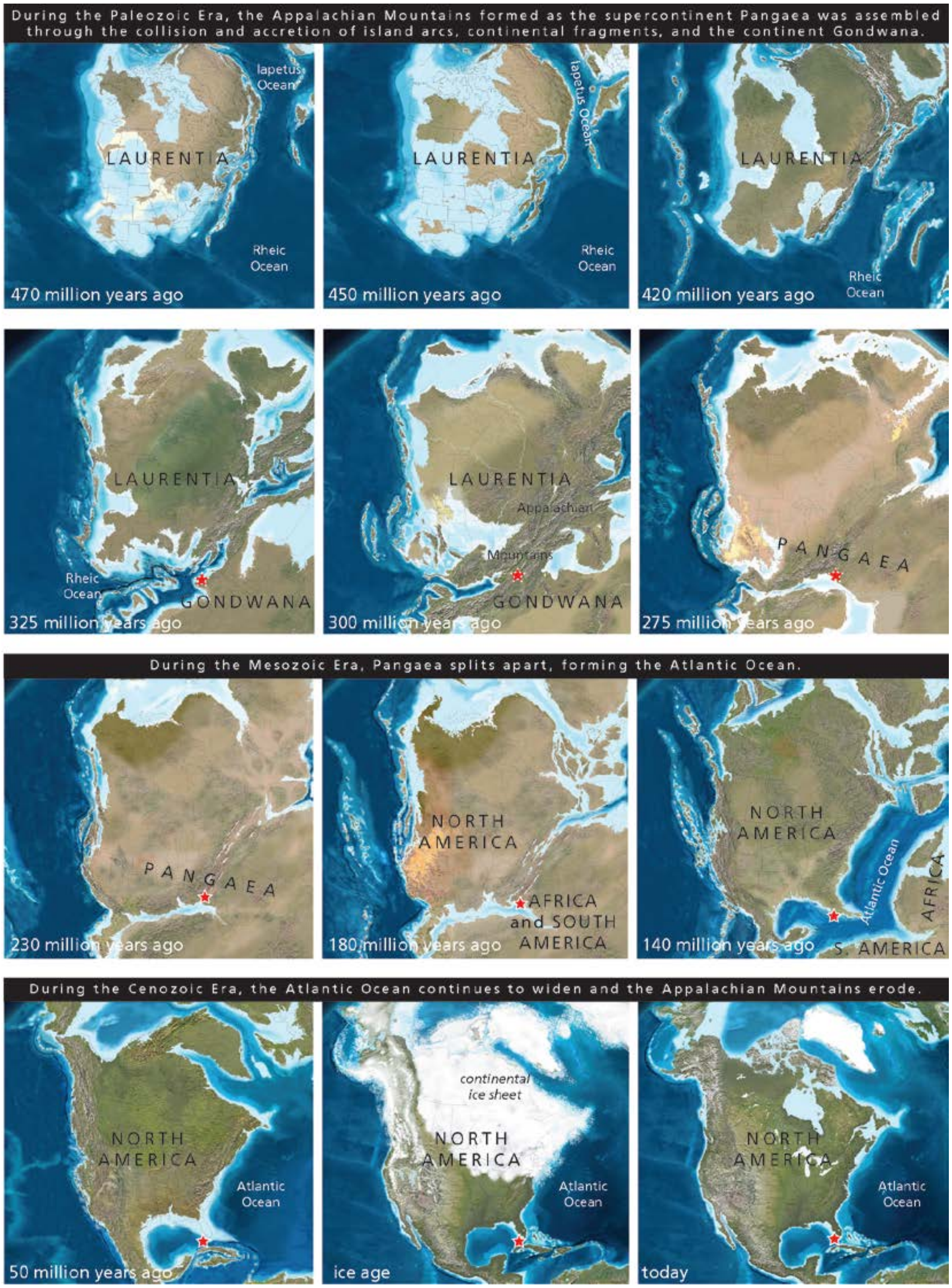

Figure 45. Paleogeographic maps for Dry Tortugas National Park. The geologic history of the Florida Keys includes continental collisions that assembled the supercontinent Pangaea. What is now Florida was originally part of Gondwana (a continent composed for Africa and Australia). The "stars" on the figure represent the approximate location of Dry Tortugas National Park during various points in geologic time. Graphic complied by Jason Kenworthy and Rebecca Port (NPS Geologic Resources Division). Base paleogeographic maps created by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/index.html (accessed 13 June 2013).

