National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Buck Island Reef National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2011/462

ON THE COVER
Aerial photograph of Buck Island Reef National Monument.
National Park Service photograph.

THIS PAGE
Patch reefs called "haystacks" off the north side of Buck Island Reef lagoon and beyond the barrier reef.
Photograph by Zandy Hillis-Starr (St. Croix and Buck Island NPS areas).

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

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

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Executive Summary

This report accompanies the digital geologic map data for Buck Island Reef National Monument in U.S. Virgin Islands, produced by the Geologic Resources Division in collaboration with its partners. It contains information relevant to resource management and scientific research. This document incorporates preexisting geologic information and does not include new data or additional fieldwork by the Geologic Resources Division.

Buck Island Reef National Monument is a jewel of the National Park System because of its beauty and accessibility (Bush 2009). The national monument features an emergent linear reef with some of the finest coral gardens in the Caribbean. Its interpretive snorkeling trail, the "underwater trail," provides an uncommon opportunity for discovery of a submerged, offshore world. The reef began developing on a preexisting carbonate platform during lower sea level about 7,700 years ago (Hubbard et al. 2005). The modern reef is dominated by the threatened elkhorn coral (*Acropora palmata*) (Bythell et al. 1989).

In 2006, the Geologic Resources Inventory (GRI) Program completed a digital geologic map for Buck Island Reef National Monument, which includes both geologic and benthic-habitat units. Sources of these data are Whetten (1966) and Kendall et al. (1999). As part of this report, an overview graphic illustrates these data. In addition, a map unit properties table summarizes the main features, characteristics, and potential management issues for each map unit (see "Geologic Map Data" and Attachment 1).

Guided by the priorities identified in the GRI scoping summary for Buck Island Reef National Monument (Hall 2005), this report discusses the following issues, features, and processes as significant for resource management:

- Oceanographic and Meteorological Variables. At Buck Island Reef National Monument, these variables include winds, waves, currents, tides, seawater temperature, and rainfall.
- Sea Level Rise. Sea level rise is a significant issue for coastal processes and the sustainability of coral reefs and other habitats at Buck Island Reef National Monument. Future sea level rise also will affect recreational activities by impacting beaches and the underwater trail.
- Sediment Characteristics and Distribution. The digital geologic map data for the national monument include surficial deposits and unconsolidated sediments. Whetten (1966) identified the surficial deposits (map unit symbol Qal) as sand, beach rock, and stream deposits, and also referred to these materials as "alluvium." Kendall et al. (1999) mapped unconsolidated sediments, including sand (s) and mud (mu). Information about sediment characteristics and distribution is useful for park management for a variety of reasons, including buoy placement and maintenance, boat anchoring, and identifying erosional hot spots.
- Erosion. Heavy rainfall results in runoff, erosion, and sedimentation. These processes are a concern for managers at the national monument because of the maintenance and sustainability of terrestrial trails and the viability of coral reef communities.
- Windblown Particulates. Dust storms traveling across the Atlantic Ocean transport windblown particulates from western Africa into the Caribbean basin. Scientists hypothesize that African dust carries viable microorganisms, including pathogens, nutrients such as iron, persistent organic pollutants, and metals across oceans, and that these contaminants play a role in the degradation of downwind ecosystems, including Caribbean coral reefs (Shinn et al. 2000; Garrison et al. 2003). However, no direct or causal link has yet been proven (Garrison et al. 2006). Data compiled from 2001–2008 and recently processed may help answer questions regarding the effects of African dust on coral reefs of the Caribbean, as well as human health (Garrison et al. 2011). However, interpretations and conclusions have yet to be reported from these data.
- Seismic Activity. The Caribbean is a seismically active region with periodic earthquakes, submarine slides, submarine volcanic eruptions, subaerial pyroclastic flows, and tsunamis. The location of Buck Island Reef, off the northeast coast of St. Croix, and between the Greater and Lesser Antilles, is an important tectonic position in the Caribbean region. It marks a transition from transform (strike-slip) to convergent (subduction) plate motion. The U.S. Geological Survey monitors seismic activity in the U.S. Virgin Islands at a seismic station in Puerto Rico.
- Hurricanes. Hurricanes affect both marine and terrestrial resources in both positive and negative ways at the national monument. Scouring and pounding from storm waves can reduce reefs to pavement and rubble. Swells and surging can undercut and temporarily alter beach dynamics and result in deposition of sediment on fragile coral populations. Changes in the landscape and beach profiles can affect nesting turtles. Flooding associated with storm surge can be extensive. Hurricane-force winds can destroy physical facilities. Positive aspects of storms include the rapid recycling of nutrients and the removal of excess sediment that could otherwise overwhelm a reef system.

- Paleontological Resources. Toscano et al. (2010) completed a paleontological resource inventory and monitoring report for the South Florida/Caribbean Network, including Buck Island Reef National Monument. Within the monument, fossils are known only from the reefs. However, Buck Island itself is composed of the Caledonia Formation (map unit symbol Kc), which is known to host fossils elsewhere. Future field investigations on Buck Island could recover fossils from the Upper Cretaceous Period (99.6 million to 65.5 million years ago).
- Reefs. Buck Island Reef National Monument is noted for its reef system. Impacts to reefs include hurricane damage, bleaching, disease, predation, and damage as a result of recreational activities.

This GRI report is written for resource managers, to assist in resource management and science-based decision making, but it also may be useful for interpretation. The report discusses distinctive geologic features and processes within the national monument and the geologic history leading to the national monument's present-day island and reef system. This report also provides a glossary, which contains explanations of technical and geologic terms, including terms on the map unit properties table. Additionally, a geologic timescale shows the chronologic arrangement of major geologic events, with the oldest events and time units at the bottom and the youngest at the top. The timescale is organized using formally accepted geologic-time subdivisions and ages (fig. 24).

Acknowledgements

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service Inventory and Monitoring Program. The GRI is administered by the Geologic Resources Division of the Natural Resource Stewardship and Science Directorate.

The Geologic Resources Division relies heavily on partnerships with institutions such as the U.S. Geological Survey, state geologic surveys, local museums, Colorado State University, and other universities in developing GRI products.

The GRI Program would like to thank Kim N. Hall, who prepared the scoping summary in 2005, and Zandy Hillis-Starr (Christiansted National Historic Site/Buck Island Reef National Monument/Salt River Bay National Historical Park and Ecological Preserve), Alyse Getty (Parsons Corporation), and Drew Getty (Parsons Corporation) for their input and guidance. Also, thanks to Trista Thornberry-Ehrlich (Colorado State University) for her assistance with the development of figures, and Zandy Hillis-Starr for providing many photographs used in this report.

Credits

Author

Katie KellerLynn (Colorado State University)

Review

Dennis Hubbard (Oberlin College)
Zandy Hillis-Starr (St. Croix and Buck Island NPS areas)
Jason Kenworthy (NPS Geologic Resources Division)

Editing

Jeff Matthews (Write Science Right)

Digital Geologic Data Production

Georgia Hybels (NPS Geologic Resources Division)
Heather Stanton (Colorado State University)

Digital Geologic Data Overview Layout Design

Philip Reiker (NPS Geologic Resources Division)

Introduction

The following section briefly describes the National Park Service Geologic Resources Inventory and the regional geologic setting of Buck Island Reef National Monument.

Purpose of the Geologic Resources Inventory

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The GRI, administered by the Geologic Resources Division of the Natural Resource Stewardship and Science Directorate, is designed to provide and enhance baseline information available to park managers. The GRI team relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

The goals of the GRI are to increase understanding of the geologic processes at work in parks and to provide sound geologic information for use in park decision making. Sound park stewardship requires an understanding of the natural resources and their role in the ecosystem. Park ecosystems are fundamentally shaped by geology. The compilation and use of natural resource information by park managers is called for in section 204 of the National Parks Omnibus Management Act of 1998 and in NPS-75, Natural Resources Inventory and Monitoring Guideline.

To realize these goals, the GRI team is systematically conducting a scoping meeting for each of the 270 identified natural area parks and providing a park-specific digital geologic map and geologic report. These products support the stewardship of park resources and are designed for non-geoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps and discuss specific geologic issues, features, and processes.

The GRI mapping team converts the geologic maps identified for park use at the scoping meeting into digital geologic data in accordance with their Geographic Information Systems (GIS) Data Model. These digital data sets bring an interactive dimension to traditional paper maps. The digital data sets provide geologic data for use in park GIS and facilitate the incorporation of geologic considerations into a wide range of resource management applications. The newest maps contain interactive help files. This geologic report assists park managers in the use of the map and provides an overview of park geology and geologic resource management issues.

For additional information regarding the content of this report and current GRI contact information please refer to the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/).

Establishment of Buck Island Reef National Monument

Established by John F. Kennedy in 1961, Buck Island Reef National Monument preserves "one of the finest marine gardens in the Caribbean Sea" (Presidential Proclamation 3443). In 1975, Gerald Ford (Presidential Proclamation 4346) slightly modified the boundaries, adding 12 ha (30 ac) of marine habitat. In 2001, the national monument was greatly expanded to 7,695 ha (19,015 ac) by Bill Clinton under Presidential Proclamation 7392 (fig. 1). At the same time, new regulations were enacted making the entire monument a no-take and "restricted anchoring" zone (Pittman et al. 2008). The national monument is now one of only a few fully marine protected areas in the National Park System.

Regional Information

Buck Island Reef National Monument is part of the U.S. Virgin Islands and situated in the Caribbean Sea (fig. 2). Buck Island Reef is 2.4 km (1.5 mi) off the northeastern shore of St. Croix, which is the largest of the U.S. Virgin Islands (fig. 3). Buck Island Channel separates St. Croix and Buck Island. The island rises in a single east-west ridge to an elevation of 104 m (340 ft) above sea level. It is 1,830 m (6,000 ft) long and 670 m (2,200 ft) wide at its widest point. Most of the island consists of steep slopes, 90% of which are steeper than 30%. There are two fairly level areas with sandy beaches—Diedrichs Point on the south side of Buck Island, and West Beach on the western end of the island.

Buck Island and the surrounding coral reef system support a large variety of native flora and fauna, including leatherback (*Dermochelys coriacae*) and hawksbill (*Eretmochelys imbricata*) turtles, which are both endangered species, and the green turtle (*Chelonia mydas*) and loggerhead turtle (*Caretta caretta*), which are both threatened species. Additionally, Buck Island Reef National Monument is one of only a few places in the Virgin Islands where threatened brown pelicans (*Pelacanus occidentalis*) and least tern (*Sterna antillarum antillarum*) nest.

Although the terrestrial part of the national monument provides many recreational and scenic values, the national monument's significance lies primarily in its magnificent coral reef. The eastern tip of the reef is referred to as one of the most beautiful "marine gardens" in the Caribbean Sea (National Park Service 1983). A linear reef wraps around the east end of Buck Island and represents one of the largest stands of elkhorn coral (*Acropora palmata*) in the Caribbean (fig. 4). In 2003, this species of coral was one of the first two marine-invertebrate species to be listed under the Endangered Species Act as threatened. Beyond the linear reef to the north and east, the seafloor is covered by patch reefs that rise to the surface from as deep as 9 m (30 ft). These seaward patch reefs are known as "haystacks" and are composed almost entirely of dead *A. palmata* (fig. 5).

Buck Island Reef National Monument is one of five National Park System units in the Virgin Islands. Virgin Islands National Park and Virgin Islands Coral Reef National Monument are approximately 64 km (40 mi) north of Buck Island Reef on and surrounding the island of St. John and Hassel Island (Hall and KellerLynn 2010). St. John is a volcanic island and contains extensive beaches, coral reefs, and upland forests. Christiansted National Historic Site is located in downtown Christiansted on St. Croix. The 2-ha (5-ac) historic site includes Fort Christianvaern and several other 18th- and19th- century historic buildings, which are outstanding examples of Danish-era architecture. Also on St. Croix, Salt River Bay National Historical Park and Ecological Preserve combines tropical land and water ecosystems with evidence of 2,000 years of human habitation. At 7,695 ha (19,015 ac) of land and water, Buck Island Reef National Monument is the largest National Park System unit in the Caribbean.

Although many of the natural features of Buck Island Reef National Monument are similar to the other Caribbean park units, the monument provides a different visitor experience that complements the offerings of the other parks. The relatively small size of the island and surrounding coral reef adds a feeling of intimacy. The variety of life-forms, colors, and clarity of water of the reef setting surpasses expectations (National Park Service 1984). Visitors to Buck Island Reef come to swim, sunbathe, hike, picnic, and snorkel (National Park Service 1983).

Geologic Setting

Buck Island is composed of the Upper Cretaceous (99.6 million to 65.5 million years ago) Caledonia Formation (map unit symbol Kc), which originated as sediments in a deep-marine setting at the base of an island-arc volcano. These sediments were later reworked by deep-ocean currents.

Since deposition of the Caledonia Formation, Buck Island has been pushed eastward, squeezed upward, and tilted to its present position. Exposures of Caledonia Formation occur along much of the coast of Buck Island, except along the west end. Holocene beach rock composed of consolidated carbonate sand also rings much of the island (Whetten 1966; Bythell et al. 1989).

The monument's modern carbonate environment is composed of a variety of benthic habitats, including coral reef, hardbottom, unconsolidated sediment, and submerged vegetation. These habitats accumulated on an ancient reef platform composed of limestone, which was exposed to subaerial weathering during the Pleistocene ice ages.

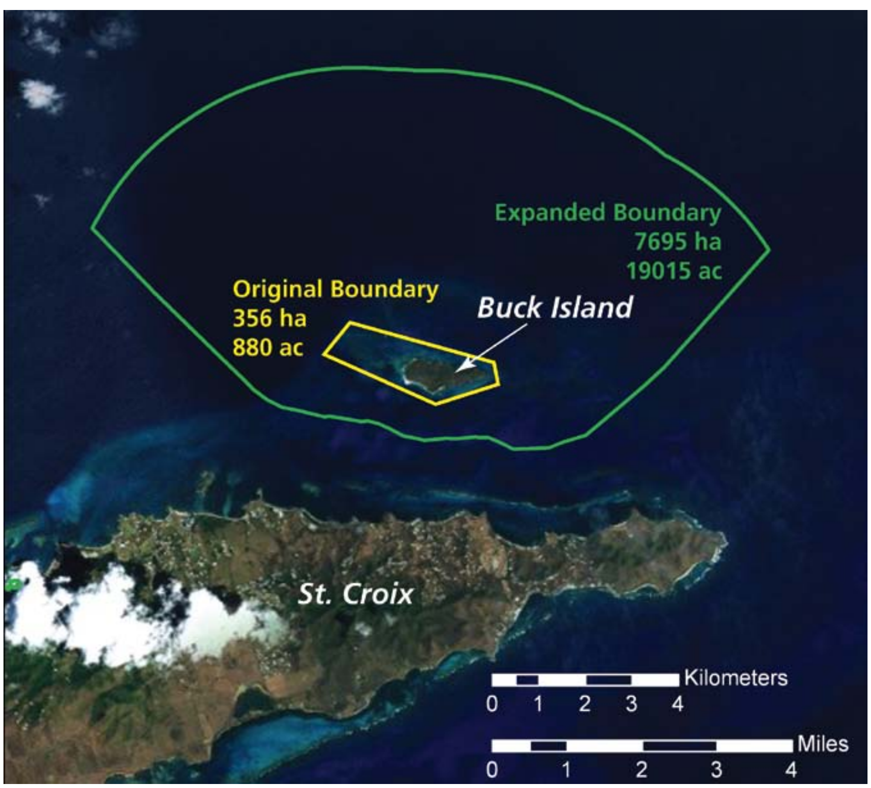


Figure 1. Boundary expansion. In 2001, presidential proclamation expanded the boundaries of Buck Island Reef National Monument. The yellow outline represents the original boundaries established in 1961. The green outline shows the expanded boundary. Aerial imagery from ESRI Arc Image Service USA Prime Imagery, compiled by Jason Kenworthy (NPS Geologic Resources Division).

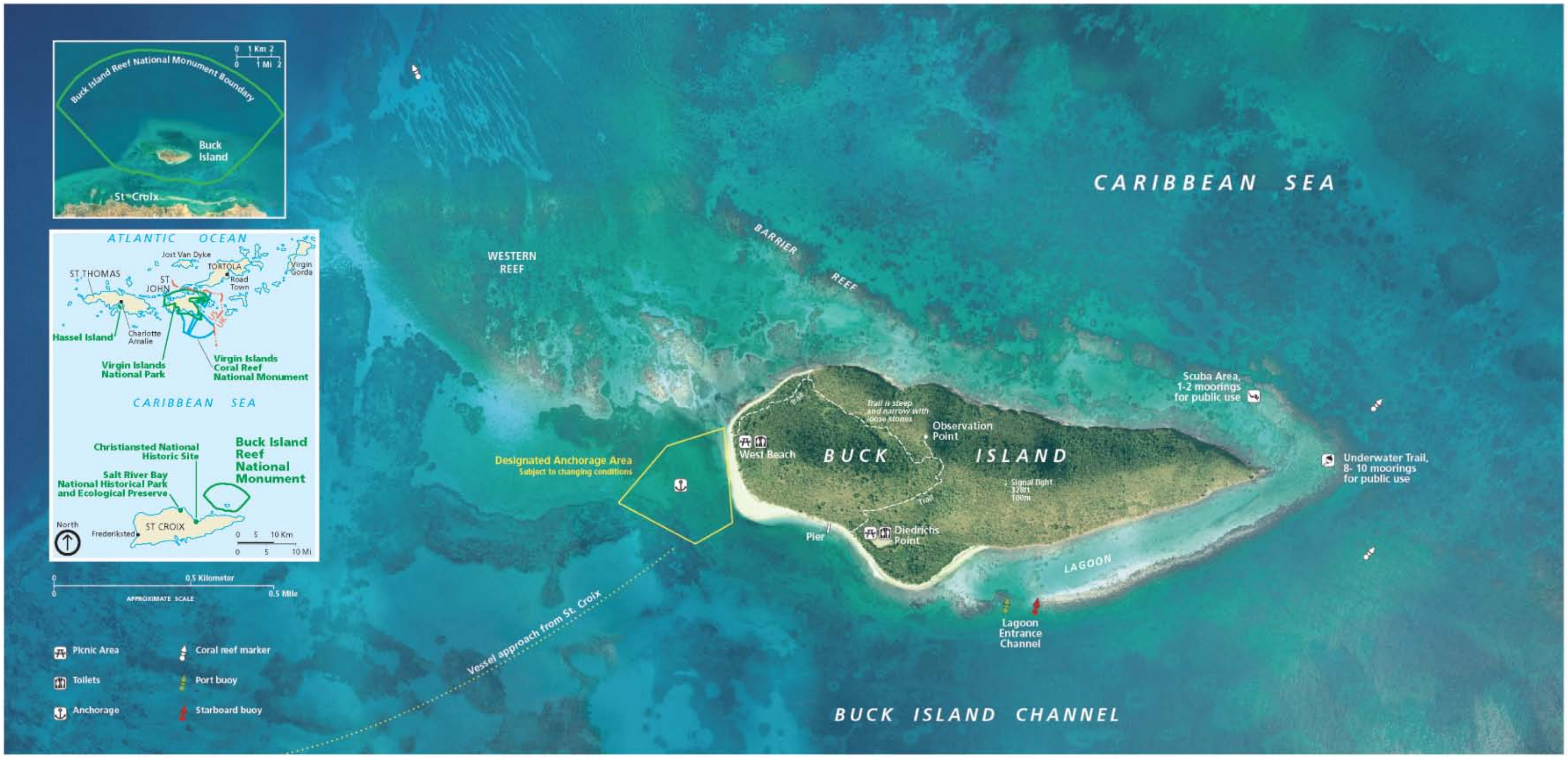


Figure 2. Location map for Buck Island Reef National Monument. Situated in the Caribbean Sea, Buck Island Reef National Monument is separated from St. Croix by Buck Island Channel. National Park Service graphic.

Figure 3. Composite aerial photograph for the main island of St. Croix, U.S. Virgin Islands. The photograph shows Buck Island Reef National Monument off the northeastern corner of St. Croix. National Park Service photograph courtesy Zandy Hillis-Starr (St. Croix and Buck Island NPS areas).

