National Park Service
U.S. Department of the Interior

Natural Resource Program Center

Virgin Islands National Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2010/226

THIS PAGE:
Underwater ecosystems including coral reefs are a primary natural resource at Virgin Islands National Park. National Park Service photograph.

ON THE COVER:
This view of Trunk Bay shows the steep slopes characteristic of Virgin Islands National Park. National Park Service photograph courtesy Rafe Boulon (Virgin Islands National Park).

Virgin Islands National Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2010/226

Geologic Resources Division
Natural Resource Program Center
P.O. Box 25287
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July 2010

U.S. Department of the Interior
National Park Service
Natural Resource Program Center
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The Natural Resource Report Series is used to disseminate high-priority, current natural resource management information with managerial application. The series targets a general, diverse audience, and may contain NPS policy considerations or address sensitive issues of management applicability.

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

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Executive Summary

This report accompanies the digital geologic map for Virgin Islands National Park in St. John, 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.

Virgin Islands National Park is world-renowned for its pristine beaches, clear turquoise waters, and remarkable natural and cultural resources. The park is home to a vast array of ecosystems, including coral reefs, mangrove forests, salt ponds, sea grass beds, subtropical forests, dry forests, and sandy (and "rocky") beaches.

Virgin Islands National Park is located primarily on the island of St. John in the Caribbean Sea. Virgin Islands Coral Reef National Monument, established in 2001, encompasses 5,143 ha (12,708 ac) of submerged lands adjacent to St. John.

More than 100 million years ago, complex geologic processes began forming the setting of Virgin Islands National Park. Many of the important resource-related issues currently faced by park managers are connected to past and ongoing geologic and hydrologic features and processes. A variety of physical processes such as seismicity, slope stability, oceanographic variables, and climatic conditions can drastically alter the landscape. Geology also plays a significant role in the protection and preservation of biological and cultural resources. Thus, a general knowledge of the geologic resources within the park is crucial for effective park management, scientific research, and interpretation.

Virgin Islands National Park is an ideal venue for studying the links between geologic, biologic, and cultural resources. Park visitors are afforded an exceptional opportunity to learn about the park's geologic resources during interpretive hikes and talks. The rich landscape provides a fitting backdrop for discussing the geologic history of the area and its ongoing physical processes, which continue to alter the landscape yearly, seasonally, and even daily.

The following geologic issues, features, and processes are of primary importance and have the highest level of management significance to Virgin Islands National Park:

- Slope stability and erosion. The park is characterized by rugged terrain and steep, rocky slopes. More than three-quarters of St. John is covered with hillsides in excess of 30% slope. Slope failure is common during storm events and can devastate terrestrial, coastal, and marine habitats. In addition, rockfalls and mudslides can pose serious hazards to park visitors and infrastructure (including roads, which can be rendered impassable). Unpaved roads throughout the park are easily eroded, creating an additional management concern. Grazing is another cause of slope failure; feral animals such as goats and hogs heavily graze on steep hillsides within the park, increasing erosion and sedimentation into adjacent coastal and marine ecosystems. Even small increases in sediment supply can have devastating effects on fragile environments such as coral reefs and sea grass beds.
- Windblown contaminants. Park employees are investigating the effects of dust particulates on park resources. Findings suggest that imported particulates, primarily from Africa, carry dust-borne pathogens that can harm fragile marine habitats such as coral reefs and sea grass beds. Dust from alternate sources (e.g., ash fall from the 1995 Montserrat eruption) could also negatively impact these habitats.
- Coastal features and processes. The park is known for its beautiful beaches and unique coastal ecosystems; thus, the protection and preservation of these valuable resources is a primary concern. Many of the threats to these resources result from visitor use and human activities, but also from natural coastal dynamics. Immediate management concerns include beach erosion, sea level rise, anthropogenic modifications, and salt pond infilling.
- Marine features and processes. Participants at the 2004 scoping meeting identified a need for additional marine mapping products—in particular, mapping that targets geologic features and processes such as sediment characteristics, oceanographic variables, and benthic habitats. Monitoring of recreational impacts from boating and surfing would also help to minimize detrimental effects on marine resources.

The glossary contains explanations of many technical terms used in this report, including terms used in the Map Unit Properties Table. A geologic time scale is provided as figure 16.

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 Program Center.

The Geologic Resources Division 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.

Special thanks to Rafe Boulon (Virgin Islands National Park) who provided additional information and many photographs used in the report.

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Introduction

The following section briefly describes the National Park Service Geologic Resources Inventory and park setting of Virgin Islands National Park.

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 Program Center, 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 nongeoscientists. 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 web site (http://www.nature.nps.gov/geology/inventory/).

Park Setting

The Virgin Islands are situated at the northern end of the Lesser Antilles island chain. The Lesser Antilles are one of three island groups in the Caribbean Sea, along with the Greater Antilles and the Bahamas.

The U.S. Virgin Islands are composed of three primary islands—St. Thomas, St. John, and St. Croix—and several smaller surrounding islands. St. Croix has the largest land mass, at 207 km^2 (80 mi^2), and a relatively high western mountainous tip. St. Croix features coral growth along much of its insular shelf. St. Thomas is the second largest of the U.S. Virgin Islands, at 83 km^2 (32 mi^2). St. John is the smallest, at 52 km^2 (20 mi^2) (Turgeon et al. 2002).

Virgin Islands National Park covers much of the island of St. John, the least developed of the three main U.S. Virgin Islands (fig. 1). The park envelopes 3,893 ha (9,620 ac) in its entirety—including more than three-quarters of St. John, part of St. Thomas, part of the smaller Hassel Island, and 229 ha (5,650 ac) of underwater marine area.

Steep rocky slopes, many in excess of 30%, characterize St. John. The highest peaks on the island are Camelberg Peak (364 m [1,193 ft]) and Bordeaux Mountain (389 m [1,277 ft]) (fig. 1). The northern slopes of St. John are covered in moist subtropical forests, while dry forests characterize the south and east sides of the island. Fringing coral reefs and sea grass beds surround the island.

Because of its incredible array of water resources, land resources, and biodiversity, in 1976, the United Nations declared Virgin Islands National Park a biosphere reserve. This designation is recognized under the United Nations Educational, Scientific, and Cultural Organization (UNESCO) Man and the Biosphere Program. The biosphere reserve serves as a "living laboratory," utilizing an integrative approach to the responsible management of natural resources while promoting sustainable economic and human development (UNESCO 2000).

The establishment of Virgin Islands Coral Reef National Monument in 2001 added 5,143 ha (12,708 ac) of submerged land to the National Park System, and approximately doubled the amount of acreage in and around St. John under NPS stewardship.

Cultural History

St. John's cultural history is colorful and complex, with the first humans arriving in 1000 BCE (Before Common Era). The first village settlements developed from 200 BCE to CE 600 (Common Era), with rapid population growth and village expansion across the landscape between 600 and 1200. Between 1200 and 1492, the Taino culture developed. Living within the sheltered bays of the island, the Taino people practiced agriculture, introducing nonnative foods such as manioc (cassava) to the island. They also hunted and gathered food from primarily marine resources. For unknown reasons, the Taino vanished from the island before 1492 (Zanhniser 1999). Archaeological sites associated with the Taino culture, as well as Danish occupation (1718–1850) and African-slave communities, are contained within Virgin Islands National Park. Many sites on St. John are listed in the National Register of Historic Places.