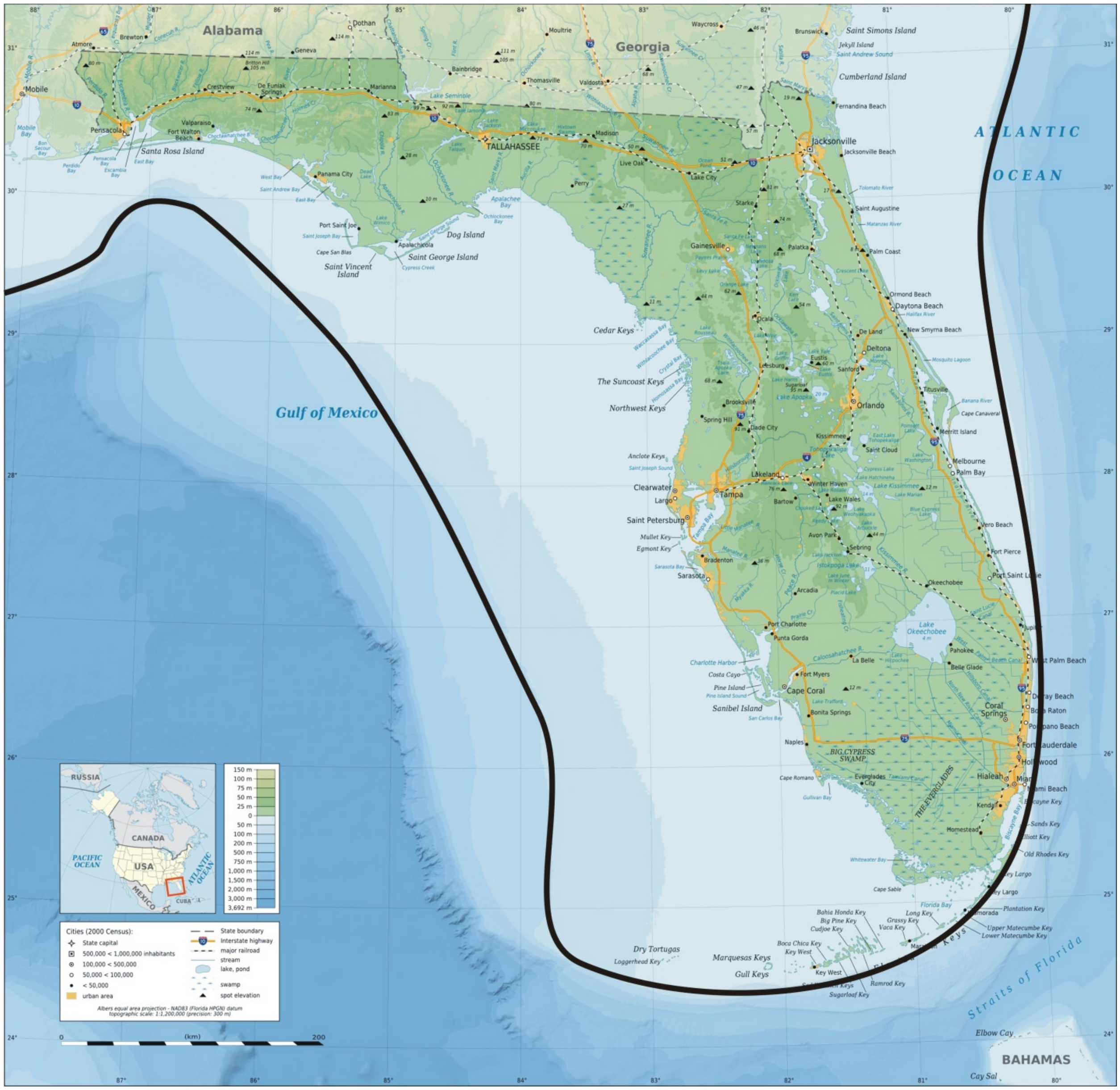

Figure 46. Last Glacial Maximum (LGM) in Florida. A modern map of Florida shows the approximate location of the coastline (as delineated by the black line) during the Last Glacial Maximum (LGM), approximately 12,000 years ago. Image from NOAA, Office of Ocean Exploration and Research, Exploring the Submerged New World 2009 Expedition, available at http://oceanexplorer.noaa.gov/explorations/09newworld/background/hires/lgmflacoast_hires.jpg (accessed 17 September).

Geologic Map Data

This section summarizes the geologic map data available for Dry Tortugas National Park. The Benthic Map Graphic (in pocket) displays the map data draped over imagery of the park and surrounding area. The Map Unit Properties Table (in pocket) summarizes this report's content for each geologic map unit. Complete GIS data are included on the accompanying CD and are also available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, these maps portray the spatial distribution and temporal relationships of rocks and unconsolidated deposits. Geologic maps can be divided into two primary types: surficial and bedrock. Surficial geologic maps typically encompass deposits that are unconsolidated and formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, typically more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type. Surficial (benthic map) data are provided for Dry Tortugas National Park.

Geologic maps often depict geomorphic features, structural interpretations (such as faults or folds), and locations of past geologic hazards that may be susceptible to future activity. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. The American Geosciences Institute website, http://www.agiweb.org/environment/publications/mapping/index.html, provides more information about geologic maps and their uses.

Source Maps

The GRI team digitizes paper maps and converts digital data to conform to the GRI GIS data model. The GRI digital geologic map product includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, references, and figures. The GRI team used the following source to produce the digital geologic data set for Dry Tortuga National Park. This sources also provided information for this report.

Waara, R. J., J. M. Patterson, A. J. Estep, A. J. Atkinson, M. D. Patterson, B. D. Witcher, M. E. Estevanez, L. T. McManus, and M. E. Brandt. 2010. Dry Tortugas National Park benthic map (scale 1:2,000). National Park Service South Florida/Caribbean Network.

Geologic GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available at http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Dry Tortugas National Park using data model version 2.1. The GRI Geologic Maps website, http://www.nature.nps.gov/geology/inventory/geo_maps.cfm, provides more information about GRI map products.

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

The following components are part of the data set:

- A GIS readme file (PDF) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information.
- Data in ESRI geodatabase and shapefile GIS format
- Layer files with feature symbology (table 2)
- Federal Geographic Data Committee (FGDC)–compliant metadata
- An ancillary map information document (PDF) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures.
- An ESRI map document (.mxd) that displays the digital geologic data

Table 2. Geology data layers in the Dry Tortugas National Park GIS data.

Data Layer	Data Layer Code	On Overview Graphic?
Benthic Habitat Units	DRTOBEN	Yes
Benthic Habitat Contacts	DRTOBENA	Yes

Benthic Map Graphic

The Benthic Map Graphic (in pocket) displays the GRI digital benthic data draped over a satellite image of the park and surrounding area. Cartographic elements and basic geographic information have been added. Geographic information which is part of the graphic is not included with the GRI digital geologic GIS data for the park, but is available online from a variety of sources.

Map Unit Properties Table

The units listed in the Map Unit Properties Table (in pocket) correspond to the accompanying digital benthic data. Following the structure of the report, the table summarizes the geologic issues, features, and processes, and geologic history associated with each map unit. The table also lists the geologic time period, map unit symbol, and a simplified geologic description of the unit. Connections between units and park stories are also summarized.

Use Constraints

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

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the Geologic Map Graphic. Based on the source map scale (1:2,000) and US National Map Accuracy Standards, geologic features represented in the geologic map data are horizontally within 1.0 m (3.3 ft) of their true locations.

Glossary

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

absolute age. The geologic age of a fossil, rock, feature, or event in years; commonly refers to radiometrically determined ages.

abyssal plain. A flat region of the deep ocean floor, usually at the base of the continental rise.

accretion. The gradual increase or extension of land by natural forces acting over a long period of time, as on a beach by the washing up of sand from the sea.

active margin. A tectonically active margin where lithospheric plates come together (convergent boundary), pull apart (divergent boundary) or slide past one another (transform boundary). Typically associated with earthquakes and, in the case of convergent and divergent boundaries, volcanism. Compare to "passive margin."

aphanitic. Describes the texture of fine-grained igneous rocks where the different components are not distinguishable with the unaided eye.

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

aragonite. An orthorhombic mineral, $CaCO_3$, trimorphous with calcite and vaterite.

ash (volcanic). Fine material ejected from a volcano (also see "tuff").

asthenosphere. Earth's relatively weak layer or shell below the rigid lithosphere.

atoll. A coral reef appearing in plan view as a ring or horseshoe shaped reef, rising from deep water.

back reef. The landward side of a reef.

bank (coast). An embankment; a sand bank.

bank atoll. A ring-shaped coral reef or reef complex rising from an oceanic plateau or submarine bank.

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

basalt. A dark-colored, often low-viscosity, extrusive igneous rock.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface.

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

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

beach. A gently sloping shoreline covered with sediment, commonly formed by the action of waves and tides.

beach face. The section of the beach exposed to direct wave and/or tidal action.

beachrock. A poorly-cemented to well-cemented sedimentary rock formed in the intertidal zone consisting of sand and gravel (fragments of rocks, marine invertebrate shells, or coral) cemented with calcium carbonate.

bed. The smallest sedimentary strata unit, commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

bedrock. A general term for the rock that underlies soil or other unconsolidated, surficial material.