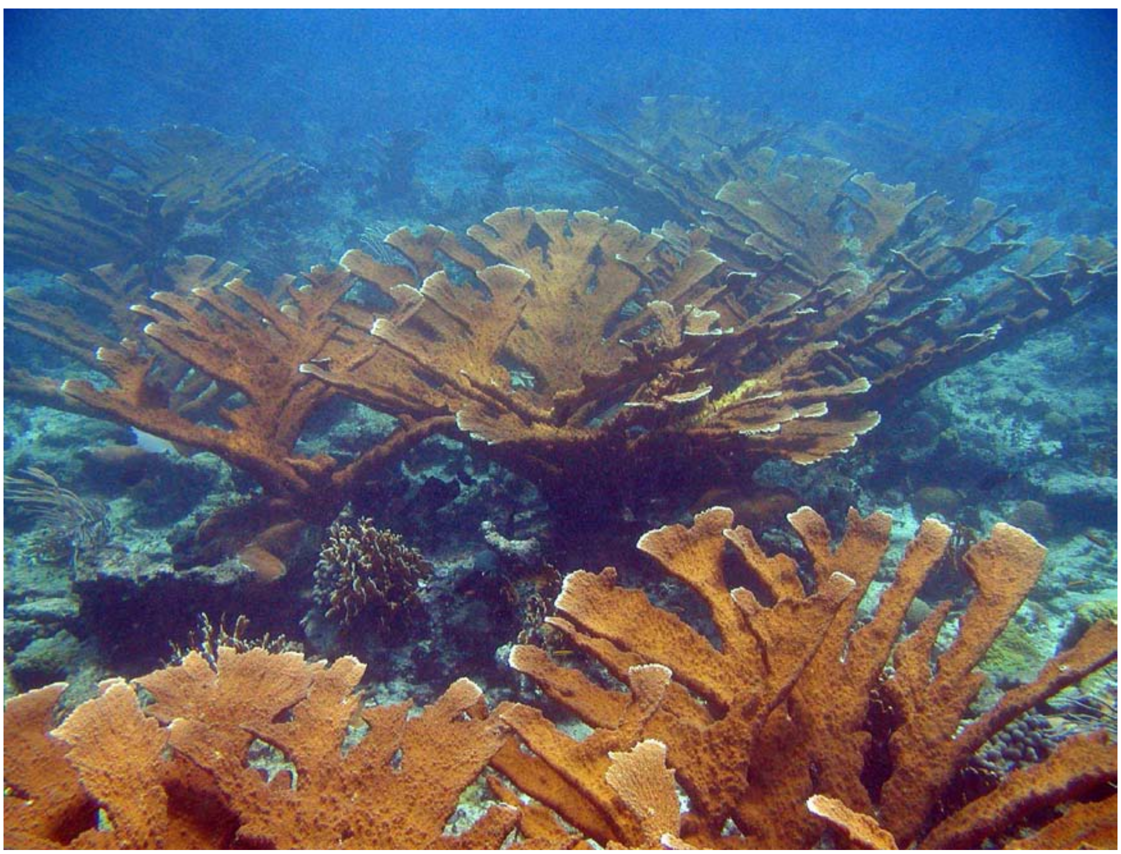


Figure 4. Elkhorn coral. Massive individual colonies of elkhorn coral (*Acropora palmata*) with branches of up to 0.5 m (1.6 ft) in diameter and several meters long are not uncommon in the dense stands near Buck Island. This photograph shows coral of the north barrier reef before the 2005 bleaching event. National Park Service photograph by Philippe Mayor (Buck Island Reef National Monument), courtesy Zandy Hillis-Starr (St. Croix and Buck Island NPS areas).

Figure 5. Haystacks. Patch reefs composed of stacked layers of dead elkhorn coral (*A. palmata*) are known as "haystacks." This is a view of the haystacks in the north lagoon at Buck Island Reef National Monument. National Park Service photograph by Zandy Hillis-Starr (St. Croix and Buck Island NPS areas).

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping meeting for Buck Island Reef National Monument on April 5, 2004, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes the scoping results, in particular those issues that may require attention from resource managers. Contact the Geologic Resources Division for technical assistance.

Participants at the GRI scoping meeting in 2004, whose names are listed in the appendix, identified the following as significant resource management issues at Buck Island Reef National Monument:

- Inventory and monitor coastal and marine processes and resources such as sediment transport, sediment thickness, coral reef populations (i.e., health, location, and species), and other benthic habitats.
- Monitor hiking trails for a significant increase in erosion.
- Investigate the possible effects of windblown particulates (i.e., Saharan dust and Montserrat dust) on resources.
- Monitor seismic activity in the Puerto Rico Trench and the Anegada Trough for earthquakes and tsunamis.

Since 2004, resource managers have identified sea level rise as a significant issue for the preservation of resources, including marine and terrestrial habitats, as well as visitor use and recreation (Zandy Hillis-Starr, Chief of Resource Management, St. Croix and Buck Island NPS areas, written communication, September 29, 2011).

Furthermore, review of management documents and the geologic literature also suggests that hurricanes are an issue of geologic significance for the national monument. Although hurricanes were not discussed during the scoping meeting, the subject is included here as a geologic issue at Buck Island Reef National Monument.

The many management issues that are associated with coral reefs such as bleaching, disease, predation, and recreational impacts are discussed in the "Features and Processes" section of this report.

Oceanographic and Meteorological Variables

Davey et al. (2007) completed a weather and climate inventory of the South Florida/Caribbean Network. This inventory identified numerous weather/climate stations within 20 km (12 mi) of Buck Island. However, none are within the national monument. Six of these stations are active, and many have fairly complete records since the mid-1940s to mid-1950s. The station at Christiansted Fort has a record since 1921 (Davey et al. 2007).

Winds

Easterly trade winds predominate in the U.S. Virgin Islands. The winds vary in direction and intensity, with maximum winds usually occurring in winter, and minimum in fall. Hurricanes usually occur between the months of June and November, with a peak in August and September (Hubbard 1989; Kendall et al. 2005; Rogers et al. 2008b). The Virgin Islands are centrally located in the trade wind belt, where the Bermuda High to the north and the Equatorial Trough to the south strongly affect oceanic and atmospheric processes. Flow around these meteorological features directs the prevailing east-to-west trade winds. These winds drive currents and waves from the northeast and east, resulting in strong east-to-west longshore drift (Hubbard et al. 1981). Shoaling from east-to-west in Buck Island Channel illustrates the regime of easterly currents (see "Currents"). However, abrupt shoaling may also be related to relict topography on a Pleistocene limestone platform (Gerhard and Cross 2005) (see "Geologic History"). Intensification of the Bermuda High and the Equatorial Trough during the winter months results in stronger winds and larger waves (Hubbard 1989).

Roughly four seasons can be defined based on wind data:

Winter (November–February): Wind speeds reach their maximum strength, blowing predominantly from the east and northeast. During the month of January, the Bermuda High is intensified, and wind speeds exceed 37 km/h (23 mph) nearly 25% of the time (Brown and Root 1974). Usually during the month of December, the locally named "Christmas Winds" blow at speeds exceeding 46 km/h (29 mph) for periods of two to three weeks. These high winds occur when cold fronts are driven to the southeast and through the Caribbean by high-pressure cells forming over North America (Hubbard 1989).

Spring (March–May): The trade winds decrease in intensity, and their approach direction is dominantly from the east (Hubbard 1989).

Summer (June–August): The trade winds increase in intensity, but a lowering of the barometric pressure within the Equatorial Trough increases the southeasterly wind component and reduces the contribution from the northeast. Warming of Caribbean and Atlantic waters during the late summer and early fall also leads to the generation of tropical storms and hurricanes (see "Hurricanes"). Local custom celebrates Hurricane Supplication Day at the beginning of "hurricane season" and Hurricane Thanksgiving at its close (Hubbard 1989).

Fall (September–November): Winds reach their minimum but still blow predominantly from the east in September and October, and the east and northeast in November (Hubbard 1989).

Currents

Currents around Buck Island Reef National Monument flow from east to west (fig. 6). Global circulation around the equator drives oceanographic currents in the region. The North Equatorial Current is deflected along the outer margin of the Windward Islands to form the Antilles Current. The South Equatorial Current passes into the Caribbean along the northern coast of South America, becoming the Caribbean Current. The Caribbean Current moves westward into the Gulf of Mexico where it enters a clockwise loop that ultimately passes south of Florida. From there, it joins the Antilles Current and the Gulf Stream (Hubbard 1989).

In general, current speeds do not exceed 10 cm (4 in) per second, though there are some exceptions. For instance, along the northwestern and southwestern corners of St. Croix, strong currents are common (Hubbard 1989). Within enclosed bays and lagoons, current circulation is dominantly wind and wave (not tidally) driven (Hubbard 1989). Knowledge of currents at headlands and in channels may reduce visitor injuries (Hall 2005).

Waves

On an annual basis, waves from the east, northeast, and southeast provide the majority of the energy expended on Caribbean shores (Hubbard 1989). In the Virgin Islands, waves come from the east nearly 60% of the time. The calmest periods are during the spring months of March–April and the fall months of September–October. Starting in November, wave intensity gradually increases to a maximum in February, with strong northeasterly and southeasterly wave components added to the easterly trade winds late in this period (Hubbard 1989).

Due to its location within the Caribbean Sea and behind the chain of northern Lesser Antilles islands, including St. John and St. Thomas to the north St. Croix, is largely protected from north Atlantic swell. Throughout the year, waves with heights less than 0.3 m (1 ft) are consistently more important on St. Croix than farther to the north. During both the summer and winter months, the wave spectrum is narrower, excluding larger swell experienced in the northern, more-exposed islands of St. Thomas, St. John, and the British Virgin Islands. Throughout the year, longer-period swell on St. Croix are confined to the southeast, with the exception of large waves that make it through the northern Anegada Passage about once a year (Hubbard 1989).

Wave heights are typically 1.0 (3.3 ft) to 2.0 m (6.6 ft) with wave periods of 5 to 7 seconds, increasing to more than 5 m (16 ft) with wave period of greater than 10 seconds during storms (Hubbard et al. 1981). Seas at the eastern end of St. Croix are typically short and about 1.0 m (3.3 ft) in height. Occasionally, North Atlantic swells reach the northern and eastern parts of the island during the winter. These long-period waves break in water depths of 10 m (33 ft) or more on the shelf edge. However, St. Croix is somewhat protected from the north and east by the northern Virgin Islands, and the "rollers" do not have the effect that they have in much of the Lesser Antilles (Adey et al. 1977).

Tides

Tidal range for the U.S. Virgin Islands is small, generally less than 20 cm (8 in) (Hubbard 1989), but can reach 40 cm (16 in) during the spring tides (Rogers et al. 2008b). Therefore, the predominant driving forces for shelf and coastal currents are wind and waves (Hubbard 1989). Tides within the region are mixed semi-diurnal (Rogers et al. 2008b).

Rainfall

According to Rogers et al. (2008b), in the U.S. Virgin Islands, rainfall is variable with no well-defined wet and dry seasons. Generally, rainfall is localized and often associated with tropical storms and hurricanes. Most rainfall occurs between August and December, and can be very intense, with significant amounts of rain falling during very short time periods. For example, in April 1983 on the north side of St. John, 48 cm (19 in) of rain fell in 21 hours. In November 2003, 28 cm (11 in) fell in 144 hours, with a total of 60 cm (24 in) for the month—one of the wettest months recorded in the past several decades (Rogers et al. 2008b). Climate-change projections for the rest of this century suggest an overall decrease in rainfall in the Caribbean, but an increased number of heavy rain events (Karl et al. 2009).

Although there are no permanent streams or rivers on the islands, brief but intense rains result in runoff into intermittent streambeds (Rogers et al. 2008b). Storm-water runoff can have profound effects on local marine sedimentation (Hubbard et al. 1981).

Seawater Temperature

Seawater temperature is extremely consistent at Buck Island Reef National Monument. According to Gladfelter et al. (1977), temperature shows an annual maximum of 29.5°C (81.5°C), which remained constant from August through November. It gradually decreased over a period of six weeks to a minimum of 26°C (79°F), which was maintained until May when the temperature again began to increase.

Climate-change projections for the rest of this century suggest increases in ocean surface temperature in the Caribbean (Karl et al. 2009), which could affect reef communities (see "Bleaching" section).

Sea Level Rise

Although not discussed during the 2004 scoping meeting, sea level rise is a current topic of concern for resource management at Buck Island Reef National Monument. With respect to geologic resources, sea level rise could impact coastal processes. In concert with wind, waves, and currents, sea level rise can trigger significant changes in the distribution and morphology of important coastal landforms and habitats, particularly on sandy beaches (National Park Service 2011). The beaches at the national monument are likely to be vulnerable to sea level rise (Zandy Hillis-Starr, Chief of Resource Management, St. Croix and Buck Island NPS areas, written communication, September 29, 2011). Sea level rise is also a concern for rocky shorelines, where increasing water levels can permanently flood or isolate critical habitats (National Park Service 2011). In addition, sea level rise could impact the popular underwater trail (Zandy Hillis-Starr, Chief of Resource Management, St. Croix and Buck Island NPS areas, written communication, September 29, 2011). Rising seas also cause saltwater contamination of coastal groundwater and surface waters, and exacerbate the impacts of coastal storms (National Park Service 2011). In addition, concern arises for the protection of coral reefs, sea turtle–nesting habitat, and coastal habitat for the globally endangered St. Croix ground lizard (*Ameiva polops*) at Buck Island Reef National Monument.

In order to understand how future sea level rise will affect coastal areas within the National Park System, the NPS Geologic Resources Division is working in conjunction with the U.S. Geological Survey and Woods Hole Oceanographic Institute, and has developed a coastal vulnerability index (CVI). This is a quantitative tool used by park managers and scientists to predict future changes to park shorelines. The geologic factors and physical processes considered in the CVI include relative sea level, wave height, tidal range, coastal erosion rate, slope, and geomorphology. Although a CVI for Buck Island Reef National Monument has not yet been prepared, Pendleton et al. (2004) prepared a CVI for Virgin Islands National Park, which may have some application to Buck Island Reef National Monument.

For the CVI at Virgin Islands National Park, investigators collected data at Charlotte Amalie on St. Thomas. These data indicate a sea level rise of 0.5 ± 0.74 mm (0.02 ± 0.03 in) per year, wave heights from 1.0 to 1.9 m (3.3 to 6.2 ft), and a mean tidal range of 0.262 m (0.860 ft) (Pendleton et al. 2004). As climate warms over the coming decades, globally averaged sea level may rise between 0.19 and 0.58 m (7.5 in and 1.9 ft) by 2100 (Meehl et al. 2007; Karl et al. 2009). The CVI for Virgin Island National Park showed that 13% of the coast within the national park is highly vulnerable to shoreline change resulting from future sea level rise. The research showed that beaches at Trunk Bay, Cinnamon Bay, and Ram Head are the most likely to experience extreme shoreline change. In addition, the CVI designated 29% of the coast within the park as highly vulnerable, 28% as moderately vulnerable, and 29% as minimally vulnerable (fig. 7).

Sediment Characteristics and Distribution

Information about sediment characteristics and distribution is useful for park management for a variety of reasons, including, but not limited, to buoy placement and maintenance, boat anchoring, and identifying erosional hot spots (Hall 2005). Moreover, an understanding of the system's sediment supply is critical for monitoring coastal areas and predicting shoreline change (Hall 2005). In 2004, scoping participants recommended that sediment thickness, type, and grain size be integrated into park maps. The source data for the digital geologic map for Buck Island Reef National Monument are Whetten (1966) and Kendall et al. (1999). Whetten (1966) mapped Quaternary alluvium (Qal), and Kendall et al. (1999) mapped areas of unconsolidated sediment, namely sand (s) (see "Geologic Map Data").

Nearshore Sedimentation Patterns

Studies conducted on the beach at the western end of Buck Island revealed a general seasonality to sedimentation patterns (Hubbard 1980). Between late fall (October–November) and late spring (April–June), there is a general onshore movement of sediment, probably from the nearshore area west and northwest of Buck Island. During summer and early fall (July–September), the tendency is towards off-beach transport and a net loss (figs. 8 and 9).

Superimposed on this exchange is a seasonal shifting of sediment back and forth between the southwestern and western beaches (fig. 8). During the late fall, winter, and spring, sediment is transported in a counterclockwise direction, moving sand from the western beach to the southwestern beach. During summer and early fall, sediment is moved in a clockwise direction around the island, reversing transport between the southwestern and western beaches (Hubbard 1980).

Marine Sedimentation

According to Gerhard and Cross (2005), the sediments within Buck Island Channel (between Buck Island and St. Croix) are mostly fine-grained carbonate sands composed of *Halimeda* (macroalgae), mollusks, foraminifera, and coral (fig. 10). Open sand areas in the channel are mostly coarse-grained and poorly sorted (Gerhard and Cross 2005). They contain standing crops of coral and are covered with thin mats of filamentous algae. Hummocky topography occurs where sand bodies are burrowed, particularly by mound-building shrimp (*Callianassa* sp.). In shallow waters, the sand bodies may be rippled (Gerhard and Cross 2005).

Sediments in the lagoon at Buck Island Reef National Monument are typically bi-modal (coarse and fine sands) and poorly sorted (Levin 1978). Hubbard (1979) suggested that grain size in carbonate environments needs to be adjusted to a "terrigenous equivalent" for a more accurate picture of lagoon systems. In systems composed of terrestrial detritus, coarse grains indicate a higher energy environment. However, such an interpretation of coarse *Halimeda* grains in the Buck

Island lagoon, which grow there, would lead to an inaccurate sediment transport model for this locale.

In both lagoon and open-shelf environments, grass beds and algal mats effectively stabilize the substrate during most fair weather conditions. During storms, however, strong, wave-generated, oscillatory and unidirectional currents move large quantities of carbonate material off the shelf (Hubbard et al. 1981). Near the shelf edge, gravitational effects can locally enhance off-shelf transport, but overall this process is quantitatively unimportant (Hubbard et al. 1981).

Factors controlling marine sediment transport are biological, gravitational, and physical, which vary depending on location—shore, nearshore lagoon, or outer shelf (Hubbard et al. 1981). In the shore zone, physical processes such as longshore transport dominate. In lagoons protected by reefs, biological processes dominate; grazers and burrowers rework and greatly modify sediment character and distribution in this depositional environment. Waves then transport sediment that has become suspended via bioturbation within and out of the nearshore lagoon zone. Physical processes, in particular wave-generated currents, dominate in the outer shelf zone.

Erosion

Intense rainfall can cause runoff, erosion, and sedimentation. Dredging and a heavy concentration of boat and human traffic also can cause sedimentation (Gladfelter et al. 1977). Erosion is a concern for park managers because of the maintenance and sustainability of terrestrial trails and the viability of coral reef communities. Suspended sediment washing into marine waters interferes with the ability of zooanthellae (symbiotic algae of coral) to photosynthesize by decreasing the amount of light that can be transmitted through the water. Sediment deposited on the coral itself buries the animal and prevents it from feeding (Pinet 1992).

Another erosion-related issue is the threat that beach erosion could cause to cultural resources. Cultural resources within the national monument include prehistoric and historic archaeological sites on land, as well as offshore shipwrecks.

In 1976, the National Park Service reported erosion as a problem in a few areas along the terrestrial hiking trail (National Park Service 1976). Park staff clears the trail of overgrowth biannually, at which time evidence of erosion is documented and corrected (National Park Service 1976). However, the problem appears to be chronic, and in 2004, scoping participants noted erosion of hiking trails as a concern. Scoping participants suggested that further study was needed because of the negative effects that terrestrial sedimentation can have on water quality and adjacent marine habitats, including coral reefs and seagrass beds (Hall 2005).

Bush (2009)—the chapter about monitoring coastal features and processes in *Geological Monitoring* (Young and Norby 2009), a guide for monitoring geologic "vital signs"—outlined methods for monitoring suspended sediment in the water column, which may indicate seasonal or event-related influx of sediment or degrading conditions caused by increased runoff from land over time.

Hubbard (1980) noted that heavy rain associated with hurricanes and tropical storms will increase erosion especially on the terrestrial trails. In 1979, Hubbard documented erosion during Tropical Storm Frederick and identified the footpath leading to West Beach as a major pathway for runoff, with serious erosion occurring locally. As an outcome of Hurricane Omar, which impacted the national monument in 2008, in 2010, the National Park Service installed water bars above an area severely eroded by storm-water runoff, referred to as the "north gut area," as well as constructed some steps along the trail to aid hikers. Resource managers have identified two dominant "guts" or drainages, which "run" after heavy rainfall events or hurricanes. In 2010 park staff observed freshwater flowing out between the rock layers at the base of the cliff formations all along the south shore and West Beach. However, improved vegetation growth and the reduction in nonnative, invasive plants are allowing the return of native plants, which seem to be mitigating the erosional effects of water running out of the guts, both on the north and south shores (Zandy Hillis-Starr, Chief of Resource Management, St. Croix and Buck Island NPS areas, written communication, September 29, 2011). Starting in 2003, the ongoing control of nonnative, invasive vegetation, such as tantan (*Desmanthus virgatus* (L.) Willd.) and various species of bunchgrass, as well as increased rainfall, have resulted in the regrowth of native vegetation along the side of the trail. This seems to be controlling excessive sediment loss, as well as keeping the south side salt pond filled with water almost annually (Zandy Hillis-Starr, Chief of Resource Management, St. Croix and Buck Island NPS areas, written communication, September 29, 2011).

Windblown Particulates

The U.S. Geological Survey estimates that eolian processes transport billions of tons of dust yearly from western Africa into the Caribbean basin and the southeastern United States. Fine particles are eroded from the surface of the Sahara Desert and the Sahel of West Africa, lifted into the atmosphere by convective storms, and transported thousands of kilometers downwind. Dust air masses predominately impact northern South America during the Northern Hemisphere winter and the Caribbean and southeastern United States in summer. Dust concentrations vary considerably temporally and spatially (Garrison et al. 2011).

African dust, also called Saharan dust, travels quickly across the Atlantic Ocean at altitudes as high as 4,570 m (15,000 ft). The intercontinental journey takes approximately five to seven days and transports a wide variety of particulates and organisms (Kellogg and Griffin 2003). Dust particulates may harbor a spectrum of toxic substances, nutrients, organic pollutants, hydrocarbons, and polychlorinated biphenyls. In addition, African dust carries a high percentage of microbes, including bacteria, fungi, and viruses, which may have a detrimental effect on ecosystem health. Many of the microbes carried within the windblown particulates are destroyed by ultraviolet radiation. However, as many as 100 microbes per gram of soil survive the journey. During dust pulses, air samples contain three to 10 times more microbes than normal levels in the Virgin Islands (Kellogg and Griffin 2003). Roughly 30% of these microbes are pathogenic and are potentially dangerous to people and the environment (Kellogg and Griffin 2003).

African dust may be directly linked to the decline of many Caribbean marine species including corals, sea fans, and sea urchins. Studies have shown a direct correlation between African dust pulses and marine ecosystem deterioration (Kellogg and Griffin 2003). Increased drought conditions in the Sahara and Sahel deserts since the 1970s correspond to increased bleaching and disease in Caribbean corals (see "Reefs"). In addition, Caribbean air samples contain many diseases such as the soil fungi, *Aspergillus*. One particular strain, *Aspergillus sydowii*, is directly responsible for a major Caribbean epizootic called sea-fan aspergillosis (Kellogg and Griffin 2003).