Following the Taino, human habitation on St. John existed as follows:

- 1450 to 1550—Contact between Taino and Carib cultures, followed by Spanish and the demise of pre-Columbian culture
- 1580 to 1700—European expansion into the Caribbean and the age of Piracy and Privateers
- 1665 to 1733—Early European settlement of St. Thomas/Hassel Island and St. John
- 1733 to 1840s—Expansion of sugar, cotton, slavery, and maritime commerce
- 1801 to 1815—The Napoleonic War and British occupation
- 1839 to 1848—Underground Railway period marked by guardhouses and escape routes
- 1840s to 1917—Emancipation, signaling the end of the sugar and cotton industry and the introduction of bay rum, cattle, and charcoal production during a new era of maritime commercial expansion (National Park Service 2010a).

In 1917, the United States purchased the Virgin Islands from Denmark, beginning the American "Naval Regime" (with military installations on Hassel Island) and continuing through World War II. Starting in the 1920s, tourism blossomed as visitors from the United States began to discover and move to the Virgin Islands. In the 1950s, tourism became the islands' major source of commerce and industry. Nearly 416,000 people visited Virgin Islands National Park in 2009. The community of St. John strives to balance the demands of tourism and economic growth while preserving this Caribbean paradise.

Establishment of Virgin Islands National Park

On August 2, 1956, President Eisenhower signed a bill that established Virgin Islands National Park. The creation of the park was in large part due to a generous donation by Laurence S. Rockefeller, who witnessed the beauty of St. John during a Caribbean cruise in the 1950s. Rockefeller and his family acquired more than 2,000 ha (5,000 ac) on St. John with the intention of preserving the pristine and untamed beauty of the area. Rockefeller donated more than half of the initial acreage of the park, including the acquisition of private inholdings, as they become available (Rockefeller Archive Center 2004).

Establishment of Virgin Islands Coral Reef National Monument

On January 17, 2001, President Clinton proclaimed Virgin Islands Coral Reef National Monument to protect and preserve the delicate coral resources. The monument encompasses submerged lands adjacent to St. John, including Hurricane Hole, a well-developed tropical marine ecosystem. On July 20, 2002, NPS Director Mainella stated before the Subcommittee on National Parks, Recreation and Public Lands that the monument should "provide for a recovery of coral reefs and associated habitats, facilitate an increase in the abundance of reef fish, sustain traditional cultural fishing practices in surrounding waters, enhance the quality of the visitor experience to the Virgin Islands, and contribute to economic growth from tourism" (Mainella 2002).

Geologic Setting

The Virgin Islands and Virgin Islands National Park are geographically part of the Lesser Antilles but are more akin geologically with the Greater Antilles (Rankin 2002). The Greater Antilles, which rise from a marine plateau, include Cuba, Hispaniola (Haiti and the Dominican Republic), Jamaica, and Puerto Rico. The Greater Antilles are situated along the northern margin of the Caribbean tectonic plate (fig. 2), 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, and on the south by a right-lateral, strike-slip fault. The eastern boundary of the Caribbean plate is a subduction zone, where oceanic crust under the Atlantic Oceans is being forced beneath oceanic crust beneath the Caribbean Sea. This subduction zone fuels the volcanoes of the Lesser Antilles, such as the Soufriere Hills volcano that has buried much of Montserrat beginning in the mid 1990s. Volcanic activity occurs as far north as the island of Saba about 160 km (100 mi) southeast of St. John (Rankin 2002). St. John is in the northeastern corner of the Caribbean plate where motion on the plate boundary is transitional from subduction to strike-slip. Plate boundaries are seismically active (fig. 3) with the potential for large earthquakes in the Caribbean as evidenced by the January 12, 2010 earthquake that devastated Haiti.

The Greater Antilles are part of an older subduction-related magmatic arc, most likely built on oceanic crust beginning in the Lower Cretaceous Period and lasting through the Eocene Epoch (Pindell and Barrett 1990; Rankin 2002) (see fig. 16 for a geologic time scale). The arc hosts two distinct magmatic series. The oldest rocks formed in an extensional (Earth's crust pulling apart) environment, and include keratophyre (sodium-rich rhyolite lava), basalt, and sheeted dikes. The character of the volcanism changed after deposition of the Water Island Formation (see Map Unit Properties Table) to the more typical island-arc volcanism represented on St. John by andesite and basalt in the Louisenhoj and Tutu formations.

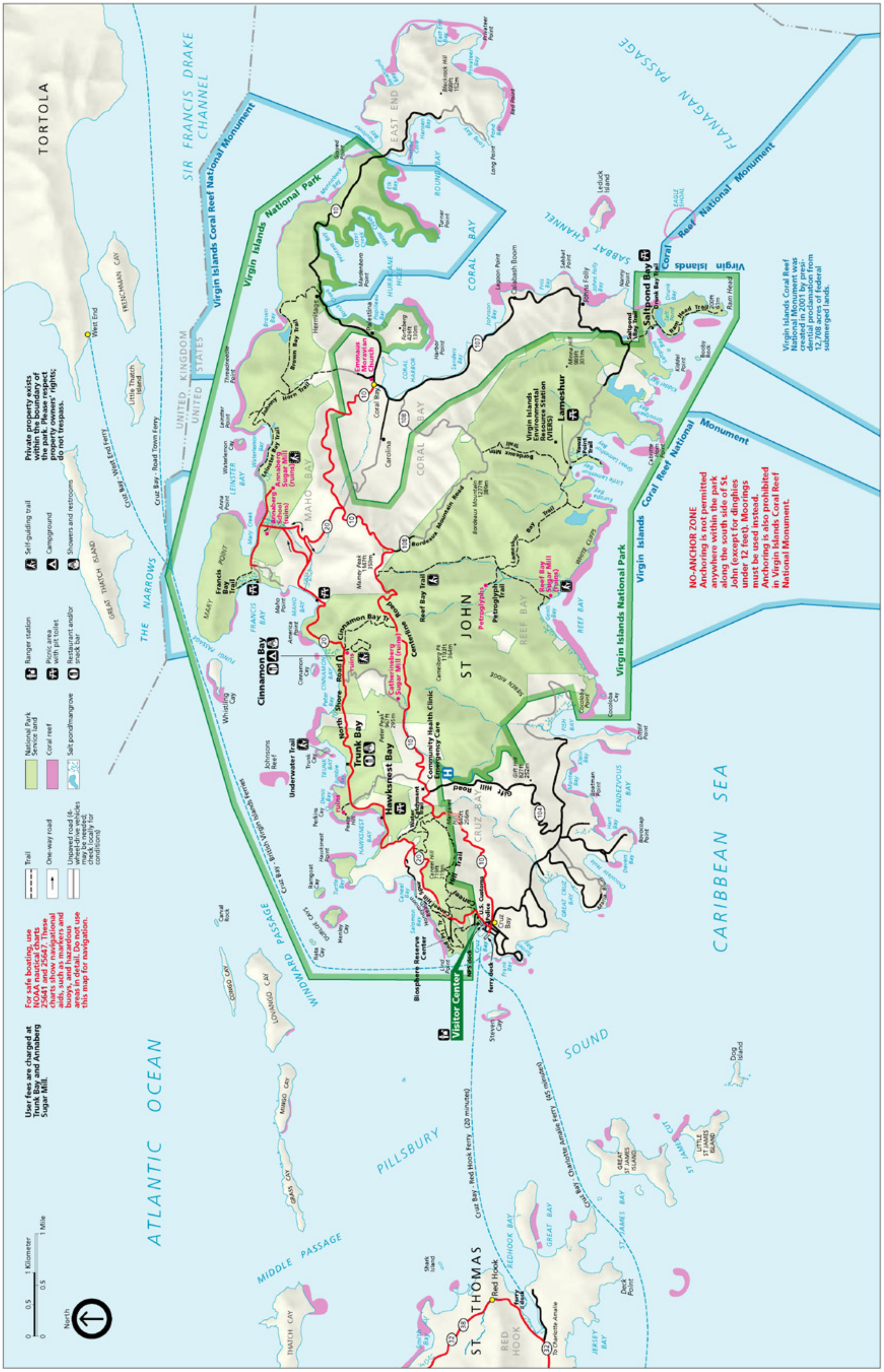

Figure 1. Map of Virgin Islands National Park, St. John, U.S. Virgin Islands. National Park Service map.