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

berm. A low, impermanent, nearly horizontal or landward-sloping bench, shelf, or ledge on the backshore of a beach.

bioherm. A mound-like, dome-like, lens-like, or reef-like mass of rock built up by sedentary organisms, composed almost exclusively of their calcareous remains, and enclosed or surrounded by rock of different lithology.

bioturbation. The reworking of sediment by organisms.

breakwater. An offshore, generally shore-parallel structure that, by breaking the force of the waves, protects a beach or shore area.

bryozoan. Any invertebrate belonging to the phylum Bryozoa and characterized chiefly by colonial growth and a calcareous skeleton.

calcarenite. A limestone consisting predominantly of sand-size carbonate grains; a consolidate calcareous sand.

calcareous. Describes rock or sediment that contains the mineral calcium carbonate ($CaCO_3$).

calcite. A common rock-forming mineral: $CaCO_3$ (calcium carbonate).

calcium carbonate. A solid, $CaCO_3$, occurring in nature chiefly as the minerals calcite and aragonite.

caliche. Hard, calcium-carbonate cemented layer commonly found on or near the surface of arid and semiarid regions.

carbonaceous. Describes a rock or sediment with considerable carbon content, especially organics, hydrocarbons, or coal.

carbonate. A mineral that has CO_3^{-2} as its essential component (e.g., calcite and aragonite).

carbonate rock. A rock consisting chiefly of carbonate minerals (e.g., limestone, dolomite, or carbonatite).

cay. A small, low, coastal island or emergent reef of sand or coral; a flat mound of sand and admixed coral fragments, built up on a reef flat at or just above high-tide level.

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

cementation. Chemical precipitation of material into pores between grains that bind the grains into rock.

channel (coast). A relatively narrow sea or stretch of water between two close landmasses and connecting two larger bodies of water.

chemical sediment. A sediment precipitated directly from solution (also called nonclastic).

chert. A extremely hard sedimentary rock with conchoidal (smooth curved surface) fracturing. It consists chiefly of interlocking crystals of quartz Also called "flint."

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

clast. An individual grain or rock fragment in a sedimentary rock, produced by the physical disintegration of a larger rock mass.

clay. Can be used to refer to clay minerals or as a sedimentary fragment size classification (less than 1/256 mm [0.00015 in]).

compaction. Reduction in bulk volume or thickness of fine grained sediments, owing to increased weight of overlying material that is continually being deposited, or to pressures resulting from earth movements.

conglomerate. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in).

continental crust. Crustal rocks rich in silica and alumina that underlie the continents; ranging in thickness from 35 km (22 mi) to 60 km (37 mi) under mountain ranges.

continental rifting. Process by which a region of crust undergoes extension (pulling apart), resulting in the formation of many related normal faults, and often associated with volcanic activity.

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

continental shelf. The shallowly submerged part of a continental margin extending from the shoreline to the continental slope with water depths less than 200 m (660 ft).

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

convergent boundary. A plate boundary where two tectonic plates are colliding.

coquina. Limestone composed of cemented shell fragments.

coral. A general name for any of a large group of bottom-dwelling, attached, marine coelenterates of the class Anthozoa.

coralline algae. A group of algae that remove calcium carbonate from the shallow water in which they live and secrete or deposit it around the thallus as a more or less solid calcareous structure.

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

core (interior Earth). The central part of Earth, beginning at a depth of about 2,900 km (1,800 mi), probably consisting of iron-nickel alloy.

core (oceanography). A relatively undisturbed, cylindrical sample of ocean-bottom sediment collected by an oceanographic corer.

crinoid. A marine invertebrate (echinoderm) that uses a stalk to attach itself to a substrate. "Arms" are used to capture food. Rare today, they were very common in the Paleozoic. Crinoids are also called "sea lilies."

cross-bedding. Uniform to highly varied sets of inclined sedimentary beds deposited by wind or water that indicate flow conditions such as water flow direction and depth.

cross section. A graphical interpretation of geology, structure, and/or stratigraphy in the third (vertical) dimension based on mapped and measured geological extents and attitudes depicted in a vertically oriented plane.

crust. Earth's outermost compositional shell, 10 to 40 km (6 to 25 mi) thick, consisting predominantly of relatively low-density silicate minerals (also see "oceanic crust" and "continental crust").

cryptocrystalline. Describes a rock texture where individual crystals are too small to be recognized and separately distinguished with an ordinary microscope.

crystalline. Describes a regular, orderly, repeating geometric structural arrangement of atoms.

differential erosion. Erosion that occurs at irregular or varying rates, caused by differences in the resistance and hardness of surface material.

dip. The angle between a bed or other geologic surface and horizontal.

divergent boundary. An active boundary where tectonic plates are moving apart (e.g., a spreading ridge or continental rift zone).

dolomite. A carbonate sedimentary rock of which more than 50% by weight or by areal percentages under the microscope consists of the mineral dolomite (calcium-magnesium carbonate).

dune. A low mound or ridge of sediment, usually sand, deposited by wind. Common dune types include "barchan," "longitudinal," "parabolic," and "transverse" (see respective listings).

emergence (coast). A change in the levels of water or land such that the land is relatively higher and areas formerly under water are exposed.

epicontinental. Describes a geologic feature situated on the continental shelf or on the continental interior. An "epicontinental sea" is one example.

erosion. The general process or the group of processes whereby the materials of the Earth's crust are loosened, dissolved, or worn away, and simultaneously moved from one place to another, by natural agencies.

eustatic. Relates to simultaneous worldwide rise or fall of sea level.

extrusive. Describes molten (igneous) material that has erupted onto Earth's surface.

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

fault. A break in rock along which relative movement has occurred between the two sides.

felsic. Describes an igneous rock having abundant light-colored minerals such as quartz, feldspars, or muscovite. Compare to "mafic."

fold. A curve or bend of an originally flat or planar structure such as rock strata, bedding planes, or foliation that is usually a product of deformation.

foraminifer. Any protozoan belonging to the subclass Sarcodina, order Foraminiferida, characterized by the presence of a test of one to many chambers composed of secreted calcite or agglutinated particles.

fore reef. The seaward side of a reef.

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

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

geomorphology. The science that treats the general configuration of the earth's surface.

graywacke. A term commonly used in the field for a dark gray to dark green, very hard, dense sandstone of any composition but with a chlorite-rich matrix; these rocks have undergone deep burial.

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

hardbottom. Hard substrate composed of exposed bedrock or created through syndepositional cementation of sediment and may be colonized by corals and other attached benthos.

hermatypic. A type of reef-building coral, incapable of adjusting to aphotic conditions.

heterogeneous. Consisting of dissimilar or diverse ingredients or constituents.

highstand. The interval of time during one or more cycles of relative change of sea level when sea level is above the shelf edge in a given local area.

homogeneous. Of uniform structure or composition throughout.

hurricane. A tropical cyclone, esp. in the North Atlantic and eastern North Pacific basins, in which the sustained near-surface wind speed equals or exceeds 64 knots (73 mph).

hydrogeologic. Refers to the geologic influences on groundwater and surface water composition, movement and distribution.

igneous. Refers to a rock or mineral that originated from molten material; one of the three main classes of rocks—igneous, metamorphic, and sedimentary.

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

isotopic age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products; "absolute age" and "radiometric age" are often used in place of isotopic age but are less precise terms.

joint. A break in rock without relative movement of rocks on either side of the fracture surface.

karst topography. Topography characterized by abundant sinkholes and caverns formed by the dissolution of calcareous rocks.

key. A cay, esp. one of the coral islets or barrier islands off the southern coast of Florida.

lagoon. A shallow body of water enclosed or nearly enclosed within an atoll.

lava. Still-molten or solidified magma that has been extruded onto Earth's surface through a volcano or fissure.

limestone. A sedimentary rock consisting chiefly of calcium carbonate, primarily in the form of the mineral calcite.

lithification. The conversion of sediment into solid rock.

lithosphere. The relatively rigid outmost shell of Earth's structure, 50 to 100 km (31 to 62 mi) thick, that encompasses the crust and uppermost mantle.

littoral. Pertaining to the benthic ocean environment or depth zone between high water and low water.