U.S. Geological Survey scientists are conducting investigations into the effects of Saharan dust on resources (Hall 2005). The study area includes sample sites on St. John and St. Croix in the U.S. Virgin Islands (Garrison et al. 2006). Scientists hypothesize that African dust carries viable microorganisms, including pathogens, nutrients such as iron, persistent organic pollutants, and metals across oceans and that these contaminants play a role in the degradation of downwind ecosystems, including Caribbean coral reefs (Shinn et al. 2000; Garrison et al. 2003). However, no direct or causal link has yet been proven (Garrison et al. 2006). Data compiled from 2001–2008 and recently processed may help answer questions regarding the effects of African dust on downwind coral reefs of the Caribbean (Garrison et al. 2011), as well as human health (Garrison et al. 2010). However, interpretations and conclusions have yet to be drawn from these data. Data are available at http://pubs.usgs.gov/ds/571/ (accessed October 21, 2011).

The NPS Air Resources Division provides technical assistance to parks with windblown-dust issues and is currently monitoring atmospheric deposition at Virgin Islands National Park (National Park Service 2009).

Seismic Activity

The Caribbean is a seismically active region (fig. 11). The Greater Antilles are located along the northern margin of the Caribbean plate (fig. 12), which is moving eastward at about 2 cm (0.8 in) per year with respect to both the North American and South American plates. The Caribbean plate is bounded on the north by a left-lateral, strike-slip fault. The southern margin of the plate is marked by a right-lateral, strike-slip fault. The eastern boundary of the Caribbean plate is a west-dipping subduction zone, down which Atlantic oceanic crust is descending, and in turn producing the island-arc volcanoes of the Lesser Antilles. Volcanic activity occurs as far north as the island of Saba (Rankin 2002).

Buck Island is situated between the Greater Antilles and the Lesser Antilles. This location (i.e., the northeastern corner of the Caribbean plate) is an important tectonic position in the Caribbean region. It marks a transition from transform (strike-slip) plate motion, which is indicative of the Greater Antilles, to convergent plate motion (subduction), represented by the volcanic arc of the Lesser Antilles.

Periodic seismic activity, including earthquakes, submarine landslides, submarine volcanic eruptions, subaerial pyroclastic flows, and tsunamis are common throughout the region. In particular, an active fault zone lies approximately 160 km (100 mi) north of Buck Island Reef National Monument in the Puerto Rico Trench (Miller et al. 1999). The Puerto Rico Trench is a depression in the ocean floor that reaches depths of 9,219 m (30,249 ft), making it the deepest known part of the Atlantic Ocean (Miller et al. 1999). In addition, the Anegada Trough, which separates St. Croix from the rest of Virgin Islands, poses a significant threat of tsunami (Office of Disaster Preparedness 1997). In 1867, a 7.5-magnitude earthquake occurred on one of a series of intraplate faults that bounds the Anegada Trough. This earthquake generated two large tsunamis that produced waves in excess of 7 m (23 ft), causing loss of life and structural damage on St. Croix.

Currently, the U.S. Geological Survey monitors earthquake activity in the U.S. Virgin Islands at a seismic station in Puerto Rico (U.S. Geological Survey 2010). Furthermore, the Virgin Island Emergency Management Team automated system reports earthquakes in the area north of St. Croix. Earthquakes, ranging from magnitude 4.0 to 4.5 on the Richter scale, occur on a weekly, if not daily, basis (Zandy Hillis-Starr, Chief of Resource Management, St. Croix and Buck Island NPS areas, written communication, September 29, 2011).

Hurricanes

Since its establishment in 1961, Buck Island Reef National Monument has sustained seven tropical storms and eight hurricanes (table 1). The most destructive to date was Hurricane Hugo in 1989. During the night of September 17, 1989, the eye of Hurricane Hugo passed over St. Croix. Central pressure dipped to 918 millibars, and the storm slowed to a forward speed of only 14 km/h (9 mph) (Rogers 1992). As a result, Hugo brought 14 hours of sustained winds of 241 km/h (150 mph) with gusts up to 274 km/h (170 mph). On St. Croix's north coast, wave heights reached 7 m (23 ft), with larger waves estimated for the south shore (Hubbard et al. 1991).

The hurricane season runs from late summer through early fall with maximum frequency in late August and early September. At this time, circumtropical waters are at their warmest, and numerous tropical storms and hurricanes are generated in the Atlantic Ocean and move westward into the Caribbean region. There are two dominant storm tracks through the region: one passes to the north of the Antilles and into the northern Bahamas; the other enters the eastern Caribbean midway along the Windward Island chain and passes to the south of St. Croix and into the southern Gulf of Mexico (Hubbard 1989). The approach of most hurricanes to the area is from the southeast (Hubbard et al. 2005).

Impacts to Terrestrial Resources

When considering the impacts of hurricanes on terrestrial systems, beach erosion is typically a major issue for NPS resource managers at "coastal parks." However, at Buck Island Reef National Monument, storm-induced beach erosion is simply a perturbation in the overall effect of the seasonal erosion-deposition pattern (Hubbard 1980). This is partially related to the paths typically taken by storms. The position of the western beach on the leeward shore affords protection from the most intense wave action, and erosion is therefore less than might be expected. Investigators reached this conclusion after studying changes in beach profiles at the western end of Buck Island before and after Tropical Storm Frederick and Hurricane David in 1979. These patterns are probably representative of what would occur during most storms (Hubbard 1980). Notably, most of the wave-related damage occurred along the westerly facing beaches (of the western beach). Erosion on the southerly facing beaches was related to storm runoff (Hubbard 1980) (see "Erosion").

The nature of post-storm recovery is controlled by seasonal patterns (Hubbard 1980). Whether a beach recovered or continued to erode after the storm was entirely a function of the normal seasonal trend. In areas of normally high sedimentation in the fall, erosion was only slight. Where less accretion was occurring at the time of the storm, beach profiles showed more storm effects.

This is not to say that beaches are not impacted during storms. Swells and surging can undercut and temporarily alter beach dynamics and result in deposition of sediment on fragile coral populations (National Park Service 1976). During Hurricane Hugo, the south shore in particular was affected by high storm surge, which cut 3 m (10 ft) to 5 m (15 ft) deep into the permanent landscape, eroding out adult trees (Hillis 1990). This, in turn, affected the nesting areas of the endangered hawksbill turtle (*Eretmochelys imbricata*). Along the north-shore nesting area, all shoreline trees, which are predominantly manchineel (*Hippomane mancinella*), were laid down parallel to the shore, which blocked access to the beach forest, which is the normal nesting areas of the turtles. In addition to the wall of fallen trees, storm erosion increased the height of the beach berm by up to 0.9 m (3 ft), which effectively closed these areas to hawksbill nesting (Hillis 1990). The obstacles along the southeast and north shores pushed the hawksbill to nest on the open beach (West Beach), which is not their normal nesting habitat. As a result of changes in the landscape and beach profile, an estimated 80% of the 55 confirmed nests on the beach that were incubating prior to Hurricane Hugo were lost in the storm or unable to be relocated afterward (Hillis 1990).

Additionally, the forces of wind can destroy physical facilities. Buck Island Reef National Monument is the first National Park System unit in the vicinity of St. Croix to be closed in preparation for storm-related winds; the island is closed 72 hours before a direct strike on St. Croix (Zandy Hillis-Starr, Chief of Resource Management, St. Croix and Buck Island NPS areas, written communication, September 29, 2011). On Buck Island, storm activity impacts rain shelters and comfort stations. In 2008, Hurricane Omar caused damage at facilities and beaches, requiring removal of debris from the shoreline and the hiking trail system, as well as requiring replacement of the damaged pier, turtle-nesting area markers, and rain gauges. High winds damaged roofs, gutters, doors, and barbeque grills at the picnic area at Deidrichs Point, and downed many trees (National Park Service 2010).

Besides wind damage, flooding associated with storm surge can be extensive (National Park Service 1983). Visitor-use areas at West Beach and Diedrichs Point are within the 100-year floodplain. According to the national monument's general management plan, however, the hurricane and warning evacuation system is sufficient to prevent danger to visitors (National Park Service 1983).

Impacts to Marine Resources

Hurricanes have caused significant deterioration of the coral reefs at Buck Island Reef National Monument (Rogers et al. 2002). Scouring and pounding from storm waves during Hurricane Hugo destroyed nearly 100% of the south reef in 1989 (National Park Service 1994) (fig. 13). This area of reef was reduced to pavement, and the coral rubble that was generated was transported onto the reef crest, forming a raised berm 30 m (98 ft) landward (Hubbard et al. 1991).

On the southeast forereef of the underwater trail, storm waves piled dead coral rubble on the reef crest, 0.3 m (1 ft) to 0.6 m (2 ft) high. Large branches of elkhom coral (*A. palmata*) were broken, exposing cross-sections of white skeleton, ranging from 20 cm (8 in) to 25 cm (10 in) in diameter. Park rangers patrolling the area also observed extensive breakage among the other coral species. For example, fire coral (*Millepora complanata*), normally erect along the reef crest, was crumbled and piled up along the foot of the forereef (Hillis 1990). However, all underwater interpretive signs except one were still in place, and all visitor moorings were still intact (Hillis 1990).

Rogers (1992) put the damage caused by Hurricane Hugo into perspective and made the following conclusions:

- The physical force of waves and impacts from storm-generated debris damage coral reefs. Organisms that survive remain to repopulate the system.
- Damage to corals will be less if there was a previous storm. However, if successive storms occur only a few years apart, damage could be especially severe because of the dislodging of loose storm debris and coral fragments that are not yet cemented to the substrate.
- In general, damage is greatest in shallow water. However, where steep slopes are present, mid-slope corals and storm-generated debris may actually fall or be transported into deeper water, causing extensive destruction.
- Total live coral cover, the preferred assessment strategy by Rogers et al. (1991), generally decreases as a result of storms. However, coral cover may increase in some areas after storms because of transport of live coral fragments into areas with relatively low cover. Over the long-term, total coral cover may also increase as corals grow and settle on rubble piles and other new substrates. In general, overall live cover from invertebrates, particularly gorgonians and sponges, will decrease after a storm.

Environmental Aspects of Storms

Although the damage wrought by hurricanes on reef systems can be severe, some investigators have highlighted the more positive roles that storms play. For instance, an immediate, beneficial effect of storms is the decay of moribund tissue or coral fauna, and the rapid recycling of nutrients. Newly available nutrients may have contributed to the rapid growth of the fleshy algae that occurred on the reef crest and forereef of the south reef at Buck Island after Hurricane Hugo (Gladfelter et al. 1990).

In addition, storms facilitate reef development by flushing excess sediment that would otherwise overwhelm the reef (Sadd 1984). Hubbard (1992) found that "hurricane export" plays a significant role in maintaining the dynamic balance between sediment production and sediment removal.

Gladfelter and Monahan (1977) observed that the form of shallow-forereef coral seems to be affected by the strength of water movement. After heavy storms, more branches are freshly broken in the shallow-forereef zone than in either the deep forereef or backreef zones. The shallow-forereef branch tips are much thicker than those of the other zones, with a more nearly circular cross section. This shape is structurally much stronger than in the other zones because it presents a minimum surface area to volume ratio (Gladfelter and Monahan 1977).

Hubbard (1989) found that storms likely play an important role in the distribution of reef-crest communities throughout the Caribbean (table 2).

Finally, it is worth noting that the greatest recovery of *A. palmata* occurred after the south reef was leveled by Hurricane Hugo (Dennis Hubbard, professor, Oberlin College, written communication, January 21, 2011). In 1989, the species was virtually absent along the monitoring profiles at the national monument and was rarely reported by casual diver observations. Starting after that, however, *A. palmata* was increasingly reported. Initially, it reached heights of approximately 30 cm (12 in) and was toppled by storm waves, owing to the instability of the substrate after Hurricane Hugo. As the substrate naturally cemented together, however, *A. palmata* colonies appear to have grown to larger sizes. Whether Hurricane Hugo triggered this sequence is unknown, but the appearance of the species (albeit in still low numbers) is suggestive.

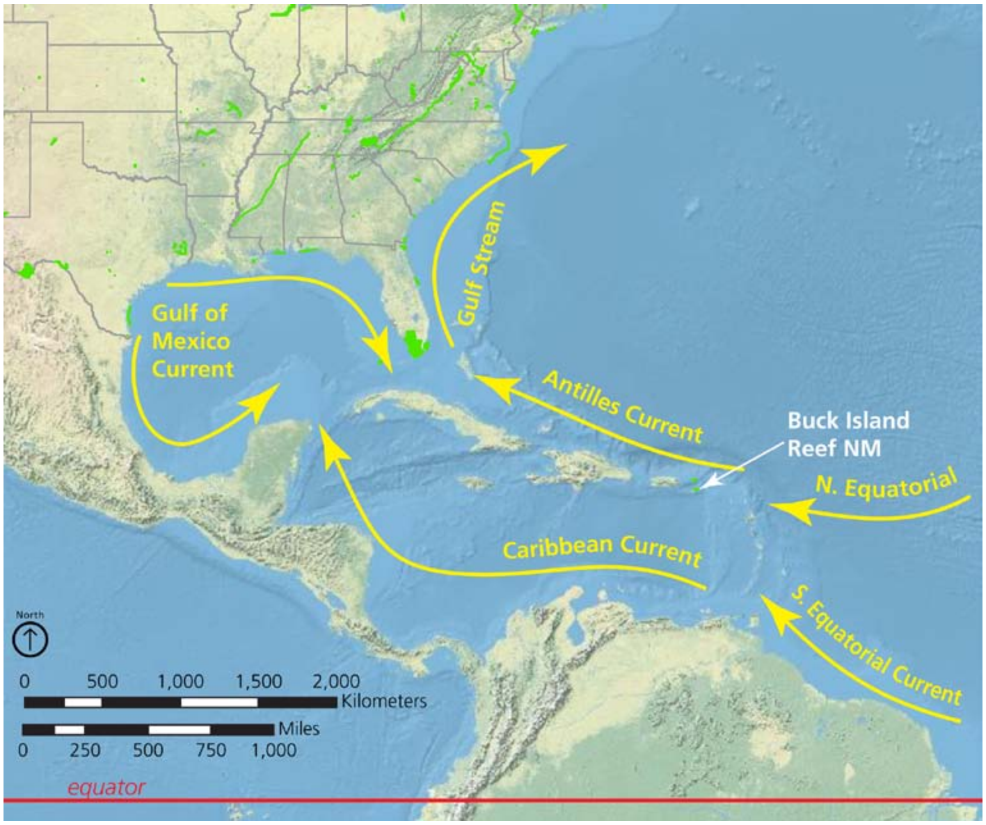


Figure 6. Major oceanographic currents. Global circulation around the equator drives oceanographic currents in the Caribbean. Currents around Buck Island Reef National Monument flow from east to west. Current directions after Hubbard (1989). Aerial imagery from ESRI Arc Image Service, USA Prime Imagery, compiled by Jason Kenworthy (NPS Geologic Resources Division).

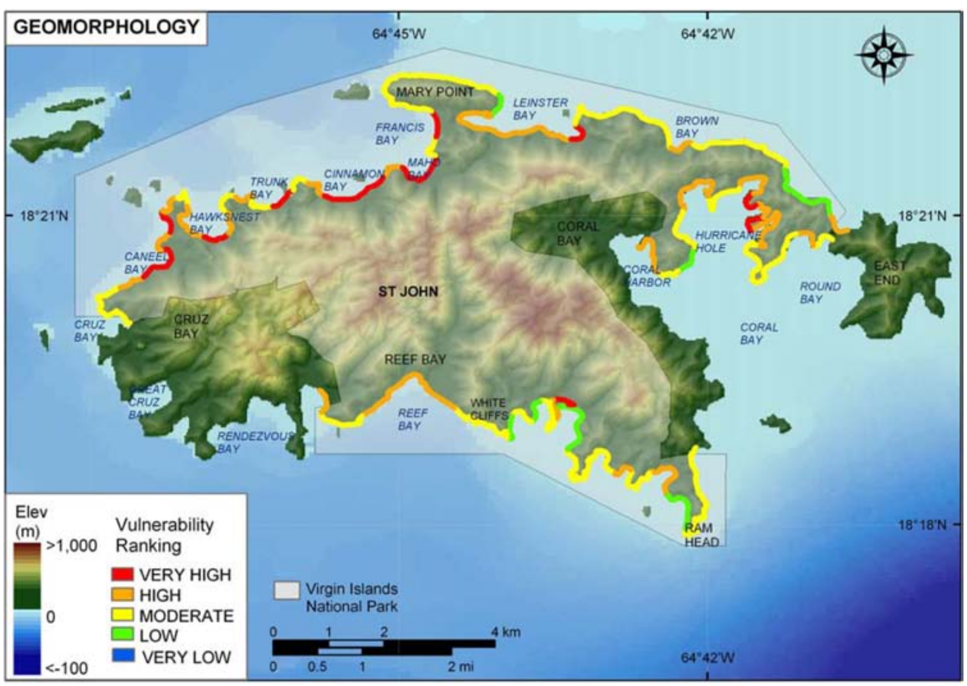


Figure 7. Coastal Vulnerability Index (CVI) for Virgin Islands National Park. The U.S. Geological Survey completed a CVI for Virgin Islands National Park in 2004. The colored shoreline represents the variations in coastal geomorphology within the park. The very high vulnerability geomorphology is mostly sand beaches or mangrove wetlands. High vulnerability geomorphology includes gravel or cobble-sized beaches or cliff-backed beaches. Moderate vulnerability geomorphology consists of alluvium or fringing reefs fronting low cliffs. Low vulnerability geomorphology includes medium cliffs and rock headlands. From Pendleton et al. (2004).

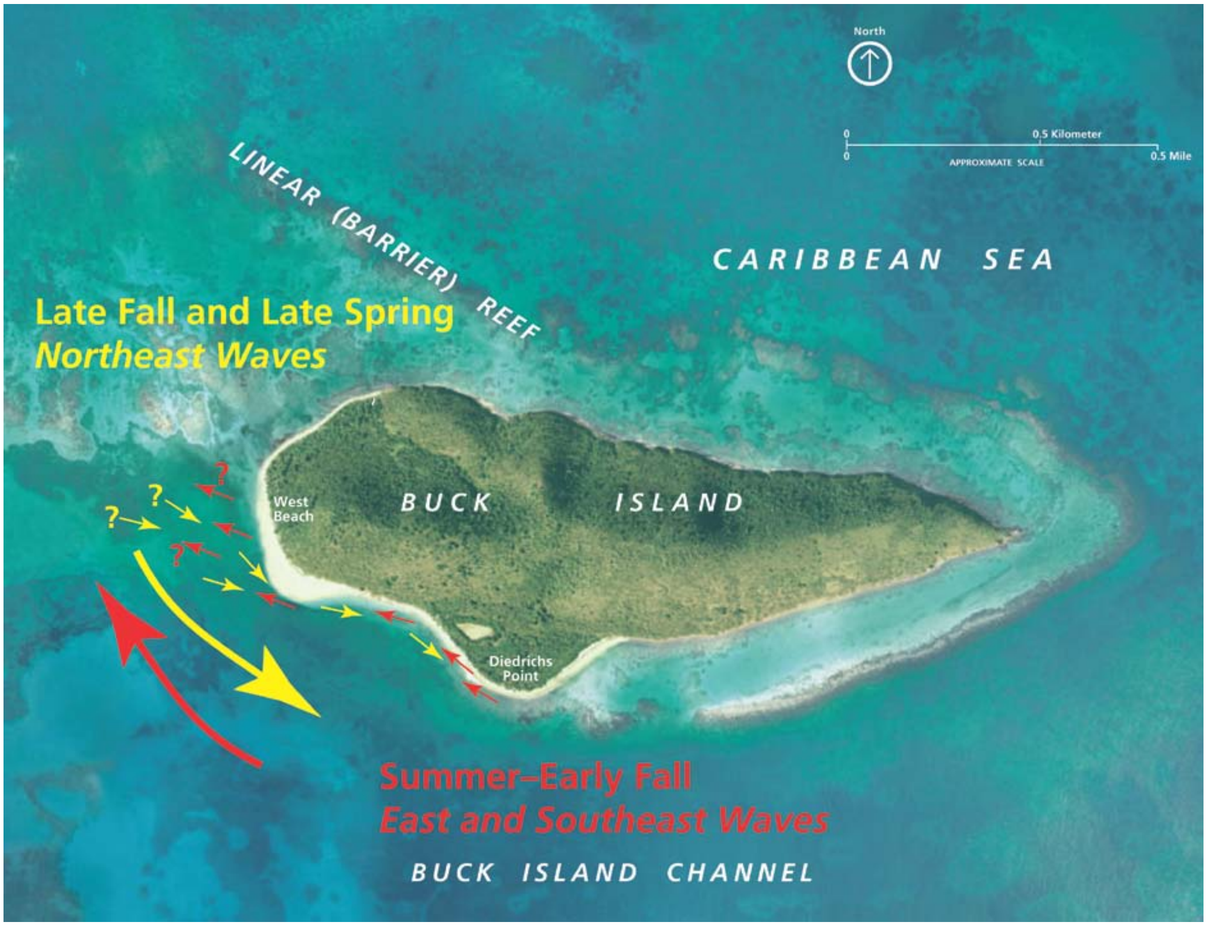


Figure 8. Sediment transport at Buck Island Reef National Monument. Seasonal wind and wave patterns direct sediment from onshore to offshore at Buck Island, as well as between the western and southwestern beaches. Yellow arrows indicate fall-spring patterns. Red arrows indicate summer and early fall patterns. Large arrows show wind movement. Small arrows show sediment movement. National Park Service base map, modified after Hubbard (1980).