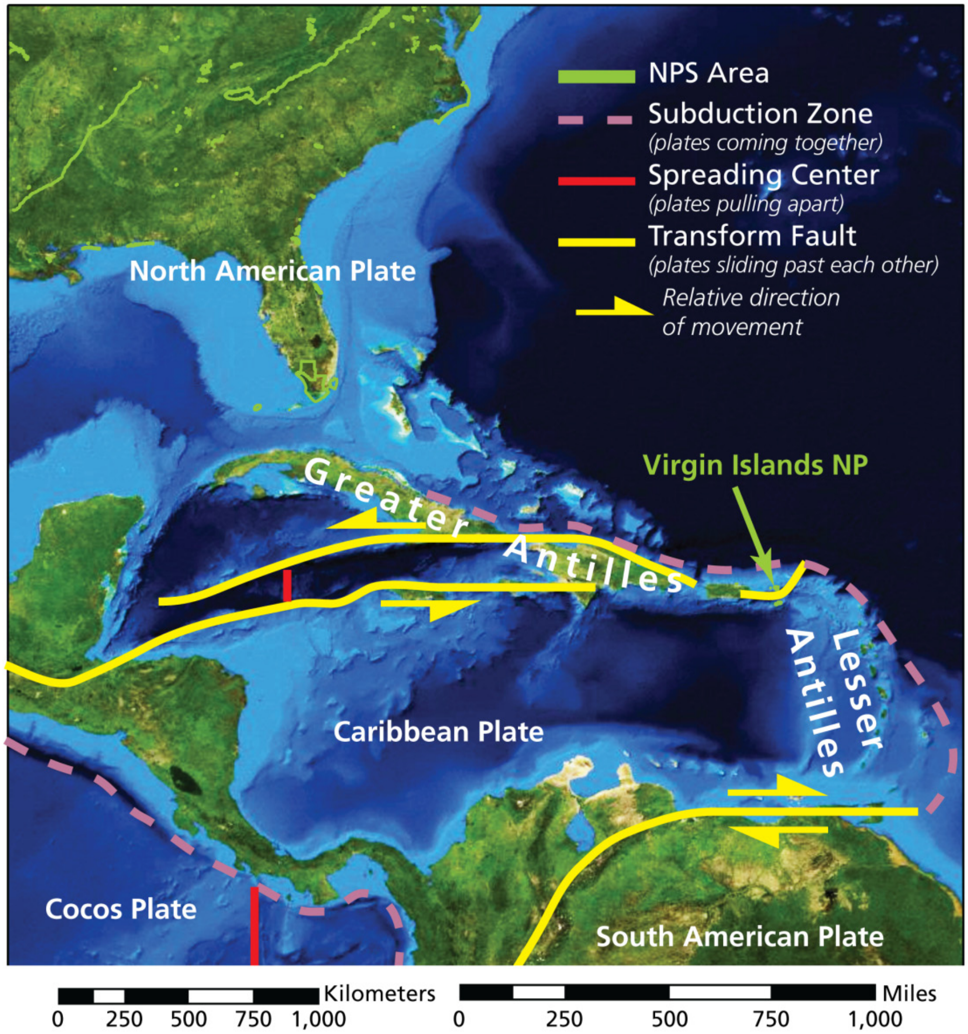

Figure 2. Tectonic map of the Caribbean plate. The Virgin Islands are situated along a zone of left-lateral, strike-slip faults that define the plate boundary between the Caribbean and North American plates. The eastern margin of the Caribbean plate is a subduction zone. The southern and northern margins are transform faults. From ESRI Arc Image Service USA Prime Imagery, compiled by Jason Kenworthy (NPS Geologic Resources Division). Plate boundaries after Lillie (2005).

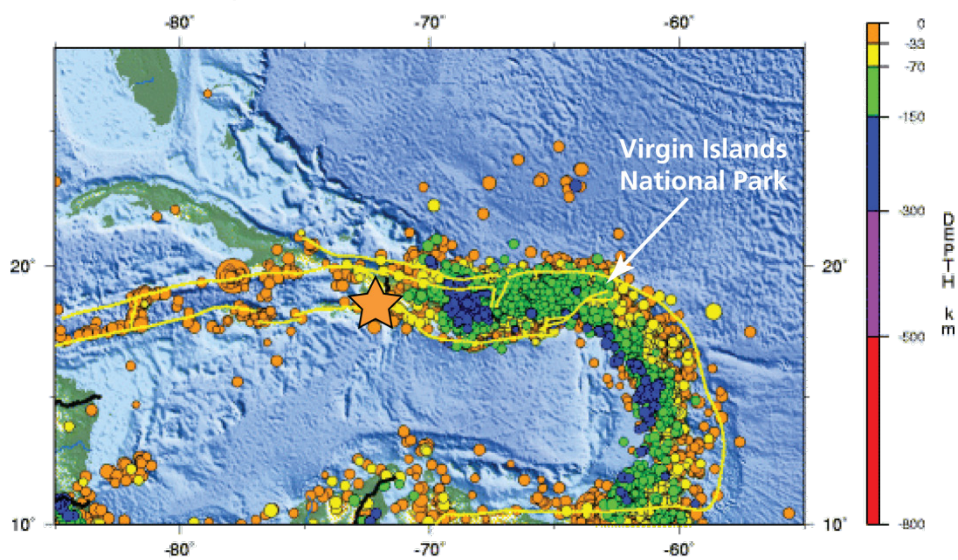

Figure 3. Seismicity map of Central America and the Caribbean. Recorded seismic activity outlines the boundary of the oval-shaped Caribbean plate. Colored dots on the figure record 16 years (1990–2006) of earthquakes and their depths. The orange star indicates the location of the January 12, 2010, earthquake in Haiti. Yellow lines show plate boundaries. Modified from U.S. Geological Survey (2009) by Jason Kenworthy (NPS Geologic Resources Division).

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping session for Virgin Islands National Park on April 7–9, 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.

Slope Stability and Erosion

St. John is characterized by rugged terrain and steep rocky slopes. More than 80% of the island is covered with hillsides in excess of 30% (CH2M Hill 1979). Runoff and slope failure are common during storm events, and can impact the park's terrestrial, coastal, and marine habitats. Slope failure—caused by a variety of factors, including climatic conditions, geologic processes, and anthropogenic modification to the landscape—can pose serious hazards to park visitors, employees, and infrastructure. Wieczorek and Snyder (2009) suggest methodology for monitoring slope movements.