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

lowstand. The interval of time during one or more cycles of relative change of sea level when sea level is below the shelf edge.

mafic. Describes dark-colored rock, magma, or minerals rich in magnesium and iron. Compare to "felsic."

magma. Molten rock beneath Earth's surface capable of intrusion and extrusion.

mantle. The zone of Earth's interior between the crust and core.

marine terrace. A narrow coastal strip of deposited material, sloping gently seaward.

mass wasting. A general term for the downslope movement of soil and rock material under the direct influence of gravity.

matrix. The fine grained material between coarse (larger) grains in igneous rocks or poorly sorted clastic sediments or rocks. Also refers to rock or sediment in which a fossil is embedded.

member. A lithostratigraphic unit with definable contacts; a member subdivides a formation.

metamorphism. Literally, a change in form. Metamorphism occurs in rocks through mineral alteration, formation, and/or recrystallization from increased heat and/or pressure.

mica. A prominent rock-forming mineral of igneous and metamorphic rocks. It has perfect basal cleavage meaning that it forms flat sheets.

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

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

mollusk. A solitary invertebrate belonging to the phylum Mollusca. Among the classes included in the mollusks are the gastropods, bivalves, and cephalopods.

oceanic crust. Earth's crust formed at spreading ridges that underlies the ocean basins. Oceanic crust is 6 to 7 km (3 to 4 mi) thick and generally of basaltic composition.

ooid. An individual spherite of an oolitic rock.
oolite. A sedimentary rock, usually limestone, made of ooliths—round or oval grains formed by accretion around a nucleus of shell fragment, algal pellet, or sand grain. These laminated grains can reach diameters of 2 mm (0.08 in), but 0.5–1 mm (0.02–0.04 in) is common.
oolith. One of the small round or ovate accretionary bodies in a sedimentary rock, resembling the roe of fish.
orogeny. A mountain-building event.
outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.
paleogeography. The study, description, and reconstruction of the physical landscape from past geologic periods.
paleontology. The study of the life and chronology of Earth's geologic past based on the fossil record.
Pangaea. A theoretical, single supercontinent that existed during the Permian and Triassic periods.
passive margin. A margin where no plate-scale tectonism is taking place; plates are not converging, diverging, or sliding past one another. An example is the east coast of North America (compare to "active margin").
pebble. Generally, small rounded rock particles from 4 to 64 mm (0.16 to 2.52 in) in diameter.
permeability. A measure of the relative ease with which fluids move through the pore spaces of rocks or sediments.
plate tectonics. The concept that the lithosphere is broken up into a series of rigid plates that move over Earth's surface above a more fluid asthenosphere.
platform. Any level or nearly-level surface, ranging in size from a terrace or bench to a plateau or peneplain.
plume. A persistent, pipe-like body of hot material moving upward from Earth's mantle into the crust.
polyp. A typical individual coelenterate, with a hollow tubular or columnar bod terminating at the top in a central mouth surrounded by tentacles. It is closed below, and attached to the bottom or more or less directly continuous with other individuals of a compound animal (as in most corals).
porosity. The proportion of void space (e.g., pores or voids) in a volume of rock or sediment deposit.
potassium feldspar. A feldspar mineral rich in potassium (e.g., orthoclase, microcline, sanidine, adularia).
principle of original horizontality. The concept that sediments are originally deposited in horizontal layers and that deviations from the horizontal indicate post-depositional deformation.
principle of superposition. The concept that sediments are deposited in layers, one atop another, i.e., the rocks on the bottom are oldest with the overlying rocks progressively younger toward the top.
principle of uniformity. The assumption of uniformity of causes or processes throughout time and space; the uniformity of natural laws. Not synonymous with the uniformitarianism of Charles Lyell, who constrained throughout geologic time both the intensity and frequency and the kinds of processes seen today.
progradation. The seaward building of land area due to sedimentary deposition.
radioactivity. The spontaneous decay or breakdown of unstable atomic nuclei.
radiometric age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products.
reef. A ridgelike or moundlike structure, layered or massive, built by sedentary calcareous organisms, esp. corals, and consisting mostly of their remains
reef crest. The sharp break in slope at the seaward margin or edge of the reef flat, located at the top of the reef front; marked by dominance of a particular coral species (such as Acropora palmata throughout the Caribbean) or by an algal ridge and/or surge channels.
reef flat. A stony platform of reef rock, landward of the reef crest at or above the low tide level.
reef front. The upper part of the outer or seaward slope of a reef, extending to the reef edge from above the depth limit of abundant living coral and coralline algae.
regression. A long-term seaward retreat of the shoreline or relative fall of sea level.
relative dating. Determining the chronological placement of rocks, events, or fossils with respect to the geologic time scale and without reference to their numerical age.
rhizome. An underground stem that lies horizontally and that is often enlarged in order to store food.
rift. A region of crust where extension results in formation of many related normal faults, often associated with volcanic activity.
ripple marks. The undulating, approximately parallel and usually small-scale ridge pattern formed on sediment by the flow of wind or water.
riprap. A layer of large, durable, broken rock fragments irregularly thrown together in an attempt to prevent erosion by waves or currents and thereby preserve the shape of a surface, slope, or underlying structure.
rock. A solid, cohesive aggregate of one or more minerals.
runup. The advance of water up the foreshore of a beach or structure, following the breaking of the wave.
sand. A clastic particle smaller than a granule and larger than a silt grain, having a diameter in the range of 1/16 mm (0.0025 in) to 2 mm (0.08 in).
seafloor spreading. The process by which tectonic plates pull apart and new lithosphere is created at oceanic ridges.
seagrass. Flowering plants from four families (Posidoniaceae, Zosteraceae, Hydrocharitaceae, or Cymodoceaceae) all in the order Alismatales, which grow in marine, fully saline environments.
sediment. An eroded and deposited, unconsolidated accumulation of rock and mineral fragments.
sedimentary rock. A consolidated and lithified rock consisting of clastic and/or chemical sediment(s). One of the three main classes of rocks—igneous, metamorphic, and sedimentary.
shoal. n. A relatively shallow place in a stream, lake, sea, or other body of water. v. To become shallow gradually.
shoreface. The zone between the seaward limit of the shore and the more nearly horizontal surface of the offshore zone; typically extends seaward to storm wave depth or about 10 m (32 ft).

silicate. A compound whose crystal structure contains the SiO_4 tetrahedra.

siliciclastic. Pertaining to clastic noncarbonate rocks that are almost exclusively silicon-bearing, either as forms of quartz or as silicates.

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

sonar. An acronym of SOund NAvigation and Ranging, a method used in oceanography to study the ocean floor.

sorted. Said of an unconsolidated sediment consisting of particles of essentially uniform size or of particles lying within the limits of a single grade.