Figure 9. Seasonal sedimentation patterns. The pair of photographs shows the varying amount of sediment at West Beach as a result of seasonal sediment transport. The photograph on the left shows the offshore movement of sediment following a tropical storm. The photograph on the right shows the onshore accumulation of sediment. National Park Service photographs courtesy Zandy Hillis-Starr (St. Croix and Buck Island NPS areas).

Figure 10. Beach sand at Turtle Bay. Whetten (1966) mapped recent surficial deposits (Qal) surrounding Buck Island. These deposits include beach sand composed of fragments of coral and mollusks. National Park Service photograph courtesy Zandy Hillis-Starr (St. Croix and Buck Island NPS areas).

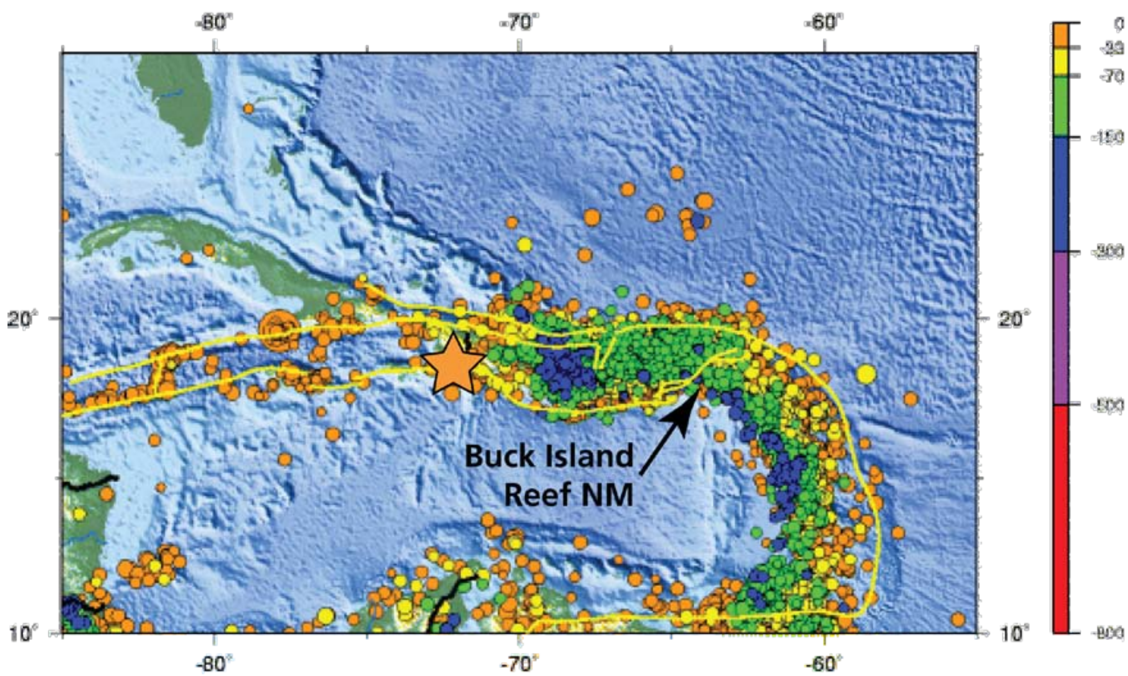


Figure 111. Seismicity map of the Caribbean. Recorded seismic activity outlines the boundary of the oval-shaped Caribbean plate. The dots on the figure record 16 years (1999–2006) of earthquakes. The colors represent depths. The size of the dots indicates relative magnitude of the earthquakes. The orange star (not to scale) indicates the location of the January 12, 2010, earthquake in Haiti. Yellow lines show plate boundaries. Modified from U.S. Geological Survey (2009) by Jason Kenworthy (NPS Geologic Resources Division).

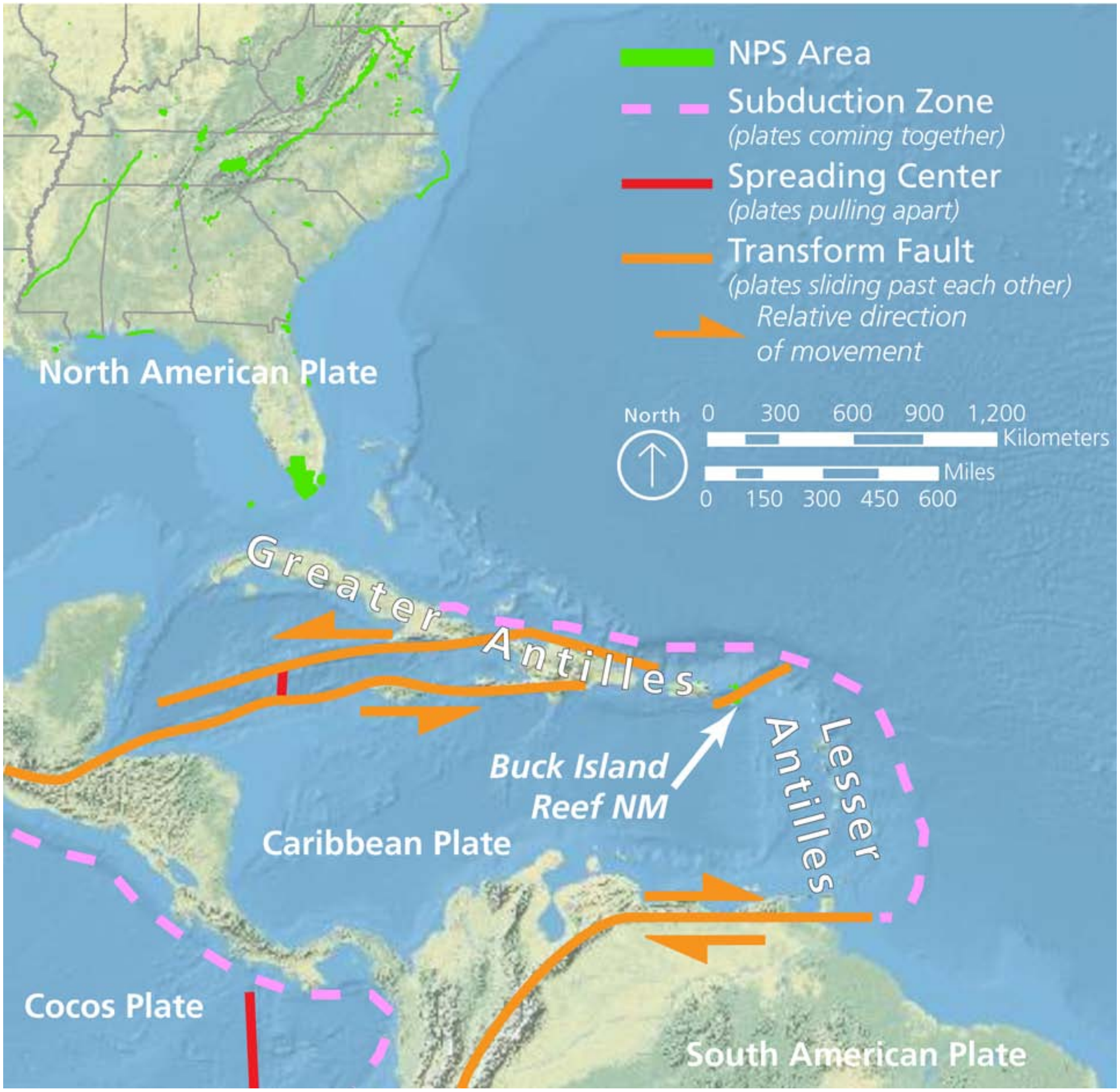


Figure 12. Tectonic map of the Caribbean plate. Buck Island lies between the Greater Antilles and the Lesser Antilles. The eastern margin of the Caribbean plate is a subduction zone. The southern and northern margins are transform faults. Plate boundaries after Lillie (2005). Graphic compiled and annotated by Jason Kenworthy (NPS Geologic Resources Division) from ESRI Arc Image Service USA Prime Imagery.

Table 1. Storm history at Buck Island Reef National Monument from 1979 to 2008

Date	Storm Name	Category	Sustained wind speed (mph)	Closest point of approach
July 18, 1979	Claudette	Tropical storm	64 km/h (40 mph)	63 km (39 mi)
September 4, 1979	Frederick	Tropical storm	93 km/h (58 mph)	43 km (27 mi)
September 8, 1981	Gert	Tropical storm	93 km/h (58 mph)	29 km (18 mi)
November 7, 1984	Klaus	Tropical storm	93 km/h (58 mph)	95 km (59 mi)
September 18, 1989	Hugo	Category 4 hurricane	241 km/h (150 mph)	1.6 km (1 mi)
September 16, 1995	Marilyn	Category 2 hurricane	175 km/h (109 mph)	23 km (14 mi)
July 8, 1996	Bertha	Category 1 hurricane	138 km/h (86 mph)	87 km (54 mi)
September 21, 1998	Georges	Category 2 hurricane	167 km/h (104 mph)	4.8 km (3 mi)
October 21, 1999	Jose	Category 1 hurricane	121 km/h (75 mph)	82 km (51 mi)
November 17, 1999	Lenny	Category 5 hurricane	249 km/h (155 mph)	31 km (19 mi)
August 22, 2000	Debby	Category 1 hurricane	121 km/h (75 mph)	90 km (56 mi)
August 22, 2001	Dean	Tropical storm	84 km/h (52 mph)	50 km (31 mi)
September 15, 2004	Jeanne	Tropical storm	111 km/h (69 mph)	45 km (28 mi)
December 11, 2007	Olga	Tropical storm	64 km/h (40 mph)	77 km (48 mi)
October 16, 2008	Omar	Category 4 hurricane	212 km/h (132 mph)	39 km (24 mi)

Source: **Caribbean Hurricane Network (2009).**

Figure 13. South reef before and after Hurricane Hugo. The photograph on the left shows the south reef before Hurricane Hugo. Rogers et al. (1992) called this part of the reef "essentially annihilated" after Hurricane Hugo in 1989. Scouring and pounding from storm waves destroyed nearly 100% of the south reef at Buck Island Reef National Monument (right photograph). National Park Service photographs.

Table 2. Controls and distribution of reef crest

Reef-crest type	Wave energy	Hurricane frequency
Pavement reef	Low	High
Acropora palmata	Moderate to High	Moderate
Algal ridges	High	High
Acropora cervicornis	Low	Low

Source: **Hubbard (1989).**

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Buck Island Reef National Monument.

Buck Island is made up of the Upper Cretaceous Caledonia Formation (map unit symbol Kc) (fig. 14). Surrounding the island are recent surficial deposits (Qal), which Whetten (1966) identified as sand, beach rock, and stream deposits. Uncolonized bedrock (hbub), colonized bedrock (rcb), and colonized pavement (rcp) also occur in the immediate vicinity of the island (figs. 15 and 16). "Colonized" is a descriptive term used in the digital geologic map data for Buck Islands Reef National Monument. For instance, macroalgae, hard coral, gorgonians, and other sessile invertebrates colonize the bedrock and pavement. Seagrass, at varying levels of "patchiness," grows primarily to the south of the island, but patches also occur in the waters to the north of the island (fig. 17).

A linear reef (rlr) surrounds the east end of Buck Island, starting midway on the south side then wrapping completely around the north side (see front cover photo and fig. 18). A segment of linear reef also runs south-east/north-west in the waters at the western end of the island. Seaward of the main linear reef is a large area of aggregated patch reef (rpra) (fig. 19). Surrounding and seaward of the aggregated patch reef are colonized pavement (rcp) (fig. 16), much with sand channels (rcpc), and areas of scattered coral or rock in unconsolidated sediment (rscr) (fig. 20).

Fossils are another geologic resource of interest at Buck Island Reef National Monument. Paleontological resources occur in the Caledonia Formation (Kc) and fossil reefs, which are discussed in the "Paleontological Resources" section.

Caledonia Formation

Buck Island is composed of the Upper Cretaceous (99.6 million to 65.5 million years ago) Caledonia Formation (Kc). Although other formations are included on the digital geologic map for the national monument (see "Geologic Map Data") and have contributed to the regional geologic history (see "Geologic History"), the Caledonia Formation is the sole bedrock unit at the national monument. Beach rock (sand and gravel cemented with calcium carbonate) might be thought of as "bedrock," but Whetten (1966) identified beach rock as a surficial deposit and mapped it as part of alluvium (Qal). With respect to the benthic-habitat categories, the Caledonia Formation is mapped as land (l) by Kendall et al. (1999).

The Caledonia Formation was named for the well-exposed outcrops in the Caledonia Valley on northwestern St. Croix. At the national monument, exposures occur on the shores of Buck Island, in particular the south shore.

About 70 million years ago, the Caledonia Formation was deposited in a tectonically active, chain of island volcanoes, called an "island arc." The formation is composed of volcaniclastic sediments from a contemporaneous arc volcano, with lesser amounts of mud, sand, limestone (skeletal remains of coral), and chert.

Sediments were deposited via gravity at the base of a slope of an island arc, specifically the lower slope apron. Later, fluid-driven processes reworked the sediments via deep-ocean bottom currents (Stanley 1989). According to Stanley (1989), most layers of the Caledonia Formation appear as intermediate between mass-flow (turbidite) and bottom-current (contourite) deposits in the rock record. Turbidites originate as turbidity (density) currents, which can be generated by storm waves, tsunami, earthquake-induced sliding, tectonic movement, or an over-supply of sediment (Neuendorf et al. 2005). In this deep-marine setting below wave base, thermohaline (deep-water) circulation, not waves, drove transport and sedimentation of contourites (Stanley 1989).

Geologists estimate that the sequence of events that culminated in the Caledonia Formation deposited 3,000 m (10,000 ft) (Stanley 1989) to 5,500 m (18,000 ft) (Whetten 1966) of sediment over 14 million years and perhaps as long as 30 million years (Speed and Joyce 1989).

Benthic Habitats

In addition to land (l), or the Caledonia Formation (Kc), Kendall et al. (1999) mapped the seafloor around Buck Island, separating the substrate into a variety of benthic habitats. The primary habitats are coral reef and hardbottom, unconsolidated sediments, and submerged vegetation (see "Geologic Map Data"). According to Pittman et al. (2008), 78% of all benthic habitat at Buck Island Reef National Monument is reef and hardbottom, and 22% is unconsolidated sediment and submerged vegetation.

Reefs

A coral reef is a dynamic, continually changing environment resulting from by both constructive and destructive processes. Construction directly depends on the activity of carbonate-secreting organisms, namely corals. Also, algae bind loose materials together, strengthening the reef edifice. When coral and other carbonate-secreting organisms die, their hard parts are added to the outer layer of the reef structure, which sustains the reef's upward and lateral growth over time. In this way, the dead marine organisms, which become limestone, record the existence of ancient reef communities in the geologic record (Pinet 1992).

Coral biomass at Buck Island Reef National Monument is composed of elkhorn coral (*Acropora palmata*), staghorn coral (*Acropora cervicornis*), brain coral (*Diploria*), fire coral (*Millepora complanata*), star coral (*Montastrea*), finger coral (*Porites*), and scarlet coral (*Siderastrea*) (Kendall et al. 1999). Branching corals such as *A. palmata* also provide topographic complexity, creating nooks and crannies that support other reef species (Fisco 2008).

Environmental Factors

Two environmental factors, water temperature and light intensity, are the primary regulators of reef development (Pinet 1992). Temperature limits reef growth by affecting the coral's carbonate-secreting ability. Optimum growth occurs between 25°C (77°F) and 29°C (84°F) (Summerfield 1991). Because water temperature decreases with water depth, carbonate secretion by corals tends to be limited to the warm, sunlit portion of the water column. Furthermore, because coral polyps are in a symbiotic relationship with unicellular algae called zooxanthellae, the presence of the photosynthesizing zooxanthellae in the coral's flesh effectively restricts coral growth to the photic zone (Pinet 1992). Depending on water clarity, light requirements limit the depth at which corals grow to around 90 m (295 ft), but the most vigorous development is confined to a depth of 20 m (65 ft) (Summerfield 1991).

Carbonate Production

The reef system at Buck Island Reef National Monument is constructed largely of in situ and broken *A. palmata* (Bythell et al. 1989). Factors in carbonate production of coral reefs are population densities and growth rates of coral species. On average, the rate of growth of *A. palmata* is 3.5 m (11.5 ft) per thousand years (Hubbard 2009). Dead coral becomes pavement and sediment and provides substrate for other organisms (Gladfelter et al. 1977). Crusts of micrite (carbonate mud) and infillings of magnesium-rich calcite also contribute to the carbonate budget (Macintyre and Adey 1990).

Gladfelter and Monahan (1977) suggested that the factors affecting carbonate production are light, heterotrophic food availability, and mechanical forces such as wave surge and currents. In the Gladfelter and Monahan (1977) study, temperature was not a factor because water temperatures remained constant at 29.5°C (85.1°F). Interestingly, two of these factors, light and water movement, also affected coral form. Findings of coral form from three zones (backreef, deep forereef, and shallow forereef) showed that corals in the shallow forereef had the greatest mean calcification. Deep-forereef corals had the greatest mean skeletal extension. The shallow forereef zone is 0.5 m (1.6 ft) to 1 m (3.3 ft) below the surface. The deep forereef zone is 8 m (26 ft) to 10 m (33 ft) below sea level.

In addition to constructive processes that produce calcium carbonate, reefs also are the end product of destructive processes. Destructive processes include bioerosion and wave action, which reduce solid substrate to sediment; and physical processes, which rework the reef fabric and transport sediment (Hubbard et al. 1990). Based on analysis of seven cores from Cane Bay, 25% of the carbonates were deposited within reef channels and flushed from the reef by major storms (Hubbard et al. 1990). Hence, detrital material is a significant constituent of a reef's fabric, and secondary processes play a major role in constantly reworking the substrate. According to Hubbard et al. (1990), the final result is a reef whose interior is more of a "garbage pile" than an in-place assemblage of corals cemented together in a rigid framework. Sediment cores from the national monument consist of approximately 30% coral with the remainder as sediment and open voids. This value is similar to cores throughout the region and infers that the relative importance of coral growth, bioerosion, and sediment export at Buck Island are similar to those documented elsewhere (Dennis Hubbard, professor, Oberlin College, written communication, January 21, 2011).

A final note about carbonate production relates to the impact that increased concentrations of carbon dioxide (CO_2) in the atmosphere could have on resources at Buck Island Reef National Monument. As atmospheric CO_2 concentration increases, more CO_2 is absorbed into the world's oceans, leading to a decrease in pH, commonly referred to as "ocean acidification" (Karl et al. 2009). Since 1750, the beginning of the industrial era, ocean pH has declined demonstrably and is projected to decline much more by 2100, if current emissions trends continue (Orr et al. 2005; Royal Society 2005). Further declines in pH are very likely to continue to affect the ability of living things to create and maintain shells or skeletons of calcium carbonate. This is because at a lower pH, less of the dissolved carbon is available as carbonate ions (Feely et al. 2008; Janetos et al. 2008). The effects on reef-building corals are likely to be particularly severe during this century (Karl et al. 2009). Such ocean acidification is essentially irreversible over a time scale of centuries (Karl et al. 2009).

Impacts to Reefs

Impacts to reefs include hurricane damage (see "Hurricanes"), bleaching, disease, predation, and recreational impacts. Two species, *A. palmata* and *A. cervicornis*, have undergone particularly drastic decline in the past 30 years. In 2006, these species were the first coral species to be protected under the Endangered Species Act (Lundgren 2008). Despite heavy impacts, however, the area around the eastern tip of Buck Island remains ecologically distinctive, having high live coral cover, high calcareous coralline algal cover, high fish species richness, notable biomass of herbivorous fish, and high abundances of many common fish species (Pittman et al. 2008).

Bleaching

Symbiotic algae provide the often-brilliant colors to corals. Under stress, algae are expelled from coral tissue, leaving coral polyps transparent, making the underlying white coral skeleton appear "bleached." Although almost any type of stress can induce bleaching, the rise in water temperature from global climate change has induced bleaching on a massive scale (Lundgren 2008). Because tropical corals live very close to their upper temperature limit, global climate change has the potential to cause more severe and more frequent mass coral bleaching events like the one observed in the Caribbean in 2005. Record high seawater temperatures and calm seas led to the most severe coral bleaching event ever observed in the U.S. Virgin Islands. More than 90% of corals were affected (Rogers et al. 2008a).

Disease

Various, poorly understood diseases affect *A. palmata*. First observed in the 1970s, white-band disease appears as a narrow band of infected tissue that migrates from the base of the colony toward the branch tips (Lundgren 2008). The disease can move at a rate of 5 cm (2 in) per day. The first documented instance of white-band disease was from Buck Island Reef National Monument (Gladfelter 1982). The cause of white band disease remains unknown.

Another disease, white pox disease, is linked to poor water quality, specifically to a bacterium (*Serratia marcescens*) present in human feces. This disease appears as expanding patches of dead tissue on the coral colony (Lundgren 2008).

Predation

Snails (*Coralliophila* spp.) and fireworms (*Hermodice* spp.) are the most significant invertebrate predators of corals. Snails are gregarious and individually consume up to 6.5 cm (2.5 in) of coral tissue per day. Fireworms prefer coral tips, where growth occurs, and their feeding on individual coral colonies can be extensive. Overfishing of hogfish (*Lachnolaimus maximus*) and lobster (*Panulirus argus*), which eat snails and fireworms, allows these coral predators to multiply, which in turn increases predation on elkhorn corals beyond natural levels (Lundgren 2008).