Severe storm events and seismic activity cause rockslides and rockfalls within the park (fig. 4). In turn, these processes can severely impact federally protected species. During Tropical Storm Frances (2002), unstable slopes decimated numerous nesting sites of the endangered brown pelican (*Pelecanus occidentalis*). In addition, roads are often impassable during storm events because of rockslides and mudslides. During and after severe storms in 2003, mud and hillside debris, some as much as 4 m (12 ft) thick, made road travel impossible in parts of the park. More recent storms have caused less damage. In 2007, Tropical Storm Olga passed 6 km (4 mi) from St. John, with maximum sustained winds of only 40 mph (65 kph) and caused minor impacts (Zengerle 2007; Caribbean Hurricane Network 2009). In 2008, Hurricane Omar passed 79 km (49 mi) from St. John, and the island escaped significant damage (Burnett 2008; Caribbean Hurricane Network 2009).

Overgrazing also causes slope failure. A variety of nonnative species (e.g., hogs, goats, and donkeys) have been introduced to the island of St. John, and many of these animals have escaped or have been released into park boundaries. These invasive animals have created large feral populations that exacerbate sedimentation rates within the park. Feral animals graze heavily on native vegetation, which is an important sediment retainer; thus, a decrease in vegetation promotes an increase in localized sedimentation rates. Heavy grazing on steep hillsides increases erosion into adjacent coastal and marine ecosystems. Even small increases in sedimentation can have devastating effects on sensitive environments such as coral reefs and sea grass beds.

The National Park Service is currently working in cooperation with non-profit organizations and numerous federal, state, and territorial agencies to safely and humanely reduce the number of feral animals within the boundaries of Virgin Islands National Park (National Park Service 2010b).

Coastal erosion may also threaten infrastructure on the island. In 2005, the NPS Geologic Resources Division responded to a technical assistance request regarding erosion impacts for a structure along Maho Bay (Beavers 2005). Due to large cracks in the walls, a non-historic portion of the structure is slated for demolition, pending funding (R. Boulon, Virgin Islands National Park, personal communication, July 15, 2010). Beavers (2005) provided guidance and recommendations for installation of erosion control structures. However, erosion at the site appears to have stabilized and erosion control structures have not yet been constructed (R. Boulon, Virgin Islands National Park, personal communication, July 15, 2010).

Windblown Dust

The U.S. Geological Survey estimates that eolian processes transport several hundred million tons of dust yearly from western Africa into the Caribbean basin and the southeastern United States. African dust storms travel quickly across the Atlantic Ocean at altitudes as high as 4,570 m (15,000 ft). The intercontinental journey, which transports a wide variety of particulates and organisms, takes approximately 5 to 7 days to complete (Kellogg and Griffin 2003). Dust particulates can harbor a wide 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 3 to 10 times more microbes than normal levels in the Virgin Islands (Kellogg and Griffin 2003); approximately 30% of these microbes are pathogenic and are potentially dangerous to people and the environment (Kellogg and Griffin 2003).

Recent studies show that African dust may be directly linked to the decline of many Caribbean marine species, including coral, sea fans, and sea urchins. Studies demonstrate a direct correlation between African dust pulses and marine ecosystem deterioration. Increased drought conditions in the Sahara and Sahel deserts since the 1970s correspond to increased disease and bleaching in Caribbean corals. In addition, Caribbean air samples contain many diseases such as the soil fungi *Aspergillus*.

One particular strain, *Aspergillus sydowii,* is directly responsible for the sea fan aspergillosis, which is a major Caribbean epizootic (similar to an "epidemic" in humans) (Kellogg and Griffin 2003).

The NPS Air Resources Division is an additional contact for technical assistance.

Sea Level Rise

The NPS Geologic Resources Division is working in conjunction with the U.S. Geological Survey and Woods Hole Oceanographic Institute to examine how future sea level rise will affect coastal areas within national parks. The Coastal Vulnerability Index (CVI) is a quantitative tool used by park managers and scientists to predict future changes to park shorelines (Pendleton et al. 2004). The geologic factors and physical processes considered in the CVI include relative sea level, wave height, tidal range, coastal erosion rate, slope, and geomorphology.

Data collected at Charlotte Amalie on St. Thomas 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) at Virgin Islands National Park (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 indicates that 13% of the coast within Virgin Islands National Park is highly vulnerable to shoreline change resulting from future sea level rise. The research shows that Trunk Bay, Cinnamon Bay, and Ram Head are the beaches most likely to experience extreme shoreline change. In addition, the CVI designates 29% of the coast within the park as highly vulnerable, 28% as moderately vulnerable, and 29% as minimally vulnerable (fig. 5).

As ranked by Pendleton et al. (2004), geomorphology, regional coastal slope, and wave energy are the most important variables in determining the spatial variability of the CVI for the park. Shoreline change rate, tidal range, and sea level rise rate do not contribute to the spatial variability in the CVI (Pendleton et al. 2004). Vulnerability based on geomorphology indicates that sandy beach shoreline areas are very highly vulnerable to change, gravel beaches are highly vulnerable, alluvium or cliffs with fringing reefs are moderately vulnerable, and rock and cliff features are minimally vulnerable (fig. 6). In addition, areas of intense wave action—especially shorelines open to the Atlantic Ocean, such as the stretch from Hawksnest Bay to Cinnamon Bay—are more likely to experience change as compared to protected shorelines on the north side of St. John, such as Leinster Bay (Pendleton et al. 2004).

Anthropogenic Modifications

The National Park Service generally allows natural coastal processes to occur without interference; however, if natural processes threaten the preservation of cultural resources, park managers may elect to modify a shoreline in an attempt to achieve a balance between preserving a historic landmark and protecting a natural ecosystem. For example, managers at Virgin Islands National Park have modified some of the park's shoreline to protect important cultural resources from coastal erosion and storm events. In the 1970s, the National Park Service placed riprap on Cinnamon Bay to protect Taino and Dutch archaeological sites. Although the riprap has slowed the rate of erosion, it has done little to diminish natural shoreline processes. The loss of adjacent shoreline vegetation, due to both erosion and recreational impacts, is another management concern.

Structures such as docks and visitor facilities at Lameshur, Caneel, Cruz Bay, and Red Hook could alter hydrodynamics and affect shoreline geomorphology, and changes in sediment transport could lead to beach erosion or accretion. Beaches naturally migrate landward to compensate for sea level rise, and the presence of anthropogenic structures hinders this natural process, potentially causing catastrophic habitat loss. Monitoring changes in oceanographic variables (i.e., temperature, salinity, and current patterns) created by anthropogenic modifications could help in preventing the loss of natural resources.

Dredging adjacent to park boundaries could cause significant impacts within the park as a result of changes to sediment transport and flow. Dredging is often conducted in Cruz Bay to benefit shipping, transport, and recreation. Coastal dredging increases turbidity and sediment loads, thereby damaging marine resources. In addition, dredged sediments can contain contaminants and pollutants that are harmful to marine and coastal environments.

Additional management concerns include the following: (1) the detrimental effects of light pollution on sea turtle nesting patterns and hatchling emergence and (2) the rapid erosion rates of beaches at many visitor parking areas.