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

spreading center. A divergent boundary where two lithospheric plates are spreading apart. It is a source of new crustal material.

strata. Tabular or sheet-like masses or distinct layers of rock.

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

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

strike. The compass direction of the line of intersection of an inclined surface with a horizontal plane.

subduction zone. A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.

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

subsidence. The gradual sinking or depression of part of Earth's surface.

tectonics. The geologic study of the broad structural architecture and deformational processes of the lithosphere and asthenosphere.

terrestrial. Relating to land, Earth, or its inhabitants.

test. The shell or internal skeleton of many invertebrates, e.g. of an echinoid or a foraminifer.

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

trace fossil. Tracks, trails, burrows, coprolites (dung), etc., that preserve evidence of organisms' life activities, rather than the organisms themselves.

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

turbidite. A sediment or rock deposited from a turbidity current (underwater flow of sediment) and characterized by graded bedding, moderate sorting, and well-developed primary structures in the sequence noted in the Bouma cycle.

unconformity. An erosional or non-depositional surface bounded on one or both sides by sedimentary strata. An unconformity marks a period of missing time.

vesicle. A void in an igneous rock formed by a gas bubble trapped when the lava solidified.

volcanic. Describes anything related to volcanoes. Can refer to igneous rock crystallized at or near Earth's surface (e.g., lava).

water table. The upper surface of the saturated zone; the zone of rock in an aquifer saturated with water.

weathering. The physical, chemical, and biological processes by which rock is broken down.

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Additional References

This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are valid as of January 2014. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

NPS Geologic Resources Division (Lakewood, Colorado): http://nature.nps.gov/geology/

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

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

NPS Views program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks): http://www.nature.nps.gov/views/

NPS Resource Management Guidance and Documents

1998 National parks omnibus management act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf

Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html

NPS-75: Natural resource inventory and monitoring guideline: http://www.nature.nps.gov/nps75/nps75.pdf

NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/

Geologic monitoring manual (Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado): http://nature.nps.gov/geology/monitoring/index.cfm

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

Climate Change Resources

NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm

US Global Change Research Program: http://globalchange.gov/home

Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Geological Surveys and Societies

Florida Geological Survey: http://www.dep.state.fl.us/geology/

US Geological Survey: http://www.usgs.gov/

Geological Society of America: http://www.geosociety.org/

American Geophysical Union: http://sites.agu.org/

American Geosciences Institute: http://www.agiweb.org/

Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

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

Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/

GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")

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

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

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Dry Tortugas National Park, held on 23-24 January 2005, or the follow-up report writing conference call, held on 17 December 2012. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

2005 Scoping Meeting Participants

Name	Affiliation
Andrea Atkinson	NPS, South Florida/Caribbean Network
Sonny Bass	NPS, Everglades National Park
Sid Covington	NPS, Geologic Resources Division
Kevin Cunningham	U.S. Geological Survey
Robert Ginsburg	University of Miami, RSMAS
Melanie Harris	U.S. Geological Survey, Center for Coastal and Watershed Studies
Fred Herling	NPS, Everglades/Dry Tortugas National Park
Todd Hickey	U.S. Geological Survey
Kelly Jackson	University of Miami, RSMAS
Bob Johnson	NPS, Everglades/Dry Tortugas National Park
Harley Means	Florida Geological Survey
Sherry Mitchell-Bruker	NPS, Everglades National Park
Doug Morrison	NPS, Everglades/Dry Tortugas National Park
Lisa Norby	NPS, Geologic Resources Division
Matt Patterson	NPS, South Florida/Caribbean Network
Anne Poole	NPS, Geologic Resources Division
Tom Schmidt	NPS, Everglades National Park
Eugene Shinn	U.S. Geological Survey
Dewitt Smith	NPS, Everglades National Park
Trista Thornberry-Ehrlich	Colorado State University
Brigitte Vlaswinkel	University of Miami, RSMAS
Harold Wanless	University of Miami, Geological Sciences
Britton Wilson	NPS, South Florida/Caribbean Network
Linda York	NPS, Southeast Regional Office

2012 Conference Call Participants

Name	Affiliation	Position
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI Reports Coordinator
Rebecca Port	NPS Geologic Resources Division	Geologist, Technical Writer/Editor
Matt Patterson	NPS, South Florida/Caribbean Network	I&M Network Coordinator
Judd Patterson	NPS, South Florida/Caribbean Network	GIS Specialist
Rob Waara	NPS, South Florida/Caribbean Network	Network Data Manager

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of January 2014. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC. § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009**, **16 USC. § 470aaa *et seq.*** provides for the management and protection of paleontological resources on federal lands.	**36 C.F.R. § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **36 C.F.R. § 13.35** prohibition applies even in Alaska parks where the surface collection of other geologic resources is permitted. Regulations in association with 2009 PRPA are being finalized (December 2013).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.
Rocks and Minerals	**NPS Organic Act**, **16 USC. § 1 *et seq.*** directs the NPS to conserve all resources in parks (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.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Coastal Features and Processes	**NPS Organic Act, 16 USC. § 1 *et. seq.*** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). **Coastal Zone Management Act, 16 USC. § 1451 *et. seq.*** requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone. **Clean Water Act, 33 USC. § 1342/Rivers and Harbors Act, 33 USC. 403** require that dredge and fill actions comply with a Corps of Engineers Section 404 permit. **Executive Order 13089** (coral reefs) (1998) calls for reduction of impacts to coral reefs. **Executive Order 13158** (marine protected areas) (2000) requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas.	**36 C.F.R. § 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 C.F.R. § 5.7** requires NPS authorization prior to constructing a building or other structure (including boat docks) upon, across, over, through, or under any park area.	**Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.8.1** requires NPS to allow natural geologic processes to proceed unimpeded. NPS can intervene in these processes only when required by Congress, when necessary for saving human lives, or when there is no other feasible way to protect other natural resources/ park facilities/historic properties. **Section 4.8.1.1** requires NPS to: -Allow natural processes to continue without interference, -Investigate alternatives for mitigating the effects of human alterations of natural processes and restoring natural conditions, -Study impacts of cultural resource protection proposals on natural resources, -Use the most effective and natural-looking erosion control methods available, and -Avoid putting new developments in areas subject to natural shoreline processes unless certain factors are present.