Recreational Impacts

Visits to Buck Island Reef National Monument generally include exploration of the reef via snorkling, primarily along the underwater trail. Within high visitor-use areas such as the underwater trail, physical damage can occur when snorkelers use the coral for handholds and footholds or as resting platforms. Scuba diving is not allowed on the underwater trail, but two moorings are maintained in the lagoon north of Buck Island. These moorings allow divers to exit the lagoon through breaks in the reef to explore the forereef zone (Bythell et al. 1989). Guides take six visitors at a time on the underwater trail, which is closed sunset to sunrise (National Park Service 2006). Interpretive signs set along the bottom of the underwater trail explain the underwater resources. The average time spent on the trail is 12.4 minutes (Gladfelter et al. 1977). This usually results in no more than 25 people on the trail at any one time, but investigators from the West Indies Laboratory documented as many as 50 concurrent visitors during surveys conducted in the 1970s (Gladfelter et al. 1977). No formal study of visitor use on the underwater trail has been conducted since that time (Zandy Hillis-Starr, Chief of Resource Management, St. Croix and Buck Island NPS areas, e-mail communication, September 20, 2011).

The National Park Service has conducted inventories of coral injury and regrowth as a result of recreational impacts (National Park Service 1983). General observations confirmed the ability of most healthy coral species to repair nonrepetitive visitor-related damage in a minimal length of time (i.e., several months to a year). However, two locations along the underwater trail failed to show significant signs of recovery. These were brain coral formations used as resting platforms by snorkelers. Recovery at these sites is unlikely as long as they continue to be used in this manner (National Park Service 1983). Today, standing on or touching the coral formations along the underwater trail is strictly prohibited. Concession-guided trips ensure both a safe snorkel for visitors and protection for the reef (Zandy Hillis-Starr, Chief of Resource Management, St. Croix and Buck Island NPS areas, written communication, September 29, 2011).

Boat anchoring and vessel groundings can damage coral reefs, causing scars and breakage. Although anchoring is permissible only in certain areas of the national monument, illegal anchoring and anchor dragging can destroy marine habitat (Hall 2005). In addition, vessel groundings resulting from inexperienced boaters can critically damage large sections of coral reefs (Hall 2005). Minor damage occurs when boats, unable to maneuver, run into the reef (Gladfelter et al. 1977).

The effects of minor boating damage can be reduced by divers righting overturned head corals. Healthy branching corals can heal themselves, and broken fragments often grow into new colonies (Gladfelter et al. 1977). However, too many boats at the mooring area at any given time increase the probability of such accidents. In the past, during peak periods, as many as three boats tied end-to-end on a single mooring resulted in boats swaying in a wider arc and coming dangerously close to boats on other moorings and snorkelers in the water (National Park Service 1976). This practice, called "rafting vessels," is now prohibited within Buck Island Reef National Monument (Zandy Hillis-Starr, Chief of Resource Management, St. Croix and Buck Island NPS areas, September 29, 2011). The general management plan (in progress) for Buck Island Reef National Monument has newly designated management zones and prescriptions that address vessel use (Alyse Getty, consultant/environmental planner, Parsons Corporation, and Zandy Hillis-Starr, Chief of Resource Management, St. Croix and Buck Island NPS areas, e-mail communications, September 20, 2011). The new plan emphasizes protection and safety in order to avoid impacts to threatened coral species, avert vessel groundings on shallow reef areas, and reduce hazardous navigating conditions for boaters.

Seagrass Beds

Seagrass beds in the Caribbean are generally a mixture of three major species: turtle grass (*Thalassia testudinum*), manatee grass (*Syringodium filiforme*), and shoal grass (*Halodule wrightii*). Seagrass is most conspicuously associated with coral reef development in shallow water less than 10 m (33 ft) deep. However, deeper sandy slopes may be covered with a fourth species, *Halophila baillonis*, which grows in thin beds at least 35 m (115 ft) deep (Gladfelter et al. 1977). Seagrass beds are usually separated from nearby reefs by a narrow band or "halo" of open sand, but on occasion grow to the bases of reefs (Gladfelter et al. 1977).

Underwater grasses help to improve water quality. Like terrestrial plants they perform photosynthesis, which in this case adds oxygen to the water. Additionally, seagrass beds catch and trap sediment that would otherwise become suspended and cloud the water. Cloudiness hinders photosynthesis and leads to low oxygen concentrations. The grasses also soften wave action near shores, thereby mitigating erosion. Furthermore, the high growth rate and high turnover of the densely packed plants of the seagrass beds create a storehouse of organic material that nourishes a complex food chain (Gladfelter et al. 1977) (fig. 17). Seagrass also absorbs excess nutrients in the water.

Paleontological Resources

Toscano et al. (2010) completed a paleontological resource inventory and monitoring report for the South Florida/Caribbean Network. Fossils within Buck Island Reef National Monument are known from the reefs, not from the Upper Cretaceous Caledonia Formation. However, the Caledonia Formation is known to host fossils elsewhere. Therefore, future field investigations at the national monument may recover fossils from the Upper Cretaceous Period (99.6 million to 65.5 million years ago) (Toscano et al. 2010).

Fossil Coral

Hubbard et al. (2005) provided detailed logs for seven cores from the main reef around Buck Island and two cores from Buck Island Bar to the north. All but one of the cores penetrated through the entire Holocene section of reef and into the Pleistocene strata. Fossil coral species documented in the cores include *A. cervicornis*, *Diploria* spp., *Millepora annularis*, and *Porites astreoides* (Hubbard et al. 2005).

Caledonia Formation

Paleontological resources from the Caledonia Formation found elsewhere (not in the national monument) include invertebrate and trace fossils. Whetten (1966) collected invertebrates of Upper Cretaceous (Campanian) age, for example marine foraminifera, rudists, and corals. Speed et al. (1979) discovered an ammonite, possibly *Tarrantoceras*, in rock fragments on the north side of St. Croix along Tague Bay about 3.5 km (2.2 mi) southeast of Buck Island. If this fossil is in situ, it would indicate that Caledonia sediments on the east end of St. Croix are 90 million to 100 million years old. The ammonite is in the collection of the Smithsonian National Museum of Natural History in Washington, D.C. (Dennis Hubbard, professor, Oberlin College, personal communication in Toscano et al. 2010). Stanley (1988) documented deep-basin trace fossils, including bioturbated sediment disturbed through biological processes such as burrowing.

Santucci et al. (2009) outlined potential threats to in situ paleontological resources, and suggested monitoring "vital signs" to qualitatively and quantitatively assess the potential impacts of these threats. Paleontological vital signs include the following: erosion (geologic factors), erosion (climatic factors), catastrophic geohazards, hydrology/bathymetry, and human access/public use. The authors also presented detailed methodologies for monitoring each vital sign.

Figure 14. Caledonia Formation. Buck Island is composed of the Upper Cretaceous (99.6 million to 65.5 million years ago) Caledonia Formation, which originated as sediments deposited at the base of a chain of island volcanoes. Note the vertical orientation of the sedimentary rock layers along the south shore today, which indicates the active tectonic history of faulting and folding in the Caribbean. National Park Service photograph by Zandy Hillis-Starr (St. Croix and Buck Island NPS areas).

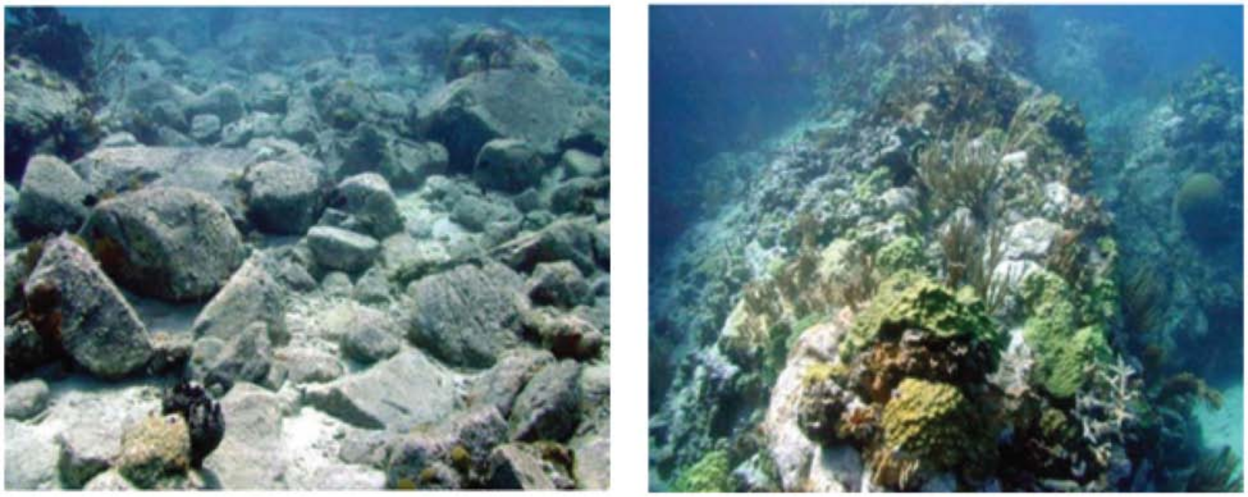


Figure 15. Uncolonized and colonized bedrock. Benthic habitats at Buck Island Reef National Monument may be colonized by sessile marine organisms. Uncolonized bedrock (left) (hbub) occurs on the south side of Buck Island. Colonized bedrock (right) (rcb) occurs on the north and south sides of the island. Photographs from Kendall et al. (2001).

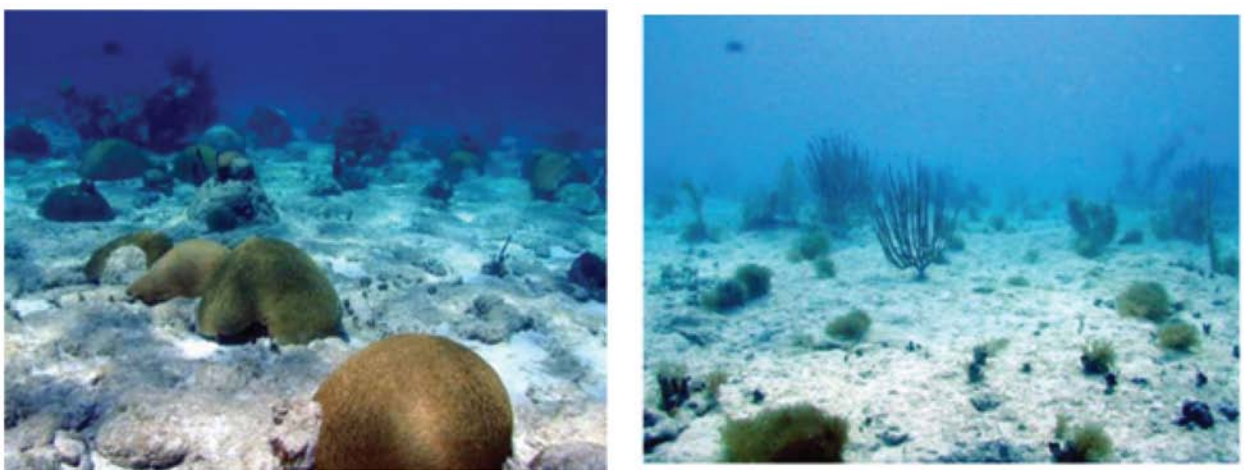


Figure 16. Colonized pavement. Colonized pavement (rcp) is common around the perimeter of Buck Island. It also occurs to the northwest of the large area of aggregated patch reef (see fig. 19). Photographs from Kendall et al. (2001).

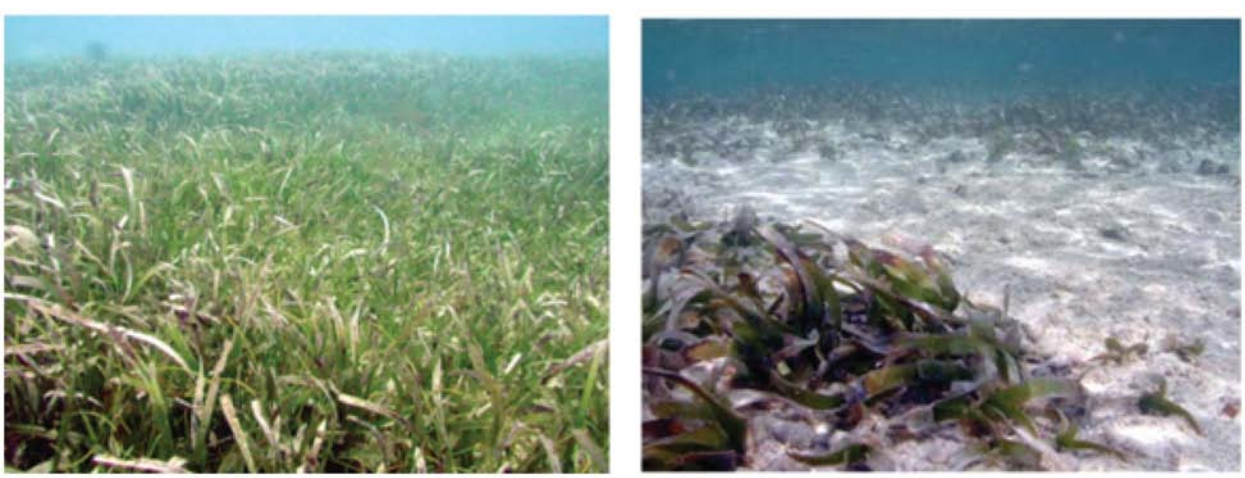


Figure 17. Seagrass. A large area of seagrass, both continuous (sgc) (left) and patchy (sgp) (right), occurs to the south of Buck Island. Photographs from Kendall et al. (2001).

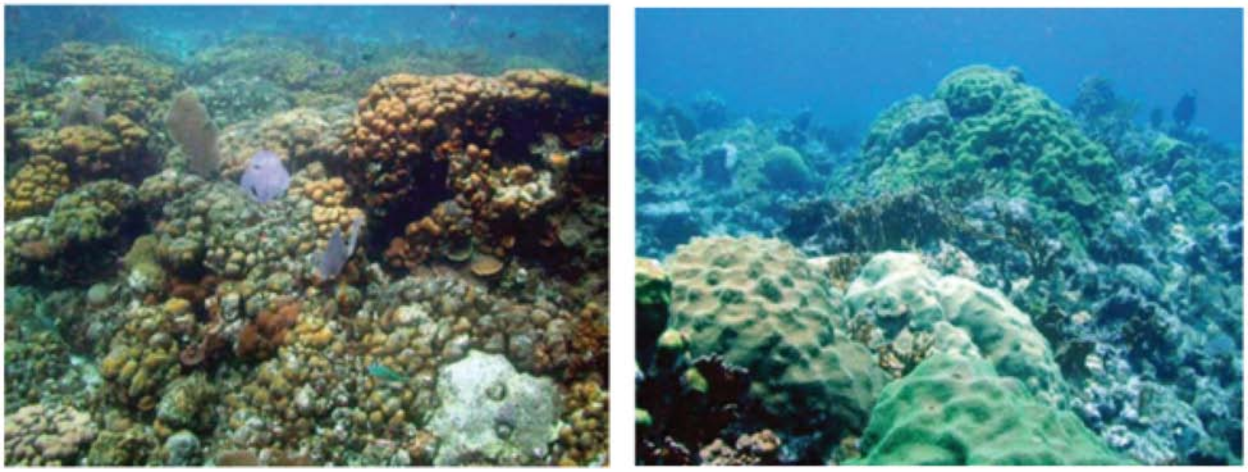


Figure 18. Linear reef. Known for its reef system, Buck Island Reef National Monument has the reputation of hosting the best "coral gardens" in the Caribbean. Linear reefs (rlr) exemplify these gardens. Photographs from Kendall et al. (2001).

Figure 19. Aggregated patch reef. Sand, seagrass, and other habitats can isolate coral reefs from one another, creating patch reefs. A large area of aggregated patch reef (rpra) occurs to the north and east of Buck Island, beyond the linear reef (rlr). Photograph from Kendall et al. (2001).

Figure 20. Scattered coral or rock in unconsolidated sediment. Scattered rocks or small, isolated coral heads that are too small to be delineated individually are considered scattered coral or rock in unconsolidated sediment (rscr). This map unit is smaller than an individual patch reef and occurs primarily in sand or seagrass. Photograph from Kendall et al. (2001).

Figure 21. Elkhorn coral. Elkhorn coral developed on the side and top of a massive, towering patch reef, referred to as a "haystack." Haystacks are isolated, typically circular patch reefs that rise from the seafloor. New colonies of coral develop on the skeletal remains of the dead structure. National Park Service photograph by Philippe Mayor (Buck Island Reef National Monument).

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map for Buck Island Reef National Monument, the environment in which those units were deposited, and the timing of geologic events that formed the present landscape and benthic habitats.

Buck Island Reef National Monument preserves 70 million years of geologic history, ranging from Upper Cretaceous deep-marine sediments to modern-day reefs. The Cretaceous sediments were deposited in an island-arc setting near an active plate boundary. Submarine debris flows moved down the slopes of island volcanoes, and volcaniclastic and tuffaceous materials settled to the seafloor. These sediments became the Caledonia Formation, which makes up Buck Island. Since the end of the Cretaceous Period (65.5 million years ago), the bedrock of Buck Island has been pushed eastward, squeezed upward, and tilted to its present vertical orientation (fig. 14) (Hubbard 1991). Tectonic forces also caused shoaling of the ocean basin, which resulted in deposition of younger sediments in shallower and shallower waters. Reef development at St. Croix began during the Pliocene Epoch, but not until the Pleistocene Epoch at Buck Island. Development of the present-day (Holocene) reef began 7,700 years ago on a preexisting Pleistocene carbonate platform.

Upper Cretaceous Period: Island-Arc Setting

In an island-arc setting 70 million years ago, sediment–laden density currents flowed down the slopes of arc volcanoes and deposited the Caledonia Formation (Kc), the bedrock unit at Buck Island Reef National Monument. Deposition was at the base of the slope in a deep-marine setting. However, the setting was not so deep as to be anoxic, and benthic organisms churned up many of the sedimentary layers. Because deposition was below wave base, thermohaline (deep-ocean) circulation, not waves, reworked the gravity-emplaced deposits. As a result, most of the beds of the Caledonia Formation appear as an intermediate type between mass-flow and bottom-current deposits (Stanley 1989).

The location of the volcanic center (and the source of the volcanic debris) is enigmatic in that no obvious source exists upwind (to the east) of St. Croix (Hubbard 1991). However, Puerto Rico—now 115 km (80 miles) northwest of Buck Island—was in closer proximity to St. Croix from 60 million to 30 million years ago and is a possible source (Gill et al. 1989). The pyroclastic debris and ash that erupted from the volcanic center traveled through the air and settled into the water. These sediments ultimately formed the tuffaceous sandstone and mudstone of the East End Member of the Caledonia Formation, as well as the Allandale Formation (Ka), members of the Cane Valley Formation (Kcvh, Kcvr, and Kcvs), and the Judith Fancy Formation (Kj). These rock units are exposed on St. Croix and included on the digital geologic map for Buck Island Reef National Monument.

Two small stocks and multiple dikes (igneous intrusions) intruded the tuffaceous sedimentary rocks. The Fountain Gabbro (Kg) is exposed in a wide valley near Estate Fountain in the Northside Range of St. Croix (Whetten 1966). The Southgate Diorite (TKdi) cuts from north to south across St. Croix in the East End Range (Whetten 1966). As a result of intrusion, contact-metamorphosed rocks surround both of these stocks. Dikes punctuate the east end of St. Croix and dot the Northside Range. Both the Fountain Gabbro and Southgate Diorite were probably intruded at shallow depth after folding of the Cretaceous sedimentary rocks (Whetten 1966). Buck Island hosts no such intrusions.

Miocene and Pliocene Epochs: Deep-Marine Rocks to Shoaling in the Basin

The depositional history of St. Croix records a tectonically quiet, deep-marine setting in which the “blue marl” of the Jealousy Formation (OLj) was deposited in water depths of 600 m (1,970 ft) to 800 m (2,625 ft) during the early Miocene Epoch (about 23 million years ago). Whetten (1966) interpreted this unit as Oligocene in age, but more recent biostratigraphic research places it in the more-recent Miocene Epoch (Gill et al. 1989, 2002; McLaughlin et al. 1995). The “tan marl” of the overlying Kingshill Marl (MIkh)—renamed the “Kingshill Limestone” by Gerhard et al. (1978)—records continuous deposition under the same environmental conditions as the Jealousy Formation (Gill et al. 1989).

As the Miocene progressed, tectonic activity increased. The elevated Northside and East End ranges of St. Croix, which are composed of Upper Cretaceous rocks, and the down-dropped central valley, which is filled with Miocene and Pliocene rocks, are evidence of this tectonic activity (fig. 22). Gill et al. (1989) estimated vertical uplift rates between 0.1 mm (0.004 in) and 0.2 mm (0.008 in) per year. The La Reine Member of the Kingshill Marl (MIkh) records the onset of faulting of the basin that cuts across what is now central St. Croix (Gill et al. 2002). Tectonic uplift caused a shallowing of the basin, and the members of the Kingshill Marl show a shoaling trend. Initially, La Reine sediments were deposited in waters of depths from 600 m (1,970 ft) to 800 m (2,625 ft). As uplift and shoaling continued, deposition occurred in shallower and shallower water. Ultimately, sediments of the younger Mannings Bay Member were deposited in 100 m (330 ft) of water (Gill et al. 1989; McLaughlin et al. 1995). Uplift and associated shoaling resulted in 400 m (1,310 ft) of sedimentation between 10.5 million (Miocene) and 3.5 million

(Pliocene) years ago (Gill et al. 1989, 2002; McLaughlin et al. 1995).