Recreational Impacts

According to the NPS Public Use Statistics Office, a total of 7,608,944 people visited Virgin Islands National Park between 1998 and 2009 (National Park Service 2010c), and the recreational impacts from these visitors are degrading natural resources. For example, recreational boating activities have damaged many fragile and cherished resources, such as coral reefs, sea grass beds, and mangrove forests. Although anchoring is permissible in certain areas of the park, illegal anchoring and anchor dragging can destroy marine habitat (Hall 2005). In addition, vessel groundings resulting from inexperienced boaters may critically damage large sections of coral reefs (Hall 2005). Minor damage to the reef occurs when boats, unable to maneuver, run into the reef (Gladfelter et al. 1977).

The National Park Service has taken great strides to prevent anchor scouring of the seabed at Virgin Islands National Park and Virgin Islands Coral Reef National Monument. In 2000, park staff initiated a buoy program to aid in the recovery of the seafloor and to prevent future damage caused by boat anchoring and grounding. Park managers maintain more than 400 floating objects, including overnight, day, scuba, and fishing moorings. This program has been highly successful, allowing sea grass beds and mangroves to recover from previous damage. Investigators are analyzing data that will document recovery rates of sea grass in the park (Loomis 2006).

Surfing is another concern for park resource managers because it poses hazards to both visitors and resources. Recreational kite surfing is prohibited in boat exclusion areas and mooring areas (Chapter 1, Title 36, Code of Federal Regulations) but occurs at many park locations, including Johnson's Reef, Fish Bay, and Cinnamon Bay. Visitors have been critically injured while body surfing at Cinnamon Bay, which has a rapid change in beach slope (K. N. Hall, written communication, November 2006). In addition to causing personal injuries, surfing can damage marine habitat when surfers brush up against fragile coral reefs.

Social trails near beaches are another management concern. Projects in the early 2000s along Trunk and Hawksnest beaches blocked off social trails which were revegetated with seagrapes (R. Boulon, Virgin Islands National Park, personal communication, July 15, 2010). Articulating ramps were installed to provide beach access.

Benthic Habitat Mapping

During GRI scoping in 2004, participants identified the need for coordination between the U.S. Geological Survey (USGS), National Oceanographic and Atmospheric Administration (NOAA), and the National Park Service in completing mapping of the benthic habitats at Virgin Islands National Park and Virgin Islands Coral Reef National Monument. Such mapping compliments the surficial and bedrock geology map of the park (see "Map Unit Properties" section and Appendix A).

Through the implementation of a multi-year, interagency agreement between the National Park Service and the National Oceanic and Atmospheric Administration, NOAA's Biogeography Branch mapped 53 km^2 (20 mi^2) of shallow-water habitats around St. John and 90 km^2 (35mi^2) of moderate-depth habitats south of St. John; Zitello et al. (2009) mapped 32 distinct benthic habitat types within 12 zones. This effort is an expansion of ongoing mapping and monitoring in the U.S. Caribbean. The GIS products originating from this work include (1) accuracy assessment data, (2) ground validation data, (3) habitat maps, (4) source imagery, and (5) associated metadata. These data and accompanying reports, which describe the classification scheme, thematic accuracy, and methods used to create the maps, are available at http://ccma.nos.noaa.gov/ecosystems/coralreef/benthic_usvi.html.

Figure 4. Rockslide. Rockslides are common along the steep slopes of Virgin Islands National Park; this slide occurred near Hawksnest Bay. The disturbed area (lighter colors and debris at bottom of slope) is approximately 12 m (40 ft) tall, road cone for scale. National Park Service photograph by Rafe Boulon (Virgin Islands National Park).

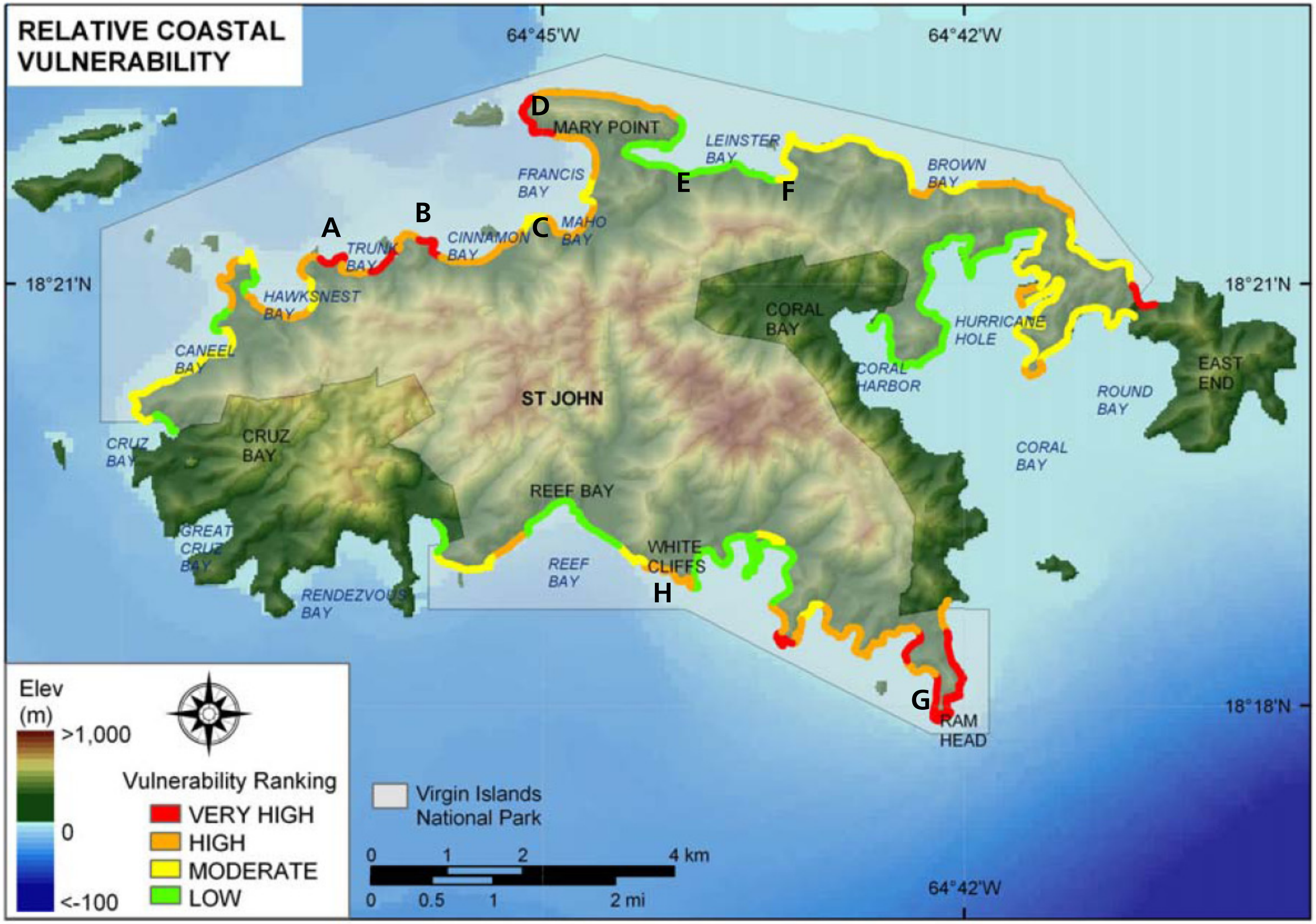

Figure 5. Relative coastal vulnerability. This figure shows the relative coastal vulnerability index (CVI) and locations of geomorphologic features (see fig. 6) that investigators assessed for Virgin Islands National Park. The six variables assessed to determine the relative CVI are geomorphology, historical shoreline change rate, regional coastal slope, relative sea-level change, mean significant wave height, and mean tidal range. The photographs of locations A through H are presented in figure 6. U.S. Geological Survey graphic from Pendleton et al. (2004).