NPS 364/124567, May 2014

National Park Service
U.S. Department of the Interior

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

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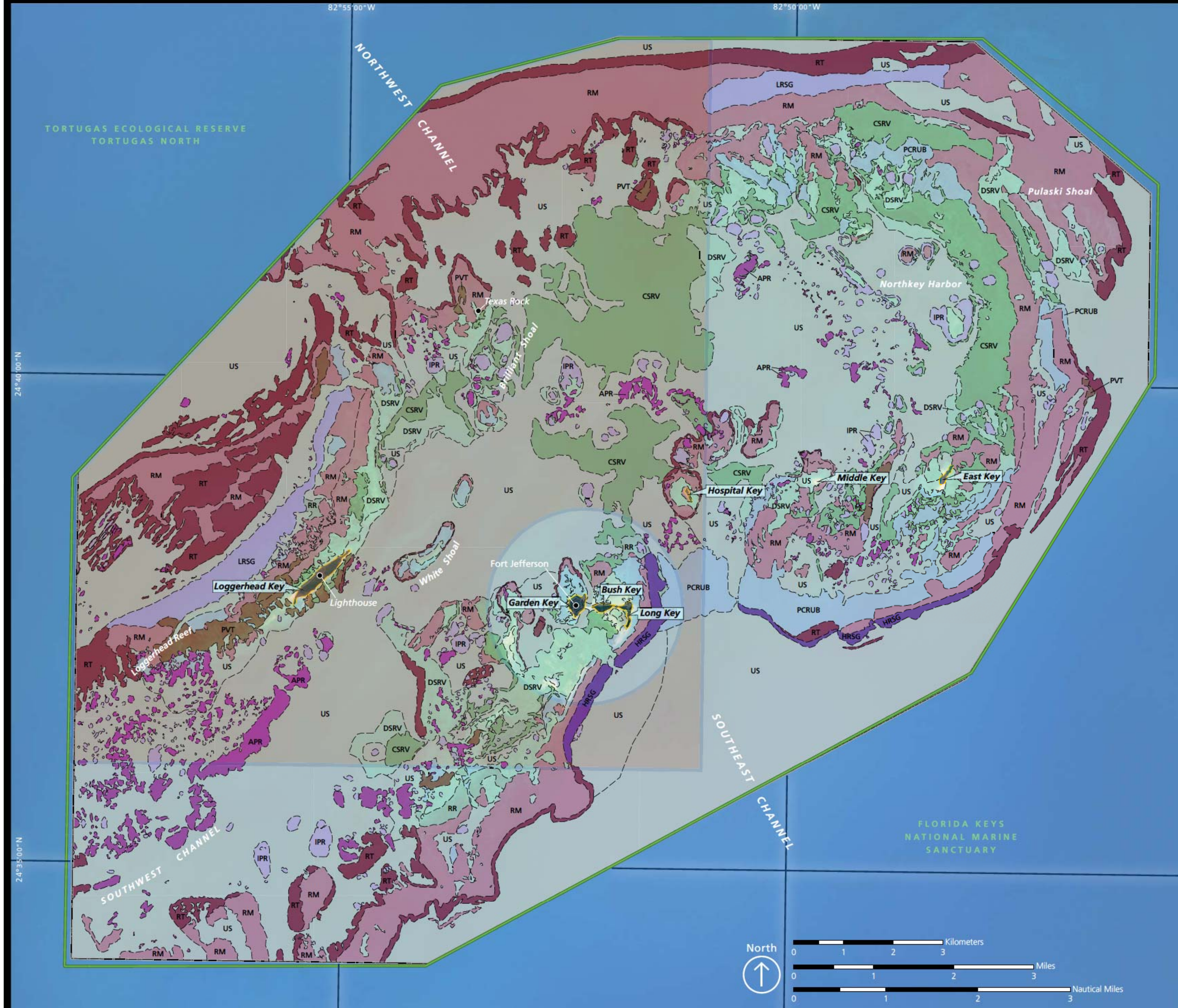
Benthic Map of Dry Tortugas National Park

Florida

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory



NPS Boundary

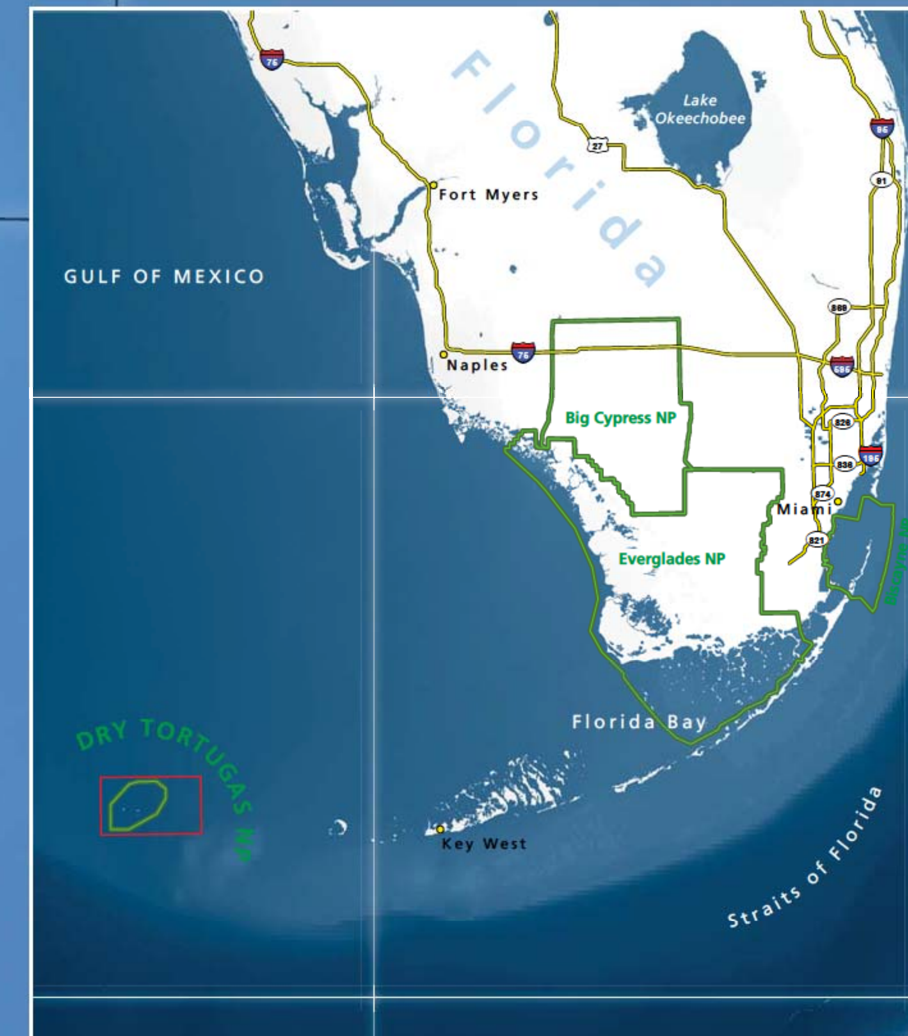
Research Natural Area

Infrastructure
- points of interest
- cities
- roads

Benthic Contacts
- approximate
- water or shoreline, approximate
- map boundary

Benthic Units

US	Unconsolidated Sediment
CSRV	Continuous SRV
DSRV	Discontinuous SRV
RT	Reef Terrace (high profile)
RM	Remnant (low profile)
HRSG	High Relief Spur and Groove
LRSG	Low Relief Spur and Groove
RR	Reef Rubble
IPR	Individual Patch Reef
APR	Aggregated Patch Reefs
PCRUB	Patchy Coral and/or Rock in Unconsolidated Bottom
PVT	Pavement
	Land



This map is an overview of compiled geologic data prepared in February 2014 as part of the NPS Geologic Resources Inventory. It is not a substitute for site-specific investigations.

The source map used in creation of the digital geologic data was:

Waara, R.J., Patterson, J.M., Estep, A.J., Atkinson, A.J., Patterson, M.E., Witcher, B.D., Estevanez, M.E., McManus, L.T., and Brandt, M.E. 2010. Dry Tortugas National Park Benthic Map (scale 1:2000). National Park Service South Florida/Caribbean Network.