Pliocene and Pleistocene Epochs: Development of Reefs around St. Croix

Shoaling continued into the Pliocene Epoch (5.3 million to 2.6 million years ago) and resulted in the development of a reef and lagoon system around St. Croix, represented by the Blessing Formation (fig. 22). Gill et al. (1989, 2002) introduced this rock formation as part of St. Croix's stratigraphy. Because its naming postdates Whetten (1966), the Blessing Formation does not appear on the digital geologic map for Buck Island Reef National Monument. The extensive reef and lagoon system of the Blessing Formation that formed along the western and southern shorelines of St. Croix indicates that by the Pliocene Epoch, the present-day shoreline configuration of St. Croix was established (Gill et al. 1989). The arcuate distribution of reef and lagoon suggests that the area was an embayment at the time of establishment (Gill et al. 1989). Tectonic and global sea level changes repeatedly exposed the reefs, notably during lower sea level at 10.5 million and 5.5 million years ago (McLaughlin et al. 1995). Normal faulting of the Blessing Formation documents continued tectonic activity on St. Croix into the Pliocene Epoch and later (Gill et al. 2002).

Pleistocene and Holocene Epochs: Reef Formation around Buck Island

The earliest known reefs in the vicinity of Buck Island were most likely formed about 125,000 years ago (Hubbard 1991). Uranium-thorium ages from the Pleistocene strata along the western end of Buck Island and beneath the eastern reefs show reef formation at 125,000 and 102,000 years ago (Dennis Hubbard, professor, Oberlin College, written communication, January 21, 2011). After these early reefs formed, however, sea level dropped to perhaps 100 m (330 ft) below present-day levels due to Pleistocene glaciation. Ice-age conditions resulted in global cooling and the incorporation of large volumes of ocean water into continental-scale glaciers and polar ice caps. Lower sea levels exposed the entire St. Croix shelf to subaerial erosion and dissolution of carbonate by rainwater (Hubbard 1991).

At 9,500 years ago, the carbonate platform around Buck Island was still flooded. The platform that underlies the Holocene reef system at the national monument is the result of both reef accretion and later physiochemical degradation during the Pleistocene (Hubbard 1991). Reef development lagged behind sea-level lowering for 1,800 years. At about 7,700 years ago, and approximately 15 m (50 ft) below present-day sea level, reef development initiated near Buck Island at Buck Island Bar. According to Hubbard et al. (2005), past topographic highs played an important role in determining the location and timing of reef development. Most reefs formed atop "benches" left after the previous sea-level low.

Throughout the development of the Holocene reef, *A. palmata* dominated the shelf edge, while massive corals prevailed closer to the island (fig. 23). However, analysis of core data shows the decline and disappearance of *A. palmata* during two periods: 7,200–5,200 years ago and 3,030–2,005 years ago. During these intervals, massive corals dominated. The reason for these gaps in *A. palmata* is not explained by local changes in the physical environment and may have a regional or global cause (Hubbard et al. 2005). Reef accretion along Buck Island Bar continued until about 1,200 years ago, and the reefs around Buck Island largely assumed their present character by 1,000 years ago.

The makeup of modern reefs mimics the composition patterns shown in the cores of past reefs with 22% coral, 19% void space, and 59% sediment (sand and gravel) (Hubbard et al. 2005). The coral fraction is dominated by *A. palmata*. With respect to structure, over the past 7,700 years, the south-reef crest appears to have remained slightly shallower than its northern counterpart, a condition that persists today. Observations after Hurricane Hugo in 1989 suggest that this difference in elevation is related to the piling up of debris on the broader, south-reef crest by high waves from storms passing south of St. Croix (Hubbard et al. 2005). Also, the south reef is more variable in species composition than the north reef, a condition that is exhibited by the modern reef community.

Figure 22. Generalized geology of St. Croix. Since Whetten (1966) mapped the geology of St. Croix, new investigations have added a unit (Blessing Formation) and reinterpreted surface geology. For example, the Jealousy Formation mapped by Whetten (1966) in the Northside Range of St. Croix is probably Kingshill Limestone. U.S. Geological Survey graphic from Gill et al. (2002).

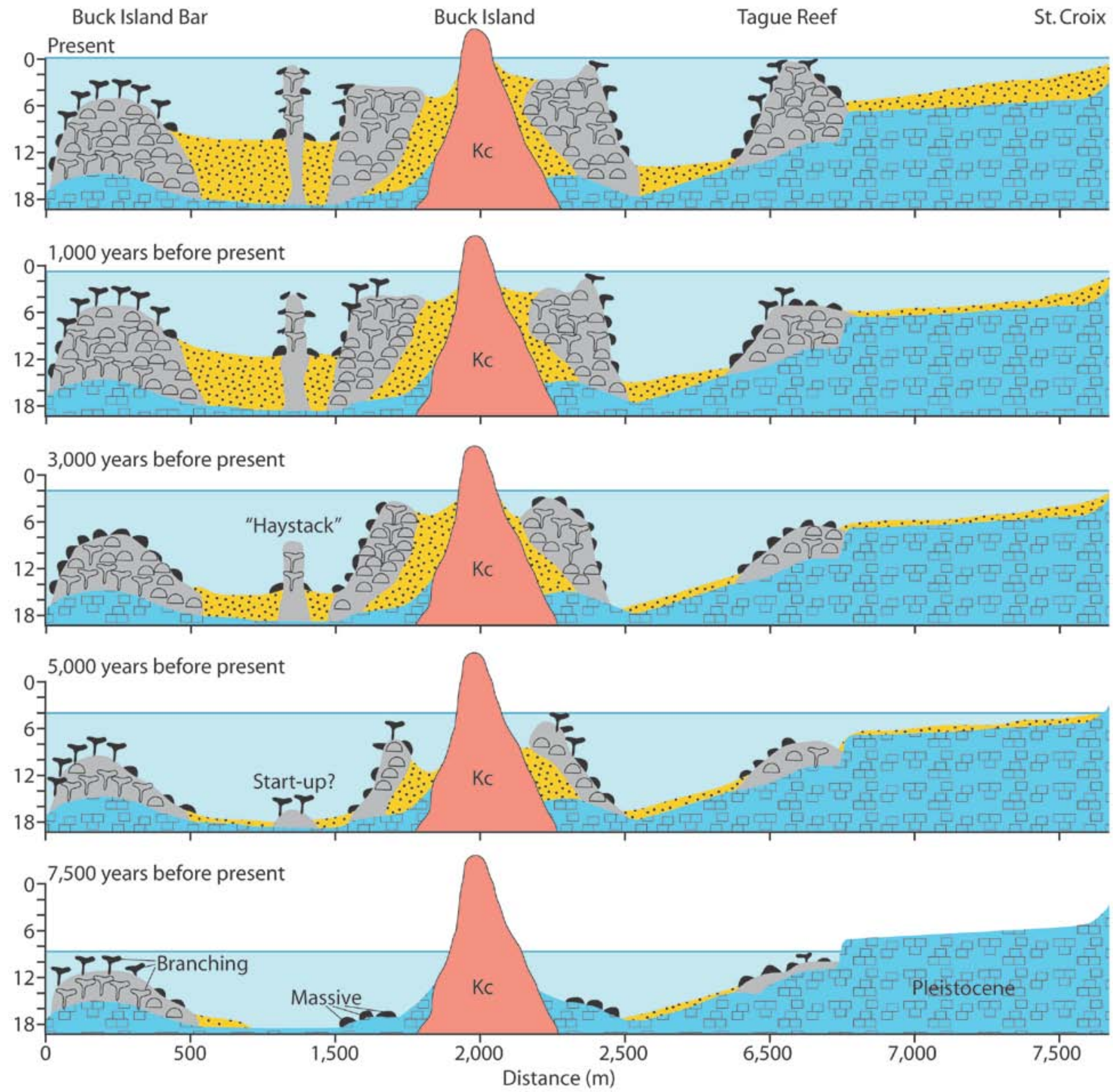


Figure 23. Reef development around Buck Island. Buck Island is composed of the Upper Cretaceous Caledonia Formation (Kc). The box pattern on the diagram represents the Pleistocene carbonate platform upon which reefs developed. In proximity to Buck Island, the earliest reef development occurred along Buck Island Bar. The reef built upward and seaward, steepening progressively over time. While it is not obvious from the time intervals shown, reefs were dominated by massive corals at 6,000 years ago. The return to massive corals just before 3,000 years before present lasted until approximately 2,100 years before present. Modified from Hubbard et al. (2005) by Trista Thornberry-Ehrlich (Colorado State University).

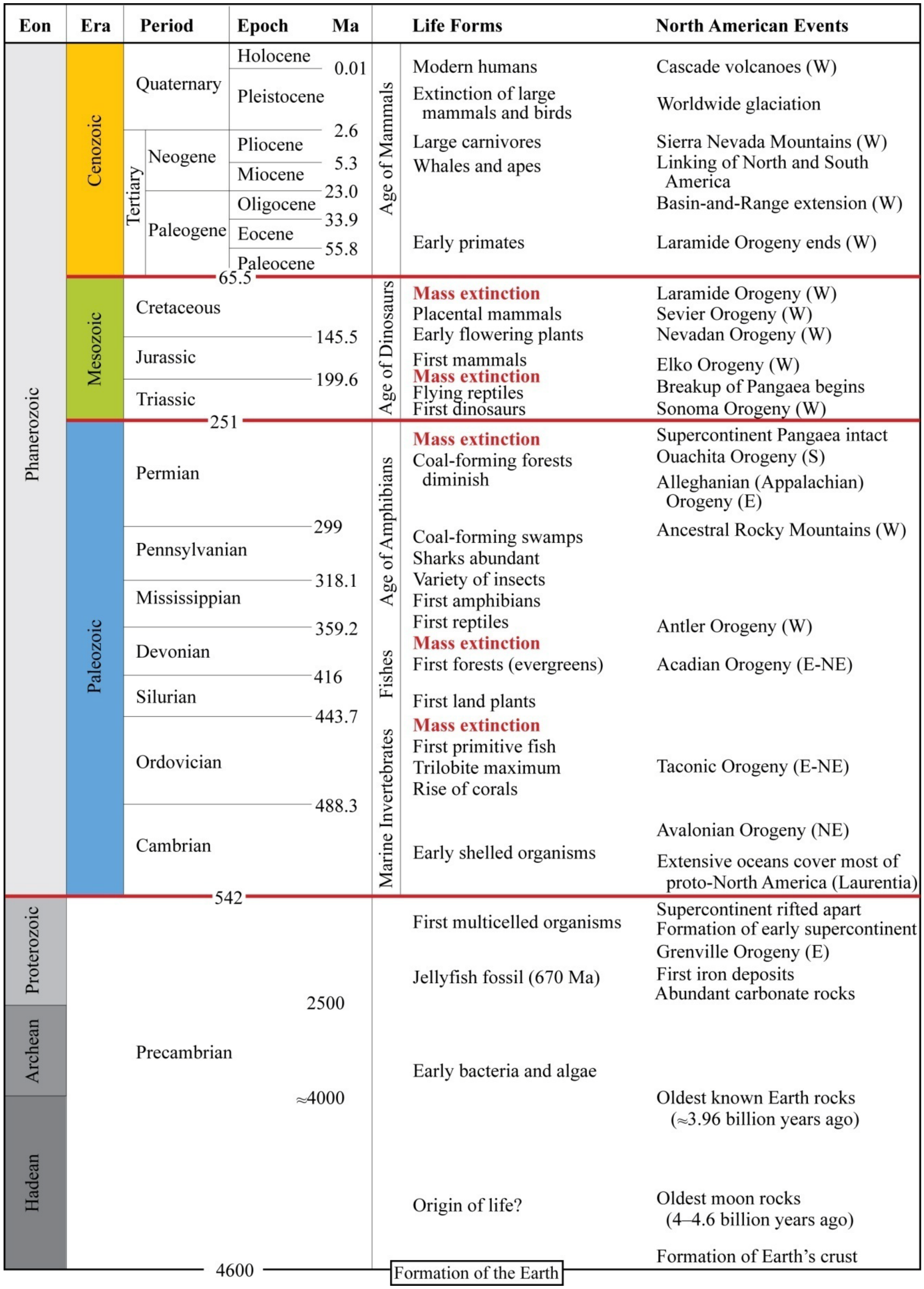


Figure 24. Geologic timescale. Included are major life history and tectonic events occurring on the North American continent. Red lines indicate major unconformities between eras. Radiometric ages shown are in millions of years (Ma). Compass directions in parentheses indicate the regional location of individual geologic events. Graphic by Trista Thornberry-Ehrlich (Colorado State University) with information from the U.S. Geological Survey (http://pubs.usgs.gov/fs/2007/3015/) and the International Commission on Stratigraphy (http://www.stratigraphy.org/view.php?id=25).

Geologic Map Data

This section summarizes the geologic map data available for Buck Island Reef National Monument. It includes a fold-out geologic map overview and a summary table that lists each map unit displayed on the digital geologic map for the park. Complete GIS data are included on the accompanying CD and are also available at the Geologic Resources Inventory (GRI) publications website: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

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, geologic maps portray the spatial distribution and relationships of rocks and unconsolidated deposits. Geologic maps also may show geomorphic features, structural interpretations, and locations of potential geologic hazards. Additionally, anthropogenic features such as mines and quarries may be indicated on geologic maps.

Source Maps

The Geologic Resources Inventory (GRI) team converts digital and/or paper source maps into the GIS formats that conform to the GRI GIS data model. The GRI digital geologic map product also includes essential elements of the source maps including unit descriptions, map legend, map notes, references, and figures. The GRI team used the following source maps to create the digital geologic data for Buck Island Reef National Monument:

Kendall, M. S., M. E. Monaco, K. R. Buja, J. D. Christensen, C. R. Kruer, M. Finkbeiner, and R. A. Warner. 1999. Benthic habitats of the U.S. Virgin Islands; St. Croix, USVI (scale 1:6,000). National Oceanographic and Atmospheric Administration, Silver Spring, Maryland, USA.

Whetten, J. T. 1966. Geology of St. Croix, U.S. Virgin Islands (scale 1:21,680). Memoir 98. Geological Society of America, Boulder, Colorado, USA.

These source maps provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report.

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 online (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 Buck Island Reef National Monument using data model version 1.4.

GRI digital geologic data for Buck Island Reef National Monument are included on the attached CD and are available through the NPS Integrated Resource Management Applications (IRMA) (https://irma.nps.gov/App/Reference/Search?SearchType=Q). Enter "GRI" as the search text and select the park from the unit list. Note that as of September 2011, IRMA is only compatible with the Internet Explorer browser. Enter "GRI" as the search text and select Buck Island Reef National Monument from the unit list. The following components and geology data layers are part of the data set:

- Data in ESRI geodatabase and shapefile GIS formats
- Layer files with feature symbology
- Federal Geographic Data Committee (FGDC) compliant metadata
- A help file (.hlp) document that contains all of the ancillary map information and graphics, including geologic unit correlation tables and map unit descriptions, legends, and other information captured from source maps.
- An ESRI map document file (.mxd) that displays the digital geologic data

Table 3. Geology data layers in the Buck Island Reef National Monument GIS data

Data Layer	Code	On Geologic Map Overview?
Geologic Attitude and Observation Points	ATD	No
Mine Point Features	MIN	No
Fault and Fold Map Symbology	SYM	Yes
Faults	FLT	Yes
Folds	FLD	Yes
Benthic Habitats	BEN	Yes
Geologic Contacts	GLGA	Yes
Geologic Units	GLG	Yes

***Note:* All data layers may not be visible on the geologic map overview graphic.**

Geologic Map Overview

The fold-out geologic map overview displays the GRI digital geologic and benthic habitat data draped over a shaded relief image of Buck Island Reef National Monument and includes basic geographic information. For graphic clarity and legibility, not all GIS feature classes are visible on the overview. The digital elevation data and geographic information are not included with the GRI digital geologic GIS data for the park, but are available online from a variety of sources.

Map Unit Properties Table

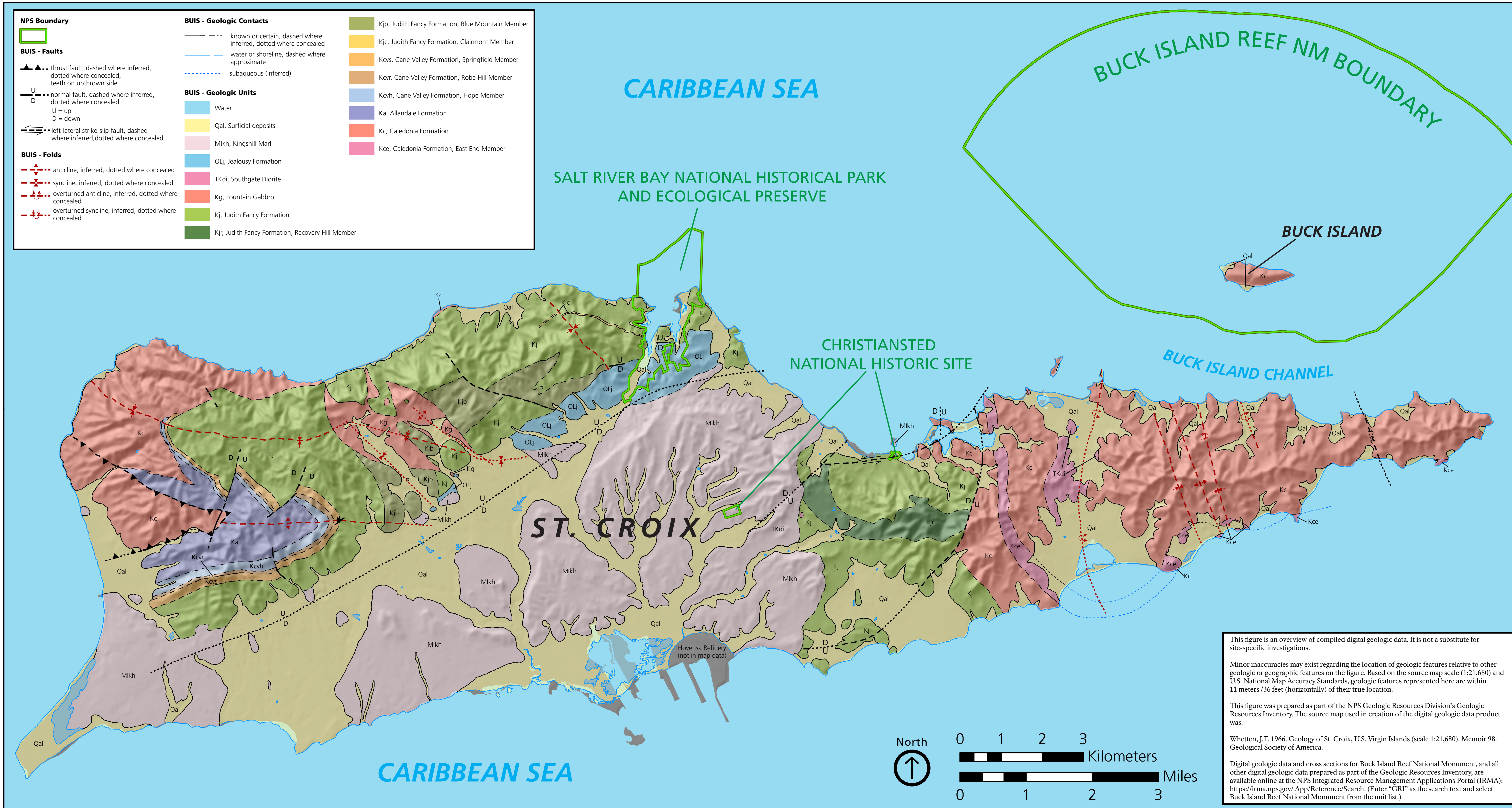
The geologic units listed in the fold-out map unit properties table correspond to the accompanying digital geologic data. Following the overall structure of the report, the table highlights the geologic issues, features, and processes associated with each map unit. The units, their relationships, and the series of events the created them are highlighted in the "Geologic History" section. Please refer to the geologic timescale (fig. 25) for the geologic period and age associated with each unit.