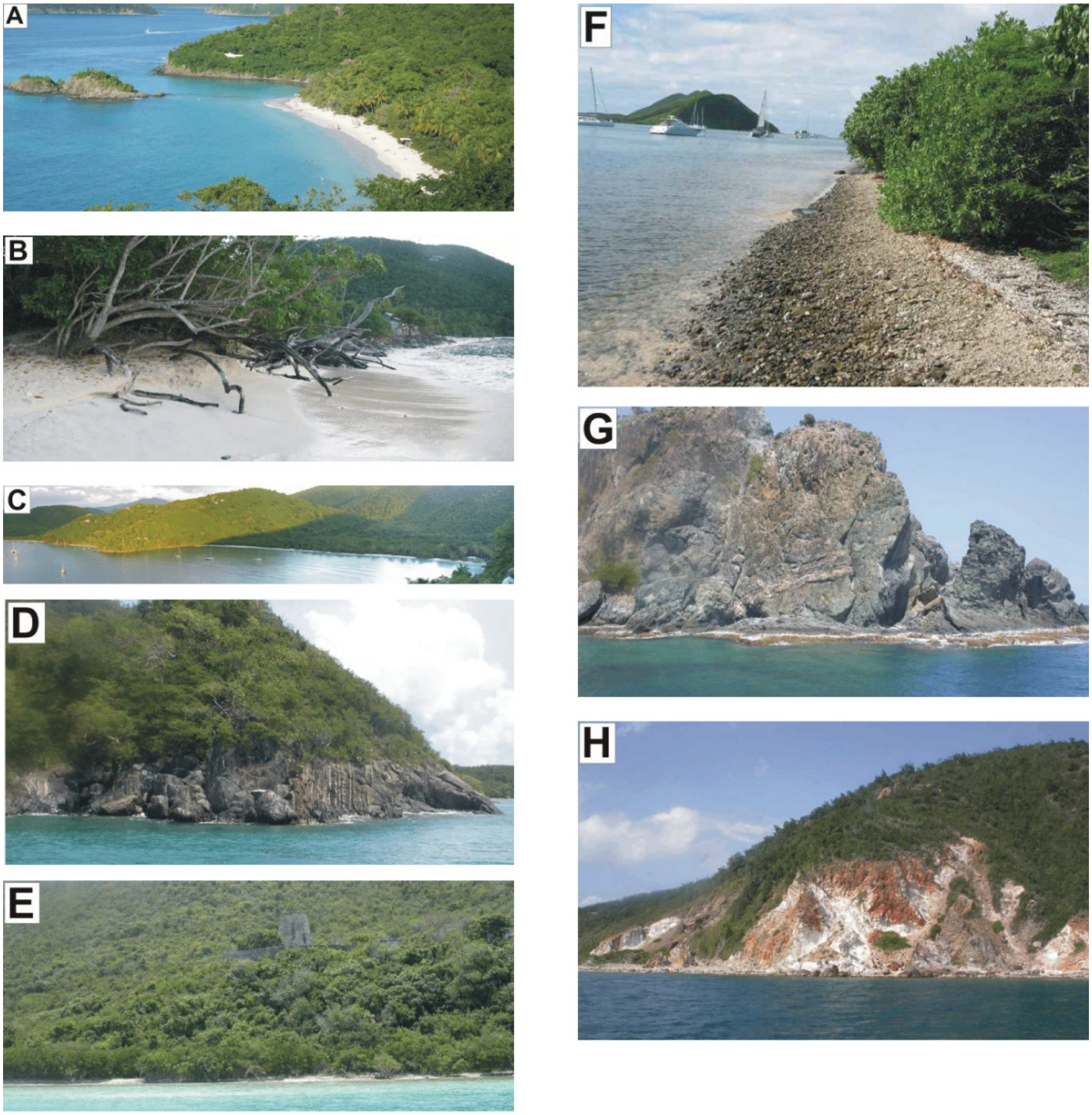

Figure 6. Geomorphologic areas. These different geomorphologic areas in Virgin Islands National Park were assessed as one of six variables that make up the coastal vulnerability index (CVI). See figure 5 for locations of photographs. (A) Trunk Bay from the east, very high vulnerability; (B) shoreline at Cinnamon Bay experiencing erosion, very high vulnerability; (C) Maho Bay from the east, very high vulnerability; (D) Mary Point, low vulnerability; (E) Annaberg Mill ruins in an area ranked as high vulnerability with respect to geomorphology; (F) shoreline surrounding Watermelon Bay (cobble beach), high vulnerability; (G) Ram Head (rocky headland), low vulnerability; and (H) White Cliffs near Reef Bay, low vulnerability. U.S. Geological Survey photographs, figure 5 in Pendleton et al. (2004).

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Virgin Islands National Park.

Beach Types

The beaches of Virgin Islands National Park are world-renowned. Factors such as bedrock composition, climate, and wave action create a diversity of beach types within the park. Although the park is famous for its sandy beaches, the park shorelines are also adorned by areas of cobbles and beachrock (fig. 7), cobblestone (fig. 8), and steep rocky slopes (fig. 9).

Resistant igneous rock combined with high-energy wind and wave activity creates areas with a steep coastal profile. Easily eroded rock found in low-energy environments forms a gradual coastal profile. This creates the fine-grained sandy beaches at the park such as those at Trunk, Cinnamon, and Solomon bays. Sandy beaches are also formed in pockets between rocky headlands. These pockets are sheltered areas of reduced wave action. The fine-grained sandy beaches are almost all "coral" sands (Douglas W. Rankin, U.S. Geological Survey, written communication, January 22, 2010).

Cobble beaches commonly occur on the exposed southern and eastern shores of St. John, including Ram Head Point and Dittlif Point. A relatively dry climate, intense wave action, and hard bedrock define these areas. While hiking on Ram Head Trail, visitors can see a classic example of a cobble beach south of Salt Pond.

Coastal Sediments

Sediments that naturally supply the park's shoreline are derived from a variety of terrestrial and marine sources (see Map Unit Properties Table). How quickly sediments weather and erode is strongly influenced by composition. For example, granitic rocks are less susceptible to erosion than those made of limestone.

Variations in chemical and mechanical weathering result in a variety of sediment sizes. In addition, wind and wave action influences sediment size and transport. Finer sediments such as the white sandy beaches at Trunk Bay need less energy for transport than the cobbles and pebbles on the beaches south of Saltpond Bay.

Longshore transport, one of the most important mechanisms for sediment movement and coastal change, is driven by waves that arrive at an angle to the coast. These waves force currents along the shore, carrying sediments. The sediment budget is the sum of the sediment supply (gains) and the sand removed (losses) from a system. Cumulative net loss is indicated by coastal erosion, whereas net growth is demonstrated by coastal expansion.

Coral Reefs

Caribbean coral reefs are one of the world's most treasured marine resources. The brilliant blue waters at Virgin Islands National Park are home to a wide variety of corals, including elkhorn (*Acropora palmata*, fig. 10) and staghorn (*Acropora cervicornis*).