For map development information refer to:

Waara, R. J., J. M. Patterson, A. J. Atkinson, and A. J. Estep. 2011. Development and policy applications of the 2010 benthic habitat map for Dry Tortugas National Park. Natural resource technical report NPS/SFCN/NRTR—2011/474. National Park Service, Fort Collins, Colorado.

As per source map scale and U.S. National Map Accuracy Standards, geologic features represented here are within 1 m (3 ft) (1:2,000 scale data) of their true location.

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

Map Unit Properties Table: Dry Tortugas National Park

Bold text corresponds to headings in the Geologic Features and Processes, Geologic Issues, and Geologic History sections of the report. Colors in the "Map Unit" column correspond to colors on the Benthic Map Graphic (in pocket).

Age	Map Unit (Symbol)	Benthic Description		Geologic Features and Processes	Geologic Issues	Geologic History
QUATERNARY (Holocene)	Unconsolidated Sediment (US)	Unconsolidated sediments with less than 10% colonization by corals or submerged aquatic vegetation. Sediments may consist of mud, sand, granules, pebbles, cobbles, shell hash, or detrital material (e.g., seagrass, algae, and leaf litter).		**Unconsolidated Benthic Sediments—** Unconsolidated sediments cover approximately 50% of the ocean floor within the park. Coarser sediments dominate the sand banks and fine sediments are found in the deeper areas of the lagoon. **Paleontological Resources—**The oldest unconsolidated sediments have been dated back to 10,000 years (Multer et al. 2002; Mallinson et al. 2003; Shinn et al. 1977). Sands contain particles of calcified algae and coral.	**Sediment Erosion and Accretion—**A channel between Garden and Bush Keys has opened and closed repeatedly since at least the early 1900s. The channel was dredged once in 1905, closed in 2000, reopened in 2004, and closed again in 2012. At the time of writing this report the channel is closed.	Broken down remains of preexisting reef building organisms from up to 10,000 years ago.
QUATERNARY (Holocene)	Submersed Rooted Vascular Plants: Continuous SRV (CSRV)	Habitat with 10% or more cover of Submersed Rooted Vascular Plants (SRV) (i.e., seagrasses and oligohaline grasses).	Continuous beds of SRV of any shoot density (i.e., sparse continuous, dense continuous, or any combination). These areas appear as continuous seagrass signatures; however, small (less than 0.2 ha [0.5 ac]) areas of bare sediment may be observed as infrequent features.	**Seagrass Beds—**Seagrass beds occupy a discontinuous ring which parallels the linear reefs on the lagoon side. A large region of continuous SRV exists in the center of the lagoon. Seagrasses occupy approximately 14% of the area of the park. Seagrasses increase sediment accumulation rates by trapping sands and other fine particles that would otherwise be carried away by currents. Their roots and rhizomes also help to stabilize the seabed. Once stabilized, seagrasses provide coastal protection against waves and erosion, and a safe harbor for marine life, including juvenile exploited reef fish species.	**Sea Level Rise—**Further research is needed to understand how the benthic environment will respond to changes in sea level. Sea level rise counteracts sediment accumulation around seagrass beds. However, if sea level rise is rapid, it may drown seagrass beds. **Hurricanes and Storms—**As of May 2007, 19.7 ha (48.7 ac) of seagrass meadows had been destroyed around Loggerhead and Bush Keys as a result of 2004–2005 hurricanes and subsequent winter and tropical storms (Morrison 2010). This loss is equivalent to nearly half of the land area in the park. Additional loss occurred in 2009 during Hurricane Ike. **Recreation and Commercial Uses—**Boat anchoring is harmful to seagrass beds.	SRV plays an important role in sedimentation, which is an ongoing geologic process. Areas of SRV have high sedimentation rates.
QUATERNARY (Holocene)	Submersed Rooted Vascular Plants: Discontinuous SRV (DSRV)	Habitat with 10% or more cover of Submersed Rooted Vascular Plants (SRV) (i.e., seagrasses and oligohaline grasses).	Areas of SRV with breaks in coverage that result in isolated patches of SRV, usually in unconsolidated bottom but also exist in hardground areas. Generally, these grass features appear as semi-round patches or elongated strands separated by bare sediment.			

Bold text corresponds to headings in the Geologic Features and Processes, Geologic Issues, and Geologic History sections of the report. Colors in the "Map Unit" column correspond to colors on the Benthic Map Graphic (in pocket).

Age	Map Unit (Symbol)			Benthic Description		Geologic Features and Processes	Geologic Issues	Geologic History
QUATERNARY (Holocene)	Coral Reef	Linear	Reef Terrace (RT)	Linear, contiguous coral formations.	Reefs with high complexity and relief greater than 2 m (7 ft). Most often has associated spur and groove and reef rubble habitats.	**Holocene Coral Reefs—**Reef terraces form a discontinuous ring around the outside of the islands and sand banks of the park. The largest area of reef terrace is northwest of Loggerhead Key. The longest continuous stretch is located near the park's northern boundary. Reef terraces occupy about 7% of the area of the park.	**Sea Level Rise—**Some rise in sea level is beneficial for corals because it gives them vertical room to grow. Corals are at risk of becoming drowned if their upward growth rate cannot keep pace with the rate of sea level rise. **Hurricanes and Storms—**Living reefs in the park are survivors of intense and frequent storm activity (Multer 1977). Reef crests and shoals typically receive the brunt of the damage (Jindrich 1972). Regeneration of reefs following a storm is a slow process. Storm-resistant coralline algae and fire coral species (*Millepora sp.*) are taking over habitat previously occupied by branching corals (*Acropora palmata* and *A. cervicornis*) (Jindrich 1972; Multer 1977; Reynolds and Steinmetz 1983). **Coral Reef Rehabilitation—**Protection and preservation of pristine coral reefs is part of the park's enabling legislation. Two species of threatened coral (*A. palmata* and *A. cervicornis*), which may be reclassified as endangered, are found within the park. Continued research and monitoring efforts will determine the best way to protect reefs and encourage new reef growth. **Recreation and Commercial Uses—**Intensive snorkeling and diving activity and boat anchoring is harmful to coral reefs. Impacts include physical contact with coral, decreased water clarity, littering, and pollution. The effects on park reefs from these activities are being assessed (Miller et al. 2010; Morrison 2010; Morrison et al. 2010; Ruzicka et al. 2012).	**Holocene Epoch: Living Coral Reefs—**Living reefs are established on top of Pleistocene reefs. Their location mimics the former locations of reefs that existed more than 125,000 years ago (Tilmant 1993; Davis 1997; Toscano et al. 2010).
			Remnant (RM)		Reefs of relief less than 2 m (7 ft) that lack distinctive spur and groove characteristics. These reefs consist of coral and hard bottom features; often support soft corals, sponges, and seagrass; and are usually found growing parallel to the reef tract, though they may form transverse features that grow perpendicular to the reef tract.	**Holocene Coral Reefs—**Remnant reefs are distributed similarly to reef terraces, although the bands tend to be thicker and more continuous. The largest area of remnant reef occurs near the park's northern boundary. Remnant reefs occupy about 16% of the area of the park.		
		Spur and Groove	High Relief Spur and Groove (HRSG)	Distinct coral bands (spurs) separated by sand or uncolonized hardbottom (grooves). This habitat type usually occurs in the fore reef zone.	The coral bands have 1.5 to 4 m (5 to 13 ft) of relief.	**Holocene Coral Reefs—**Bands of low relief spurs and grooves line the northwestern perimeter of the park where wave energy is less intense. High relief spurs and grooves are prominent in the southeast. Spurs dampen the energy of incoming waves, helping to protect the more fragile reef crests (Shinn et al. 1989). Spur and groove habitat make up only about 2% of the area of the park.		
			Low Relief Spur and Groove (LRSG)		The coral bands are oriented perpendicular to the shore or bank and have less than 1.5 m (5 ft) relief.			
		Reef Rubble (RR)		Dead, unstable coral rubble that often occurs landward of platform reefs.		**Holocene Coral Reefs—**Reef rubble occupies a very small part of the benthic environment (less than 0.5%). The largest concentration is on the lagoon side of Southeast Reef. **Geologic Materials Used in Fort Jefferson—**Coral rubble from outlying reefs appears to have been mixed in with cement made on-site and used in fort construction (Davis 1997).	None documented.	**Holocene Epoch: Living Coral Reefs—**Rubble provides evidence of formerly dominant species such as the threatened elkhorn and staghorn corals.