Use Constraints

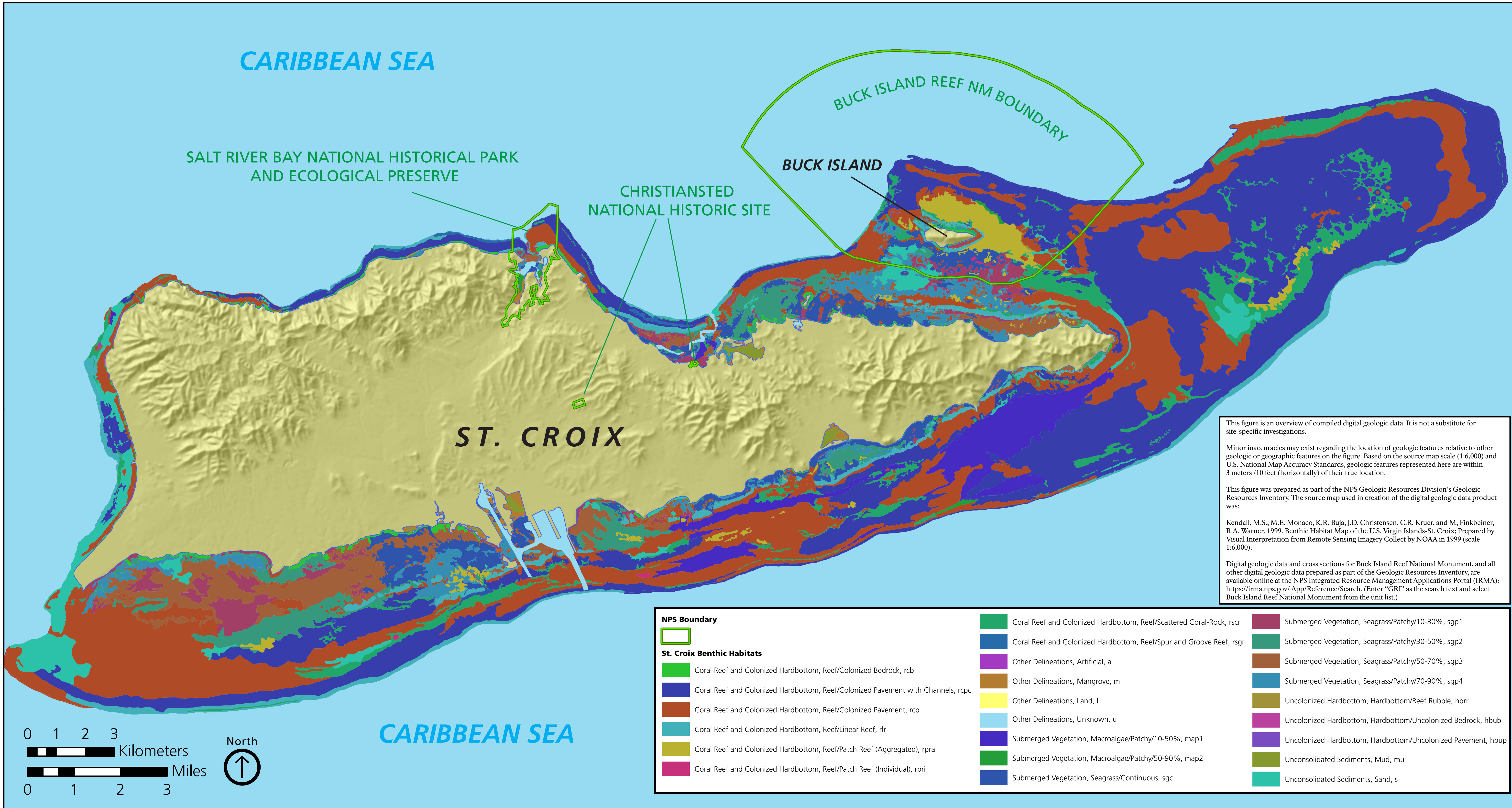
Graphic and written information provided in this section is not a substitute for site-specific investigations, and ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the overview graphic. Based on the source map scales of 1:6,000 and 1:21,680 and U.S. National Map Accuracy Standards, geologic features represented here are horizontally within 3 meters / 10 feet (1:6,000 scale) or 11 meters / 36 feet (1:21,680 scale) of their true location.

Please contact GRI with any questions.

Overview of Digital Geologic Data for Buck Island Reef NM



Overview of Digital Benthic Habitat Data for Buck Island Reef NM



This figure is an overview of compiled digital geologic data. It is not a substitute for site-specific investigations.

Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the figure. Based on the source map scale (1:6,000) and U.S. National Map Accuracy Standards, geologic features represented here are within 3 meters /10 feet (horizontally) of their true location.

This figure was prepared as part of the NPS Geologic Resources Division's Geologic Resources Inventory. The source map used in creation of the digital geologic data product was:

Kendall, M.S., M.E. Monaco, K.R. Buja, J.D. Christensen, C.R. Kruer, and M, Finkbeiner, R.A. Warner. 1999. Benthic Habitat Map of the U.S. Virgin Islands-St. Croix; Prepared by Visual Interpretation from Remote Sensing Imagery Collect by NOAA in 1999 (scale 1:6,000).

Digital geologic data and cross sections for Buck Island Reef National Monument, and all other digital geologic data prepared as part of the Geologic Resources Inventory, are available online at the NPS Integrated Resource Management Applications Portal (IRMA): https://irma.nps.gov/ App/Reference/Search. (Enter "GRI" as the search text and select Buck Island Reef National Monument from the unit list.)

Produced by the Geologic Resources Inventory

September 2011

Map Unit Properties Table: Buck Island Reef National Monument

Gray-shaded rows indicate units not mapped within Buck Island Reef National Monument. *MMU = minimum mapping unit, which is 0.4 ha (1 ac) at a scale of 1:6,000 (Kendall et al. 1999). Geologic units mapped as "land (l)" on benthic habitat layer.

Age		Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History and Park Connections
QUATERNARY (Holocene)	Benthic Habitats	Submerged Vegetation Continuous Seagrass, ≥90% (sgc)	**Submerged Vegetation**: Greater than 10% cover of submerged vegetation in unspecified substrate type (usually sand, mud, or hardbottom). **Continuous Seagrass**: Seagrass covering 90% or more of the substrate. May include blowouts of less than 10% of the total area that are too small to be mapped independently, less than the minimum mapping unit (MMU*). This includes continuous beds of any shoot density (may be a continuous sparse or dense bed).	Damage by boat anchorage and vessel groundings. Physical baffling of sediment.	Habitat with 10% or more cover of *Thalassia testudinum, Syringodium filiforme, Halodule wrightii, Halophila baillonis*, or some combination thereof. Habitat for juvenile queen conch (*Strombus gigas*) and Caribbean spiny lobster (*Panulirus argus*).	Part of the Holocene reef system.
		Submerged Vegetation Patchy Seagrass, 10%–30% (sgp1)	**Submerged Vegetation**: See description above. **Patchy Seagrass**: Discontinuous seagrass with breaks in coverage that are too diffuse or irregular, or result in isolated patches of seagrass that are too small (smaller than the MMU*) to be mapped as **continuous seagrass (sgc)**.	Damage by boat anchorage and vessel groundings. Physical baffling of sediment.	Habitat with 10% or more cover of *Thalassia testudinum, Syringodium filiforme, Halodule wrightii, Halophila baillonis*, or some combination thereof. Habitat for juvenile queen conch (*Strombus gigas*) and Caribbean spiny lobster (*Panulirus argus*).	Part of the Holocene reef system.
		Submerged Vegetation Patchy Seagrass, 30%–50% (sgp2)	**Submerged Vegetation**: See description above. **Patchy Seagrass**: See description above.	Damage by boat anchorage and vessel groundings. Physical baffling of sediment.	Habitat with 10% or more cover of *Thalassia testudinum, Syringodium filiforme, Halodule wrightii, Halophila baillonis*, or some combination thereof. Habitat for juvenile queen conch (*Strombus gigas*) and Caribbean spiny lobster (*Panulirus argus*).	Part of the Holocene reef system.
		Submerged Vegetation Patchy Seagrass, 50%–70% (sgp3)	**Submerged Vegetation**: See description above. **Patchy Seagrass**: See description above.	Damage by boat anchorage and vessel groundings. Physical baffling of sediment.	Habitat with 10% or more cover of *Thalassia testudinum, Syringodium filiforme, Halodule wrightii, Halophila baillonis*, or some combination thereof. Habitat for juvenile queen conch (*Strombus gigas*) and Caribbean spiny lobster (*Panulirus argus*).	Part of the Holocene reef system.
		Submerged Vegetation Patchy Seagrass, 70%–90% (sgp4)	**Submerged Vegetation**: See description above. **Patchy Seagrass**: See description above.	Damage by boat anchorage and vessel groundings. Physical baffling of sediment.	Habitat with 10% or more cover of *Thalassia testudinum, Syringodium filiforme, Halodule wrightii, Halophila baillonis*, or some combination thereof. Habitat for juvenile queen conch (*Strombus gigas*) and Caribbean spiny lobster (*Panulirus argus*).	Part of the Holocene reef system.
		Submerged Vegetation Patchy Macroalgae, 10%–50% (map1)	**Submerged Vegetation**: See description above. **Patchy Macroalgae**: Discontinuous macroalgae with breaks in coverage that are too diffuse or irregular, or result in isolated patches of macroalgae that are too small (smaller than MMU*) to be mapped as continuous algae.	Stabilizes sediment but can be disrupted during storm events.	An area with 10% or greater coverage of any combination of numerous species of red, green, or brown macroalgae. Usually occurs in deeper waters on the bank/shelf zone. Representative Species: *Caulerpa* spp., *Dictyota* spp., *Halimeda* spp., *Lobophora variegata, Laurencia* spp.	Part of the Holocene reef system.
		Submerged Vegetation Patchy Macroalgae, 50%–90% (map2)	**Submerged Vegetation**: See description above. **Patchy Macroalgae**: See description above.	Stabilizes sediment but can be disrupted during storm events.	An area with 10% or greater coverage of any combination of numerous species of red, green, or brown macroalgae. Usually occurs in deeper waters on the bank/shelf zone. Representative Species: *Caulerpa* spp., *Dictyota* spp., *Halimeda* spp., *Lobophora variegata, Laurencia* spp.	Part of the Holocene reef system.
		Mangrove (m)	Emergent habitat composed of red, black, or white mangroves, or some combination thereof. Mangroves must be part of an open tidal system to be mapped. This habitat type is found only in the shoreline/intertidal, back reef, or barrier reef crest zone.	Generally found in areas sheltered from high-energy waves, but hurricane winds can damage.	Representative Species: *Rhizophora mangle, Avicennia germinans, Laguncularia racemose*	None within the national monument.

Gray-shaded rows indicate units not mapped within Buck Island Reef National Monument. *MMU = minimum mapping unit, which is 0.4 ha (1 ac) at a scale of 1:6,000 (Kendall et al. 1999). Geologic units mapped as "land (l)" on benthic habitat layer.

Age		Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History and Park Connections
QUATERNARY (Holocene)	Benthic Habitats	Artificial Habitat (a)	Artificial habitats such as submerged wrecks, large piers, submerged portions of rip-rap jetties, and the shoreline of islands created from dredge spoil.	Coral species affected by bleaching, disease, and predation.	Colonization by live coral. Representative coral species: *Acropora palmata*, *Acropora cervicornis*, *Diploria* spp., *Millespora complanata*, *Montastrea* spp., *Porites* spp., *Siderastrea* spp.	The Shipwreck lies off the northwest corner of Buck Island in approximately 5 m (17 ft) of water (National Park Service 1983).
		Unknown Habitat Type (u)	**Unknown**: Unable to interpret bottom type due to turbidity, cloud cover, water depth, or other interference.	Unknown.	Unknown.	Unknown.
		Unconsolidated Sediment Mud (mu)	Unconsolidated sediment covered by <10% submerged vegetation. **Mud**: Fine sediment often associated with river discharge and buildup of organic material in areas sheltered from high-energy waves and currents.	Heavy boat and human traffic can cause turbidity.	Burrowing shrimp (*Callianassa* spp.). Mangroves.	None within the national monument.
		Unconsolidated Sediment Sand (s)	Unconsolidated sediment covered by <10% submerged vegetation. **Sand**: Coarse carbonate sediment typically found in areas exposed to currents or wave energy.	Heavy boat and human traffic can cause turbidity. Source of carbonate sand. Potential anchorage and buoy-placement areas. Transported by seasonal wind and wave patterns.	Primary habitat type along with submerged vegetation, and coral reef and hardbottom.	Along with submerged vegetation, makes up 22% of habitat at Buck Island Reef National Monument (Pittman et al. 2008).
		Coral Reef and Hardbottom Uncolonized Hardbottom Reef Rubble (hbrr)	**Coral Reef and Hardbottom**: Hardened substrate of unspecified relief formed by the deposition of calcium carbonate by reef building corals and other organisms (relict or ongoing) or existing as exposed bedrock. **Uncolonized Hardbottom**: Hard substrate composed of relict deposits of calcium carbonate or exposed bedrock. **Reef Rubble**: Dead, unstable coral rubble often colonized with filamentous or other macroalgae. This habitat often occurs landward of well developed reef formations, along the reef crest or in the backreef.	Damage from physical force of waves during hurricanes.	Sparse or no colonization by live coral.	Part of the Holocene reef system.
		Coral Reef and Hardbottom Uncolonized Hardbottom Uncolonized Bedrock (hbub)	**Coral Reef and Hardbottom**: See description above. **Uncolonized Hardbottom**: See description above. **Uncolonized Bedrock**: Exposed bedrock contiguous with the shoreline that has sparse coverage of macroalgae, hard coral, gorgonians, and other sessile invertebrates that does not obscure the underlying rock.	Unknown.	Sparse or no colonization by live coral. Continuous with the shoreline, consisting of rocky shores and small, submerged rocky outcrops.	Part of the Holocene reef system.
		Coral Reef and Hardbottom Uncolonized Hardbottom Uncolonized Pavement (hbup)	**Coral Reef and Hardbottom**: See description above. **Uncolonized Hardbottom**: See description above. **Uncolonized Pavement**: Flat, low relief, solid carbonate rock that is often covered by a thin sand veneer. The pavement's surface often has sparse coverage of macroalgae, hard coral, gorgonians, and other sessile invertebrates that does not obscure the underlying carbonate rock.	Source of carbonate sand. Pavement indicates low wave energy and high hurricane frequency.	Sparse or no colonization by live coral. Pavement is composed of dead coral, which provides substrate for other organisms.	Part of the Holocene reef system.
		Coral Reef and Hardbottom Colonized Hardbottom Colonized Bedrock (rcb)	**Coral Reef and Hardbottom**: See description above. **Colonized Hardbottom**: Substrates formed by the deposition of calcium carbonate by reef building corals and other organisms. Habitats within this category have some colonization by live coral, unlike the **Uncolonized Hardbottom** category. **Colonized Bedrock**: Exposed bedrock contiguous with the shoreline that has coverage of macroalgae, hard coral, gorgonians, and other sessile invertebrates that partially obscures the underlying rock.	Coral species affected by bleaching, disease, and predation.	Colonization by live coral. Representative coral species: *Acropora palmata*, *Acropora cervicornis*, *Diploria* spp., *Millespora complanata*, *Montastrea* spp., *Porites* spp., *Siderastrea* spp.	Part of the Holocene reef system.

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Age		Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History and Park Connections
QUATERNARY (Holocene)	Benthic Habitats	Coral Reef and Hardbottom Colonized Hardbottom Colonized Pavement (rcp)	**Coral Reef and Hardbottom**: See description above. **Colonized Hardbottom**: See description above. **Colonized Pavement**: Flat, low-relief, solid carbonate rock with coverage of macroalgae, hard coral, gorgonians, and other sessile invertebrates that are dense enough to partially obscure the underlying carbonate rock.	Coral species affected by bleaching, disease, and predation. Pavement indicates low wave energy and high hurricane frequency.	Colonization by live coral. Representative coral species: *Acropora palmata*, *Acropora cervicornis*, *Diploria* spp., *Millespora complanata*, *Montastrea* spp., *Porites* spp., *Siderastrea* spp.	Part of the Holocene reef system.
		Coral Reef and Hardbottom Colonized Hardbottom Colonized Pavement with Sand Channels (rcpc)	**Coral Reef and Hardbottom**: See description above. **Colonized Hardbottom**: See description above. **Colonized Pavement with Sand Channels**: Habitat having alternating sand and colonized pavement formations that are oriented perpendicular to the shore or bank/shelf escarpment. The sand channels of this feature have low vertical relief compared to **spur and groove (rsgr)** formations. This habitat type occurs in areas exposed to moderate wave surge such as that found in the bank/shelf zone.	Coral species affected by bleaching, disease, and predation. Pavement indicates low wave energy and high hurricane frequency. Source of carbonate sand.	Colonization by live coral. Representative coral species: *Acropora palmata*, *Acropora cervicornis*, *Diploria* spp., *Millespora complanata*, *Montastrea* spp., *Porites* spp., *Siderastrea* spp. Pavement is composed of dead coral, which provides substrate for other organisms.	Part of the Holocene reef system.
		Coral Reef and Hardbottom Coral Reef and Colonized Hardbottom Linear Reef (rlr)	**Coral Reef and Hardbottom**: See description above. **Coral Reef and Colonized Hardbottom**: Substrates formed by the deposition of calcium carbonate by reef building corals and other organisms. Habitats within this category have some colonization by live coral, unlike the **Uncolonized Hardbottom** category. **Linear Reef**: Linear coral formations that are oriented parallel to the shore or the shelf edge. These features follow the contours of the shore/shelf edge. This category covers such commonly used terms as forereef, fringing reef, and shelf-edge reef.	Affected by bleaching, disease, and predation. Damage by snorkelers, primarily repeated use as a standing/resting platform but also fin kicks and touching with hands. Damage by boat anchorage and vessel groundings. Damage by waves during hurricanes. Source of carbonate sand.	Holes and grottos provide habitat for reef species. Colonization by live coral. Representative coral species: *Acropora palmata*, *Acropora cervicornis*, *Diploria* spp., *Millespora complanata*, *Montastrea* spp., *Porites* spp., *Siderastrea* spp.	Part of the Holocene reef system. Monitoring transects since 1976.
		Coral Reef and Hardbottom Coral Reef and Colonized Hardbottom Patch Reef Aggregated Patch Reef (rpra)	**Coral Reef and Hardbottom**: See description above. **Coral Reef and Colonized Hardbottom**: Substrates formed by the deposition of calcium carbonate by reef building corals and other organisms. Habitats within this category have some colonization by live coral, unlike the **Uncolonized Hardbottom** category. **Patch Reef**: Coral formations that are isolated from other coral formations by sand, seagrass, or other habitats and have no organized structural axis relative to the contours of the shore or shelf edge. A surrounding halo of sand is often a distinguishing feature of this habitat type when it occurs adjacent to submerged vegetation. **Aggregate Patch Reef**: Clustered patch reefs that individually are too small (smaller than the MMU*) or are too close together to map separately. Where aggregate patch reefs share halos, the halo is included as part of the map unit.	Affected by bleaching, disease, and predation. Damage by snorkelers, primarily repeated use as a standing/resting platform but also fin kicks and touching with hands. Damage by boat anchorage and vessel groundings. Damage by waves during hurricanes. Source of carbonate sand.	Colonization by live coral. Representative coral species: *Acropora palmata*, *Acropora cervicornis*, *Diploria* spp., *Millespora complanata*, *Montastrea* spp., *Porites* spp., *Siderastrea* spp.	Part of the Holocene reef system.
		Coral Reef and Hardbottom Coral Reef and Colonized Hardbottom Patch Reef Individual Patch Reef (rpri)	**Coral Reef and Hardbottom**: See description above. **Coral Reef and Colonized Hardbottom**: See description above. **Patch Reef**: See description above. **Individual Patch Reef**: Distinctive single patch reefs that are equal to or larger than the MMU*. When patch reefs occur in submerged vegetation and a halo is present, the halo is included as part of the patch reef.	Affected by bleaching, disease, and predation. Damage by snorkelers, primarily repeated use as a standing/resting platform but also fin kicks and touching with hands. Damage by boat anchorage and vessel groundings. Damage by waves during hurricanes. Source of carbonate sand.	Colonization by live coral. Representative coral species: *Acropora palmata*, *Acropora cervicornis*, *Diploria* spp., *Millespora complanata*, *Montastrea* spp., *Porites* spp., *Siderastrea* spp.	Part of the Holocene reef system.

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Age		Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History and Park Connections
QUATERNARY (Holocene)	Benthic Habitats	Coral Reef and Hardbottom Coral Reef and Colonized Hardbottom Scattered Coral or Rock in Unconsolidated Sediment (rscr)	**Coral Reef and Hardbottom**: See description above. **Coral Reef and Colonized Hardbottom**: See description above. **Scattered Coral or Rock in Unconsolidated Sediment**: Primarily sand or seagrass bottom with scattered rocks or small, isolated coral heads that are too small to be delineated individually (i.e., smaller than an individual patch reef).	Damage by snorkelers, primarily repeated use as a standing/resting platform but also fin kicks and touching with hands. Damage by boat anchorage and vessel groundings. Damage by waves during hurricanes.	Colonization by live coral. Representative coral species: *Acropora palmata*, *Acropora cervicornis*, *Diploria* spp., *Millespora complanata*, *Montastrea* spp., *Porites* spp., *Siderastrea* spp.	Part of the Holocene reef system.
QUATERNARY (Holocene)	Benthic Habitats	Coral Reef and Hardbottom Coral Reef and Colonized Hardbottom Spur and Groove Reef (rsgr)	**Coral Reef and Hardbottom**: See description above. **Coral Reef and Colonized Hardbottom**: See description above. **Spur and Groove Reef**: Habitat having alternating sand and coral formations that are oriented perpendicular to the shore or bank/shelf escarpment. The coral formations (spurs) of this feature typically have a high vertical relief compared to pavement with sand channels and are separated from each other by 1-5 meters of sand or bare hardbottom (grooves), although the height and width of these elements may vary considerably. This habitat type typically occurs in the fore reef or bank/shelf escarpment zone.	Affected by bleaching, disease, and predation. Damage by snorkelers, primarily repeated use as a standing/resting platform but also fin kicks and touching with hands. Damage by boat anchorage and vessel groundings. Damage by waves during hurricanes. Source of carbonate sand.	Colonization by live coral. Representative coral species: *Acropora palmata*, *Acropora cervicornis*, *Diploria* spp., *Millespora complanata*, *Montastrea* spp., *Porites* spp., *Siderastrea* spp.	Part of the Holocene reef system.
QUATERNARY (Holocene)	Geologic Units	Surficial Deposits (Qal)	Recent surficial deposits (also referred to as alluvium). Includes beach sand, beach rock (sand and gravel cemented with calcium carbonate), and stream deposits.	Hurricanes alter beach dynamics. Flooding during hurricanes. Source of carbonate sand. Potential anchorage and buoy-placement areas. Streams are intermittent and run only after storm events.	Nesting areas for threatened and endangered species.	Coral mounds and aboriginal sites. Beaches for sunbathing and swimming.
NEOGENE (Lower Miocene)	Geologic Units	Kingshill Marl (MIkh)	Buff-to-white, moderately thick-bedded limestone, alternating with soft cream or white marl. Limestone has structureless appearance, and the bedding planes are obscure when composed of coral debris. Forms the surface of the coastal plain, except where covered by **alluvium (Qal)**. Thickness up to 180 m (600 ft). Subdivided into two members—La Reine and Mannings Bay—by Gill et al. (1989), McLaughlin et al. (1995), and Gill et al. (2002).	Karst cavities.	Planktonic foraminifera: *P. glomerosa, G. peripheroronda, G. fohsi fohsi, G. fohsi robata, G. fohsi robusta, G. mayerii, G. menardii, G. acostaensis, G. numerosa, and G. margaritae.* Corals.	Originated in quiet, deep-marine setting.
PALEOGENE (Upper Oligocene)	Geologic Units	Jealousy Formation (OLj)	Dark-colored clay and conglomerate. In places, the conglomerate is poorly stratified and consists of pebbles, cobbles, and boulders of the **Judith Fancy Formation (Kj)** and minor diorite; pockets of red and green clay up to 6 m (20 ft) long and 1.5 m (5 ft) deep; and a calcareous sandy matrix. Clay is about 90% montmorillonite and 10% angular fragments of quartz, plagioclase, hornblende, and hematite. Total thickness 426 m (1,398 ft).	Exposures are highly weathered (Gerhard et al. 1978).	Paleontological Resources—Thin oyster beds, corals, and fossil shell fragments. Planktonic foraminifera: *P. glomerosa*, *G. peripheroronda*, and *G. fohsi fohsi*	Originated in quiet, deep-marine setting.
EARLY "TERTIARY"–UPPER CRETACEOUS	Geologic Units	Southgate Diorite (TKdi)	Discordant, unfoliated intrusion into unmetamorphosed country rock, about 1.2 km (0.75 mi) wide at center of East End Range. Hornblende and plagioclase are essential minerals and occur in nearly equal amounts. Hornblende varies from completely anhedral to euhedral crystals averaging about 1 mm (0.4 in) long, strongly pleochroic from olive green to brownish green and poikilitically encloses other minerals, particularly small crystals of plagioclase. Augite, magnetite, and apatite are accessory minerals. Alteration products include chlorite, epidote, clinozoisite, prehnite, and saussurite. Small anhedral quartz grains in some rocks near the margin of the intrusion.	Easily weathered.	Stocks and dikes on St. Croix.	Probably intruded before folding of Cretaceous rocks. Buck Island Reef National Monument hosts no intrusions.