Coral reefs serve important geologic functions. During storm events and periods of high wave activity, coral reefs serve as a barrier against coastal erosion. They also act as an obstruction to reduce wave and wind impacts on inland environments. Elkhorn and staghorn corals have undergone particularly drastic decline in the past 30 years, and in 2006 were the first coral species to be protected under the Endangered Species Act (Lundgren 2008). Decline in coral has exposed shorelines to greater wave energies.

In addition, coral reefs alter flow dynamics and initiate the deposition of fine-grained sediments on the downside of reefs. The reduction in suspended sediments helps to improve water quality in the surrounding waters.

Igneous and Volcanic Features and Processes

Virgin Islands National Park hosts both volcanic and intrusive igneous rocks. These rocks display many distinctive features worthy of interpretation.

Columnar Jointing

The Careen Hill Intrusive Suite contains many fine examples of columnar jointing—a geologic feature associated with the slow cooling and contraction of igneous rock. As magma of a tabular body (e.g., dike or sill) crystallizes and continues to cool, it contracts. Cooling cracks or joints develop perpendicular to the cooling surface (e.g., dike walls) and extend through the igneous body. The intersection of these fractures results in the formation of columns. Columnar joints generally develop a hexagonal pattern, but patterns of four, five, seven, or eight sides are also relatively common. This form of jointing develops in lava flows, sills, dikes, ignimbrites, and shallow intrusions of all compositions. Most columns are straight with parallel sides and diameters from a few centimeters to 3 m (10 ft).

A prime example of columnar jointing occurs on Leduck Island, located on the southeastern side of St. John adjacent to John's Folly Beach (fig. 11). The columnar jointing on Leduck Island is composed of light-colored granitic rock called trondhjemite. The Water Island Formation hosts other examples of columnar jointing (see Map Unit Properties Table).

Hydrothermal Alteration

Hydrothermal alteration created the beautifully colored (white, red, and brown) igneous rocks of south and central St. John. The presence of hot solutions—e.g., the fluids that generally accompany magmatic intrusions—alter the chemical composition of the preexisting rocks, resulting in changes in mineralogy. The resulting rocks and colors have been further modified by modern weathering.

Hydrothermal alteration is evident in the Water Island Formation on St. John. The White Cliffs provide a beautiful example of this alteration (fig. 12). Hydrothermal alteration includes the addition of water, silica, potassium, iron, and, in places, copper, sulfur, kaolinite, and limonite. The latter two minerals are, in part, also the product of recent oxidation and weathering of the already hydrothermally altered rocks; combined with alunite, they give the White Cliffs their distinctive white and red colors (Douglas W. Rankin, U.S. Geological Survey, written communication, January 22, 2010).

Pillow Basalts

Pillow basalts are formed during the rapid underwater cooling of the surface of lava. The surface in contact with water cools quickly and forms a hard crust. Further cooling and contracting produces cracks through which still-molten lava emerges into the water in bulbous masses. These bulbous masses, called pillows, are quickly encased in a crust that itself cracks and allows the escape of another bulbous mass of lava. The result is layers and stacks of masses of pillows. In places, the rapid cooling causes shattering of the pillow, which results in rock composed of pillow fragments called hyaloclastite (Douglas W. Rankin, U.S. Geological Survey, written communication, January 22, 2010).

Most basalt in the Water Island Formation is pillow or hyaloclastite. Classic pillows occur to the west of Ram Head Trail, on Harbor Point, and on the peninsula of Turner Point (fig. 13). Because pillows are formed with the convex side up, geologists commonly use pillow basalt "bedding" to define a stratigraphic "way up." Observations of the layering in pillow basalt and the way up have been helpful in working out the overall structure and stratigraphy of the Water Island Formation (Rankin 2002).

Plutons

Igneous intrusions called plutons form when molten magma cools and hardens underground. Size and mineral composition determine the specific type of pluton. The most common igneous intrusions located on and adjacent to the island of St. John are dikes, sills, and batholiths.

Dikes are small, tabular, intrusive bodies that form when magma is forced into fractures that cut across preexisting bedrock. The magma then cools and crystallizes, forming a dike. In many cases, a multitude of dikes form in a localized area, creating a "swarm." Successive intrusions that lie adjacent and parallel to one another are "sheeted dikes." Sheeted dikes are significant in that they indicate crustal extension—measured in miles—perpendicular to the walls of the dikes. The Tertiary (now officially called "Neogene;" International Commission on Stratigraphy 2009) rocks of Virgin Islands National Park contain both dike swarms and sheeted dikes (see Map Unit Properties Table).

Sills are another form of igneous intrusion common to St. John. Sills are created when magma intrudes and hardens between preexisting rock layers. Similar to dikes, sills are tabular or sheetlike in shape, but form parallel to preexisting layering. Both dikes and sills are common features of the Careen Hill Intrusive Suite and intrude the Water Island Formation. In addition, excellent examples of dikes and sills occur within the Louisenhoj and Tutu formations. The dikes and sills are likely of more than one age.

A batholith is the largest type of igneous intrusion. This feature is formed by the slow underground cooling of a massive magma plume within the overlying country rock. The extreme temperature changes brought on by these large, molten rock bodies change the preexisting rock via the process of contact metamorphism. Through contact metamorphism, both the Narrows pluton and the Virgin Gorda batholith have transformed the surrounding rocks of northern St. John (see "Geologic History" section)—portions of the Outer Brass Limestone have become marble; garnets are abundant in the Tutu Formation on Mary Point; and skarn has developed locally in the Tutu Formation (fig. 14).

Salt Ponds

Salt ponds are the primary wetland ecosystem of the U.S. Virgin Islands (Stengel 1998). Virgin Islands National Park hosts 34 salt ponds within its boundaries (fig. 15). Salt ponds serve many valuable functions. They act as a nursery, providing food and shelter for many terrestrial and aquatic species. Salt ponds also serve as a sediment trap for storm runoff and pollution, thereby reducing the amount of siltation and suspended sediments in adjacent marine environments. In addition, these vital habitats protect the mainland from storm events, acting as a barrier against inland erosion (Stengel 1998; Gangemi 2003).

Salt ponds are created when a bay or inlet is closed off via berm formation on an existing obstruction such as a coral reef or sandbar. Geologically, ponds form by the gradual closing of sheltered bays as fringing reefs grow upwards and create rubble berms over which mangroves grow (Jarecki 1999; Gangemi 2003). These berms eventually close the salt pond from the sea (Stengel 1998), drastically reducing seawater interchange.

Mangroves are necessary for salt pond productivity and function. White and black mangroves (*Laguncularia racemosa* and *Avicennia germinans*) grow in salt ponds and in the soil and sediment upland from the distinctive red mangroves (*Rhizophora mangle*), which grow in saltwater or brackish water in the mudflats near shorelines (National Park Service 2009). More than half of the mangroves in the U.S. Virgin Islands have been destroyed by natural or human causes. Because this vegetation type is a vital component of the salt pond ecosystem, mangrove species are now protected by the Territory of the U.S. Virgin Islands (Gangemi 2003).

Salt ponds host a wide range of physical conditions, including major fluctuations in temperature, salinity, dissolved oxygen, and turbidity (Gangemi 2003). These "extremes" present a challenge for many wetland species, but provide a perfect habitat for a variety of fish, invertebrate, and bird species. Both terrestrial and migratory birds, many threatened or endangered, rely on food and protection found within salt ponds (Stengel 1998). In addition, larval and juvenile species rely on the nursery function provided by these ecosystems. Mangrove roots provide refuge for a variety of fish and invertebrates species, and mangrove leaf litter (organic detritus) shelters small invertebrates (Stengel 1998).