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Age	Map Unit (Symbol)			Benthic Description		Geologic Features and Processes	Geologic Issues	Geologic History
QUATERNARY (Holocene)	Coral Reef	Patch	Individual Patch Reef (IPR)	Irregularly shaped reef communities. They may range in size from tens to thousands of square meters. Patches are separated from each other by uncolonized hard bottom, sand, or colonized substrate with submerged aquatic vegetation, macroalgae, gorgonians or sponges. Most often the patches are surrounded by a halo or bare substrate created by foraging, obligate reef inhabitants.	Isolated, single reef without associated halo area. Individual reefs may have an associated halo. However, if the halo is large enough to be delineated at map scale, it is mapped as its own subclass.	**Holocene Coral Reefs—**Patch reefs are mostly found on the lagoon side of the islands. They are frequently surrounded by seagrass or sand. A large concentration of aggregated patch reefs exists southwest of Loggerhead Key. Patch reefs occupy less than 5% of the area of the park.	**Sea Level Rise—**Some rise in sea level is beneficial for corals because it gives them vertical room to grow. Corals are at risk of becoming drowned if their upward growth rate cannot keep pace with the rate of sea level rise. **Hurricanes and Storms—**Living reefs in the park are survivors of intense and frequent storm activity (Multer 1977). Reef crests and shoals typically receive the brunt of the damage (Jindrich 1972). Regeneration of reefs following a storm is a slow process. Storm-resistant coralline algae and fire coral species (*Millepora* sp.) are taking over habitat previously occupied by branching corals (*A. palmata* and *A. cervicornis*) (Jindrich 1972; Multer 1977; Reynolds and Steinmetz 1983). **Coral Reef Rehabilitation—**Protection and preservation of pristine coral reefs is part of the park's enabling legislation. Two species of threatened coral (*A. palmata* and *A. cervicornis*), which may be reclassified as endangered, are found within the park. Research and monitoring efforts should be directed toward determining the best way to protect reefs and encourage new reef growth. **Recreation and Commercial Uses—**Intensive snorkeling and diving activity and boat anchoring is harmful to coral reefs. Impacts include physical contact with coral, decreased water clarity, littering, and pollution. The effects on park reefs from these activities are being assessed (Miller et al. 2010; Morrison 2010; Morrison et al. 2010; Ruzicka et al. 2012).	**Holocene Epoch: Living Coral Reefs—**Living reefs are established on top of Pleistocene reefs. Their location mimics the former locations of reefs which existed more than 125,000 years ago (Tilmant 1993; Davis 1997; Toscano et al. 2010).
			Aggregated Patch Reefs (APR)		Clustered patch reefs, usually too small or too close together to map individually. Aggregated patch reefs may also occur where halos coalesce. Includes halo areas if present.			
		Patchy Coral and/or Rock in Unconsolidated Bottom (PCRUB)		Areas of primarily sand, submerged aquatic vegetation or low relief rock covered with a sand veneer. Often adjacent to spur and groove habitats. These areas contain small, individual corals or rocks that are distinctive yet a very low percentage of the total cover.		**Holocen Coral Reefs—**Approximately 4% of the park is covered by this map unit. The largest area is a discontinuous eastward thinning curved band extending from off the coast of Long Key to the south of Hospital, Middle and East keys.		
	Pavement (PVT)			Flat, low relief, mostly solid rock substrate composed of bedrock or created through syndepositional cementation of sediment (i.e., "hardground").		**Pavement—**Pavement represents less than 1% of the area of the park. The highest concentration of pavement exists around Loggerhead Key, particularly to the southwest. Octocoral communities are established in some places (Davis 1979).	None documented.	Pavement formation is a geologic process occurring in the park today. Pavement forms where calcite precipitated form algae or directly from the seawater partially cements unconsolidated sediments on the seafloor.

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Age	Map Unit (Symbol)	Benthic Description	Geologic Features and Processes	Geologic Issues	Geologic History
QUATERNARY (Holocene)	Land (Land)	Mainland, islands, causeways, and other land normally above the high tide line. The line delineating the water/land interface may be formed anywhere between the extreme low and extreme high tide marks.	**Islands and Sediment Transport—**Islands make up only about 0.2% of the area of the park. Currently seven islands composed of unconsolidated sand and coral rubble exist in the park. Beachrock is present on Loggerhead Key. The size, shape, and location of the islands are constantly changing. **Paleontological Resources—**The islands are composed of fossil material including particles of coral skeleton, coralline algae, mollusk shells, and foraminifera.	**Sea Level Rise—**Half of the coastline in the park is highly vulnerable to the physical effects of sea level rise (Pendleton et al. 2004). The very gentle slope of the coast indicates that inundation will occur rapidly under rising sea level conditions. **Hurricanes and Storms—**Hurricanes and storms can alter island morphology drastically, eroding large sections of beach in only a few hours. Waves produced by storm and hurricane winds are capable of moving large quantities of sediment very quickly. The larger and more powerful the wave, the larger the sediment size it is able to transport. Boulder size coral rubble can be moved by hurricane-generated waves. **Sediment Erosion and Accretion—**Erosion and accretion are affecting facilities on Garden Key. Sand is accreting behind a dock and at two moat locations. The shoreline between the seaplane ramp and the north coaling dock is eroding. The channel between Garden Key and Bush Key has opened and closed several times. **Subsidence**—Fort Jefferson is unevenly subsiding atop the sands and coral rubble that make up Garden Key. Efforts to stabilize the fort are ongoing. **Groundwater Flow and Salinity—**Nutrients from waste enter the marine environment via groundwater flow and surface runoff where they may have deleterious effects on marine organisms and habitats. The relationship between groundwater flow dynamics and overall marine quality must be quantitatively determined (Thornberry-Ehrlich 2005).	Shape, size, location, and existence of islands are a result of geologic processes.