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Age	Map Unit (Symbol)				Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History and Park Connections
UPPER CRETACEOUS	Geologic Units			Fountain Gabbro (Kg)	Two-pyroxene gabbro with accessory biotite, magnetite, apatite, and hornblende. Plagioclase (labradorite) and augite are the essential minerals. Hypersthene occurs in variable amounts and may be essential or accessory. Hypersthene granules are distinctly smaller than augite, 0.1 mm (0.004 in) in diameter. Exposed pluton—3.6 km (2.3 mi) long and a maximum of 2 km (1.3 mi) wide—shaped in plan view like a malformed letter "H." Sharp, steeply dipping (in many cases vertical) contact with adjacent metasedimentary rocks. Locally foliated, but most of the pluton is unfoliated and without lineation. Small dikes branch outward from the main pluton and intrude nearby sedimentary rocks. Discordant, almost completely lacking in foliation, and unmetamorphosed country rock surrounding the contact aureole indicate a shallow depth of intrusion.	Easily weathered.	Stocks and dikes on St. Croix.	Probably intruded before folding of Cretaceous rocks. Buck Island Reef National Monument hosts no intrusions.
UPPER CRETACEOUS	Geologic Units	Mount Eagle Group		Judith Fancy Formation (Kj)	Fine- to coarse-grained tuffaceous sandstone, breccia and lapilli tuff, or tuff and lapilli tuff. About 4,570 m (15,000 ft) thick. Largely undifferentiated but separated and mapped into members at various locations.	Easily weathered.	Fossils—A few thin beds of fossiliferous fragmental limestone interbedded with the tuffaceous rocks, corals, and foraminifera.	Originated in island-arc setting.
UPPER CRETACEOUS	Geologic Units	Mount Eagle Group	Judith Fancy Formation	Recovery Hill Member (Kjr)	Blue-gray mudstone and subordinate fine-grained tuffaceous sandstone. Estimated thickness 305 m (1,000 ft).	Easily weathered.	Fossils—A few thin beds of fossiliferous fragmental limestone interbedded with the tuffaceous rocks, corals, and foraminifera.	Originated in island-arc setting.
UPPER CRETACEOUS	Geologic Units	Mount Eagle Group	Judith Fancy Formation	Blue Mountain Member (Kjb)	Hard, resistant olive-green siliceous siltstone interbedded with fine-grained tuffaceous sedimentary rocks. Maximum thickness 1,130 m (3,700 ft).	Easily weathered.	Fossils—A few thin beds of fossiliferous fragmental limestone interbedded with the tuffaceous rocks, corals, and foraminifera.	Originated in island-arc setting.
UPPER CRETACEOUS	Geologic Units	Mount Eagle Group	Judith Fancy Formation	Clairmont Member (Kjc)	Resistant bed of limestone and volcanic pebble conglomerate 15 m (50 ft) thick or less.	Easily weathered.	Fossils—A few thin beds of fossiliferous fragmental limestone interbedded with the tuffaceous rocks, corals, and foraminifera.	Originated in island-arc setting.
UPPER CRETACEOUS	Geologic Units	Mount Eagle Group	Cane Valley Formation	Springfield Member (Kcvs)	Mudstone and fine-grained tuffaceous sandstone. Approximately 180 m (600 ft) thick.	Easily weathered.	No fossils.	Originated in island-arc setting.
UPPER CRETACEOUS	Geologic Units	Mount Eagle Group	Cane Valley Formation	Robe Hill Member (Kcvr)	Medium- and coarse-grained tuffaceous sandstone interbedded in a 3:1 ratio with mudstone. Thickness 120 m (400 ft) where best exposed.	Easily weathered.	No fossils.	Originated in island-arc setting.
UPPER CRETACEOUS	Geologic Units	Mount Eagle Group	Cane Valley Formation	Hope Member (Kcvh)	**Lower half:** About equal amounts of green fine-grained tuffaceous sandstone and black mudstone. **Upper half:** Entirely mudstone. Total thickness 210 m (700 ft).	Easily weathered.	No fossils.	Originated in island-arc setting.
UPPER CRETACEOUS	Geologic Units	Mount Eagle Group		Allandale Formation (Ka)	Tuffaceous sandstone and mudstone. Estimated thickness 610 m (2,000 ft).	Easily weathered. Displaced by faulting on St. Croix.	No fossils.	Originated in island-arc setting.
UPPER CRETACEOUS	Geologic Units	Mount Eagle Group		Caledonia Formation (Kc)	Volcaniclastic sandstone and mudstone and turbidites. Composed of a variety of rock types, including, in order of abundance, mudstone, sandstones, limestone, chert, and conglomerate. Thickness of any particular lithology is generally on a scale of inches, and most rock types are regularly repeated, giving a homogeneous aspect to the entire formation. Sedimentary structures in sandstone beds include graded bedding, current bedding, deformed bedding, load casts, and surface markings. Estimated maximum thickness 5,490 m (18,000 ft).	Erosion during heavy rains. Thin soils.	Representative terrestrial plant species: seagrape (*Coccoloba uvifera*), manchineel (*Hippomane manicinella*), and coconut palm (*Cocos nucifera*). Potential for fossils—marine invertebrates (foraminifera, rudists, corals, and gastropods). Trace fossils (bioturbation). Ammonite found along Tague Bay, southeast of Buck Island.	Originated in island-arc setting. Primary bedrock unit at Buck Island Reef National Monument.
UPPER CRETACEOUS	Geologic Units	Mount Eagle Group		Caledonia Formation East End Member (Kce)	Tuffaceous rocks (metamorphosed in places) in three subdivisions (from oldest to youngest): (1) volcanic breccia and tuffaceous sandstone, 50 m (175 ft) thick; (2) black mudstone, 60 m (200 ft) thick, thins to a feather edge; and (3) light-green coarse-grained tuffaceous sandstone, at least 90 m (300 ft) thick. Total thickness 275 m (900 ft).	Erosion during heavy rains.	Potential for fossils—Marine invertebrates (foraminifera, rudists, corals, and gastropods). Trace fossils (bioturbation). Ammonite found along Tague Bay, southeast of Buck Island.	Originated in island-arc setting.

Glossary

This glossary contains brief definitions of technical geologic terms used in this report. Not all geologic terms used are referenced. For more detailed definitions or to find terms not listed here please visit: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html. Definitions are based on those in the American Geological Institute Glossary of Geology (fifth edition; 2005).

alluvium. Stream-deposited sediment.
anhederal. A mineral crystal that shows no rational faces or a detrital grain that shows no crystal outline.
anticline. A convex-upward ("A" shaped) fold. Older rocks are found in the center.
anticlinorium. A large, regional feature with an overall shape of an anticline. Composed of many smaller folds.
apatite. A group of variously colored phosphate minerals. Tooth enamel and bones contain minerals from the apatite group.
arc. See "volcanic arc" and "magmatic arc."
ash (volcanic). Fine material ejected from a volcano (also see "tuff").
augite. A dark-green to black pyroxene mineral that contains large amounts of aluminum, iron, and magnesium. Found in igneous and high-temperature metamorphic rocks.
aureole. A zone surrounding an igneous intrusion in which the country rock shows the effects of contact metamorphism from the high temperature, molten material.
basin (structural). A doubly plunging syncline in which rocks dip inward from all sides.
basin (sedimentary). Any depression, from continental to local scales, into which sediments are deposited.
beach. A gently sloping shoreline covered with sediment, commonly formed by the action of waves and tides.
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.
biotite. A widely distributed and important rock-forming mineral of the mica group. Forms thin, flat sheets.
bioturbation. The reworking of sediment by organisms.
breccia. A coarse-grained, generally unsorted sedimentary rock consisting of cemented angular clasts greater than 2 mm (0.08 in).
breccia (volcanic). A coarse-grained, generally unsorted volcanic rock consisting of partially welded angular fragments of ejected material such as tuff or ash.
brittle. Describes a rock that fractures (breaks) before sustaining deformation.
calcareous. Describes rock or sediment that contains the mineral calcium carbonate ($CaCO_3$).
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).
chert. A extremely hard sedimentary rock with conchoidal (smooth curved surface) fracturing. It consists chiefly of interlocking crystals of quartz Also called "flint."
chlorite. A group of platy, usually greenish minerals that are widely distributed in low-grade metamorphic rocks.
clast. An individual grain or rock fragment in a sedimentary rock, produced by the physical disintegration of a larger rock mass.
clastic. Describes rock or sediment made of fragments of pre-existing rocks (clasts).
clay. Can be used to refer to clay minerals or as a sedimentary fragment size classification (less than 1/256 mm [0.00015 in]).
claystone. Lithified clay having the texture and composition of shale but lacking shale's fine layering and fissility (characteristic splitting into thin layers).
clinozoisite. A grayish-white, pink, or green mineral of the epidote group.
cleavage (mineral). The tendency of a mineral to break preferentially in certain directions along planes of weaknesses in the crystal structure.
conglomerate. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in).
contact metamorphism. Changes in rock as a result of contact with an igneous body.
convergent boundary. A plate boundary where two tectonic plates are colliding.
country rock. The rock surrounding an igneous intrusion or pluton. Also, the rock enclosing or traversed by a mineral deposit.
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.
dike. A narrow igneous intrusion that cuts across bedding planes or other geologic structures.
diorite. A type of plutonic igneous rock. It is the approximate intrusive equivalent of andesite.
dip. The angle between a bed or other geologic surface and horizontal.
discordant. Describes contacts between strata that cut across or are set at an angle to the orientation of adjacent rocks.
epiclastic rock. A rock formed at Earth's surface by consolidation of fragments of pre-existing rocks.
epicontinental. Describes a geologic feature situated on the continental shelf or on the continental interior. An "epicontinental sea" is one example.

epidote. A yellow-green, pistachio-green, or blackish-green mineral.

escarpment. A steep cliff or topographic step resulting from vertical displacement on a fault or by mass movement. Also called a "scarp."

estuary. The seaward end or tidal mouth of a river where freshwater and seawater mix; many estuaries are drowned river valleys caused by sea-level rise (transgression) or coastal subsidence.

euhedral. Mineral grains that are completely bounded by crystal faces.

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

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

fault gouge. Soft, uncemented, pulverized, clay-like material found along some faults. Formed by friction as the fault moves.

floodplain. The surface or strip of relatively smooth land adjacent to a river channel and formed by the river. Covered with water when the river overflows its banks.

foraminifera. Any protozoan belonging to the subcalss Sarcodina, order Foraminiferida, characterized by the presence of a test with one to many chambers composed of secreted calcite (rarely silica or aragonite) or of agglutinated particles. Most foraminifers are marine but freshwater forms are known. The first occurrence was in the Cambrian; they exist today.

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

gabbro. A group of dark-colored, intrusive igneous rocks. The intrusive equivalent of basalt.

gastropod. Mollusks (e.g., snails, slugs, clams, or squids) of the class Gastropoda; usually have a univalve shell, or no shell, and a distinct head bearing sensory organs. "Gasto" means stomach; "pod" means foot.

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

graben. A down-dropped structural block bounded by steeply dipping, normal faults (also see "horst").

hematite. A common iron mineral.

hornblende. The most common mineral of the amphibole group. Hornblende is commonly black and occurs in distinct crystals or in columnar, fibrous, or granular forms.

horn. A high pyramidal peak with steep sides formed by the intersection walls of three or more cirques.

horst. Areas of relative "up" between grabens, representing the geologic surface left behind as grabens drop. The best example is the Basin-and-Range province of Nevada. The basins are grabens and the ranges are weathered horsts. Grabens become a locus for sedimentary deposition (also see "graben").

hypersthene. A common rock-forming mineral of the orthopyroxene group; it is an essential constituent of many igneous rocks.

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

intrusion. A body of igneous rock that invades (pushes into) older rock. The invading rock may be a plastic solid or magma.

island arc. A line or arc of volcanic islands formed over and parallel to a subduction zone.

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

lamination. Very thin, parallel layers.

lapilli. Pyroclastics in the general size range of 2 to 64 mm (0.08 to 2.5 in.).

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

left lateral fault. A strike slip fault on which the side opposite the observer has been displaced to the left Synonymous with "sinistral fault."

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

limy. Containing a significant amount of lime or limestone.

lineation. A general, nongeneric term for any linear structure in a rock such as flow lines, stretched clasts, slickensides, preferred alignment of fossils, or axes of folds.

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

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

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

magnetite. A black, strongly magnetic mineral.

marl. An unconsolidated deposit commonly with shell fragments and sometimes glauconite consisting chiefly of clay and calcium carbonate that formed under marine or freshwater conditions.

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.

meta–. A prefix used with the name of a sedimentary or igneous rock, indicating that the rock has been metamorphosed.

metamorphic. Describes the process of metamorphism or its results. One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

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

metasedimentary. A sediment or sedimentary rock that has been subjected to metamorphism.

montmorillinite. A clay mineral.

mudstone. A fine-grained sedimentary rock whose original constituents were clay or mud.
outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.
packstone. A sedimentary carbonate rock whose granular material is arranged in a self-supporting framework, yet also contains some matrix of calcareous mud.
paleontology. The study of the life and chronology of Earth's geologic past based on the fossil record.
pebble. Generally, small rounded rock particles from 4 to 64 mm (0.16 to 2.52 in) in diameter.
plagioclase. An important rock-forming group of feldspar minerals.
plastic. Capable of being deformed permanently without rupture.
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.
pleochroic. The ability to absorb various wavelengths of light in various crystallographic directions and thus to show different colors in different directions.
pluton/plutonic. A body of intrusive igneous rock that crystallized at some depth beneath Earth's surface.
poikilitic. An igneous rock in which small grains of one mineral are irregularly scattered without common orientation in a typically anhedral larger crystal of another mineral.
prehnite. A pale-green, yellow-brown, or white mineral commonly associated with geodes, druses, fissures, or joints in altered igneous rocks.
pyroclast. An individual particle ejected during a volcanic eruption.
pyroclastic. Describes clastic rock material formed by volcanic explosion or aerial expulsion from a volcanic vent; also pertaining to rock texture of explosive origin. In the plural, the term is used as a noun.
pyroxene. A common rock-forming mineral. It is characterized by short, stout crystals.
quartz. Crystalline silica (SiO_2). It is the most common mineral after feldspar.
rock. A solid, cohesive aggregate of one or more minerals.
rudist. A bivalve mollusk frequently found in association with corals. Their range is Upper Jurassic to Upper Cretaceous, possibly Paleocene.
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).
sandstone. Clastic sedimentary rock of predominantly sand-sized grains.
saussurite. A tough, compact mineral aggregate.
scarp. A steep cliff or topographic step resulting from displacement on a fault, or by mass movement, or erosion. Also called an "escarpment."
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.
sequence. A major informal rock-stratigraphic unit that is traceable over large areas and defined by a sediments associated with a major sea level transgression-regression.
shoaling. To become shallow gradually; to fill up or block off with a shoal (a relatively shallow place in a body of water of a submerged bank, ridge, or bar of sand or other unconsolidated material).
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]).
siltstone. A variably lithified sedimentary rock composed of silt-sized grains.
sinkhole. A circular depression in a karst area with subterranean drainage and is commonly funnel-shaped.
slope. The inclined surface of any geomorphic feature or measurement thereof. Synonymous with "gradient."
stock. An igneous intrusion exposed at the surface; less than 100 km^2 (40 mi^2) in size. Compare to "pluton."
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.
strike-slip fault. A fault with measurable offset where the relative movement is parallel to the strike of the fault. Said to be "sinistral" (left-lateral) if relative motion of the block opposite the observer appears to be to the left. "Dextral" (right-lateral) describes relative motion to the right.
subduction zone. A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.
tectonic. Relating to large-scale movement and deformation of Earth's crust.
tectonics. The geologic study of the broad structural architecture and deformational processes of the lithosphere and asthenosphere.
tephra. A collective term used for all pyroclastic material, regardless of size, shape, or origin, ejected during an explosive volcanic eruption.
terrace. A relatively level bench or step-like surface breaking the continuity of a slope (also see "stream terrace").
terrestrial. Relating to land, Earth, or its inhabitants.
terrigenous. Derived from the land or a continent.
trace fossil. Tracks, trails, burrows, coprolites (dung), etc., that preserve evidence of organisms' life activities, rather than the organisms themselves.
transform fault. A strike-slip fault that links two other faults or two other plate boundaries (e.g. two segments of a mid-ocean ridge). A type of plate boundary at which lithosphere is neither created nor destroyed, and plates slide past each other on a strike-slip fault.
trend. The direction or azimuth of elongation of a linear geologic feature.

tuff. Generally fine-grained, igneous rock formed of consolidated volcanic ash.

uplift. A structurally high area in the crust, produced by movement that raises the rocks.

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

volcanic arc. A commonly curved, linear, zone of volcanoes above a subduction zone.

volcaniclastic. Describes clastic volcanic materials formed by any process of fragmentation, dispersed by any kind of transporting agent, deposited in any environment.

volcanogenic. Describes material formed by volcanic processes.

wackestone. A "dirty" sandstone that consist of a mixture of poorly sorted mineral and rock fragments in an abundant matrix of clay and fine silt.

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Additional References

This section lists additional references, resources, and web sites that may be of use to resource managers. Web addresses are current as of September 2011.

Geology of National Park Service Areas

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

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

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Lillie, R. J. 2005. Parks and Plates: The geology of our national parks, monuments, and seashores. W.W. Norton and Co., New York, New York, USA. [Geared for interpreters].

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

Resource Management/Legislation Documents

NPS 2006 Management Policies (Chapter 4; Natural Resource Management): http://www.nps.gov/policy/mp/policies.html#_Toc157232681

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

NPS Technical Information Center (Denver, repository for technical (TIC) documents): http://etic.nps.gov/

Geological Survey Information

U.S. Geological Survey: http://www.usgs.gov/

USGS Caribbean Water Science Center: http://vi.water.usgs.gov/

U.S. Geological Survey in Puerto Rico / U.S. Virgin Islands: GSA Center, 651 Federal Drive, Suite 400-15, Guaynabo, PR 00965; 787-749-4346

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

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

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

Other Geology/Resource Management Tools

Bates, R. L. and J. A. Jackson, editors. American Geological Institute dictionary of geological terms (3rd Edition). Bantam Doubleday Dell Publishing Group, New York.

U.S. Geological Survey National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/

U.S. Geological Survey Geologic Names Lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

U.S. Geological Survey Geographic Names Information System (GNIS; search for place names and geographic features, and plot them on topographic maps or aerial photos): http://gnis.usgs.gov/

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

U.S. Geological Survey Publications Warehouse (many USGS publications are available online): http://pubs.er.usgs.gov

U.S. Geological Survey, description of physiographic provinces: http://tapestry.usgs.gov/Default.html

Appendix: Scoping Session Participants

The following is a list of participants from the GRI scoping session for Buck Island Reef National Monument, held on April 5, 2004. The contact information and email addresses in this appendix may be outdated; please contact the Geologic Resources Division for current information. The scoping meeting summary was used as the foundation for this GRI report. The original scoping summary document is available on the GRI publications website: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

Name	Affiliation	Position	Phone	E-mail
Rebecca Beavers	Geologic Resources Division	Coastal Geologist	303-987-6945	rebecca_beavers@nps.gov
Tim Connors	Geologic Resources Division	Geologist	303-969-2093	tim_connors@nps.gov
Melanie Harris	U.S. Geological Survey	Geographer	727-803-8747	mharris@usgs.gov
Bruce Heise	Geologic Resources Division	Geologist	303-969-2017	bruce_heise@nps.gov
Zandy Hillis-Starr	Buck Island Reef National Monument	Chief of Resource Management	340-773-1460 x235	zandy_hillis-starr@nps.gov
Matt Patterson	South Florida/Caribbean Network	Inventory and Monitoring Coordinator	305-230-1144	matt_patterson@nps.gov
Kimberly Woody	Buck Island Reef National Monument	Biologist		

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