The expanding coastal development on St. John has increased awareness of the importance of salt ponds. Specifically, salt ponds act as an effective sediment trap for storm runoff and terrestrial pollution. Sediments and pollutants are filtered through a salt pond prior to deposition in adjacent marine environments. This decreases siltation and suspended sediments in adjacent marine habitats, including coral reefs and sea grass beds. The decrease in sediments in the marine environment can improve water quality (Stengel 1998).

Salt ponds also protect inland environments from storms. They serve as a buffer that effectively lessens storm erosion and reduces habitat loss in adjacent areas. In addition, salt ponds cushion wave action and provide a catchment basin for rising tides, thereby acting as a flood control agent (Stengel 1998).

Seismic Activity

The Caribbean is a seismically active region (fig. 2). As mentioned in the "Geologic Setting," Virgin Islands National Park is situated on the tectonically active Caribbean plate, which is moving eastward at about 2 cm (0.8 in) per year with respect to both the North American and South American plates (fig. 3). 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 fueling the volcanoes (island arc) of the Lesser Antilles. Volcanic activity occurs as far north as the island of Saba (Rankin 2002).

The Virgin Islands are 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 the convergent (subduction) plate motion 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. Two features are of interest for Virgin Island National Park: the Puerto Rico Trench and the Anegada Trough. The Puerto Rico Trench, located on the boundary between the Caribbean and North American plates, is an active fault zone. The 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). The Anegada Trough is situated on the Caribbean plate and separates St. Croix from the other Virgin Islands. The trough poses a significant threat of tsunami (Office of Disaster Preparedness 1997). Currently, a U.S. Geological Survey (USGS) seismic station in Puerto Rico monitors earthquake activity in the U.S. Virgin Islands (U.S. Geological Survey 2010).

Paleontological Resources

Paleontological resources (fossils) require science-based resource management as directed by the 2009 Paleontological Resources Preservation Act (Public Law 111-11). The National Park Service is currently developing regulations associated with the Act (J. Brunner, Geologic Resources Division, personal communication, May 2010). Santucci et al. (2009) suggest strategies for monitoring in situ paleontological resources.

The NPS conducted a paleontological inventory from literature of known and potential fossil occurrences in Virgin Islands National Park (Toscano et al. 2010). Paleontological resources are not common with the park. Nevertheless microfossils called radiolarians were discovered in chert of the Cretaceous-aged Water Island Formation (Rankin 2002). Limestone clasts in the Louisenhoj Formation occasionally preserve fossil fragments (Rankin 2002). Holocene (younger than 11,700 years) coral reef deposits also contain fossil fragments. Modern fossil-forming ecosystems exist within the park, including nearshore marine mangrove areas, shallow seagrass beds, and coral reefs (Toscano et al. 2010).

Figure 7. Cobbles and beachrock. The shoreline of Saltpond Bay displays dark-colored cobbles and lighter-colored beachrock. The beachrock formed when calcium carbonate precipitated from seawater, causing sand grains to cement together into a calcareous sandstone crust. Photograph by K. N. Hall.

Figure 8. Cobblestone beach. Different lithologies create the variety of color of beach sediments at Saltpond Bay along Ram Head Trail. The darker cobbles are pieces of basalt of the Water Island Formation derived from the breakup of adjacent ledges and then rounded by wave action. The white cobbles are pieces of modern coral, also rounded by wave action. Photograph by K. N. Hall.

Figure 9. Rocky shoreline. Steep rocky slopes (e.g., Ram Head Point) characterize the topography at Virgin Islands National Park. Photograph by K. N. Hall.

Figure 10. Elkhorn coral. Most reefs in the Caribbean are "fringing reefs" that grow close to the shore or in small patches. Coral species at Virgin Islands National Park include elkhorn (*Acropora palmata*) and staghorn (*Acropora cervicornis*). National Park Service photograph courtesy Rafe Boulon (Virgin Islands National Park).

Figure 11. Columnar jointing. On Leduck Island, exposures of light-colored granitic rock (called trondhjemite) display columnar jointing. This feature is commonly exhibited within the Careen Hill Intrusive Suite. The eastern shoreline of St. John is visible in the background. Photograph by K. N. Hall.

Figure 12. White Cliffs. Hydrothermal alteration has changed the mineralogy of the Water Island Formation exposed on the east side of Reef Bay, St. John. National Park Service photograph by Carolyn Stengel.

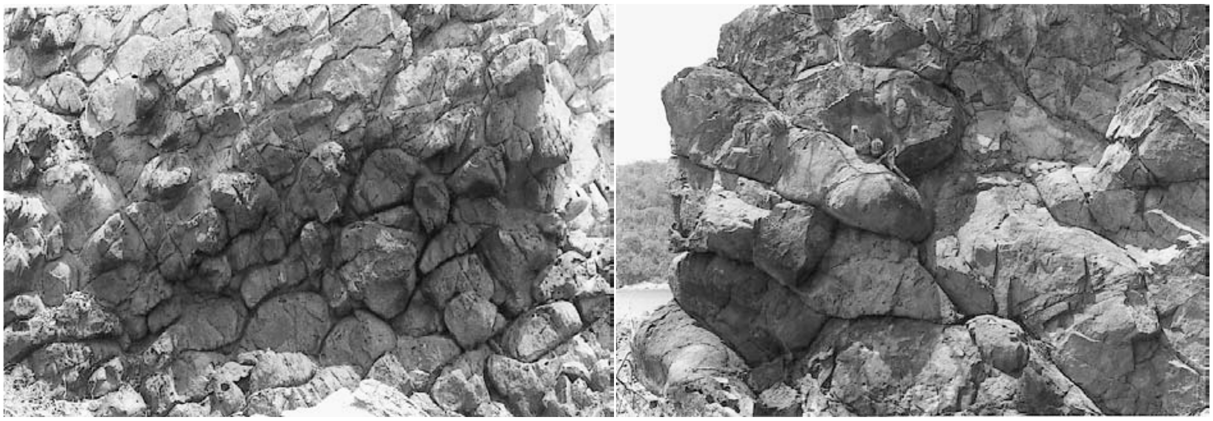

Figure 13. Pillow basalt. Water Island Formation, Harbor Point in Coral Bay. A) View looking east. Pillows are as large as a meter across. Pillow asymmetry indicates that layers are right side up. B) View looking north shows that pillows in (A) are cross sections of tubes elongated down dip. Hammer is 28.5 cm (11 in) long. U.S. Geological Survey photographs, figure 4 in Rankin (2002).

Figure 14. Metamorphosed and interlayered sandstone and shale. The adjacent Narrows pluton provided the heat source that metamorphosed the Mandal Member of the Tutu Formation at Mary Point. Metamorphism also caused the growth of abundant garnet, biotite, and tremolite. Tectonic forces have tilted the rocks, resulting in vertical bedding. Photograph by K. N. Hall.

Figure 15. Salt ponds—a primary wetland type at Virgin Islands National Park—serve many ecosystem functions, providing food and shelter for both terrestrial and aquatic species. This salt pond is located near Newfound Bay. National Park Service photography courtesy Rafe Boulon (Virgin Islands National Park).

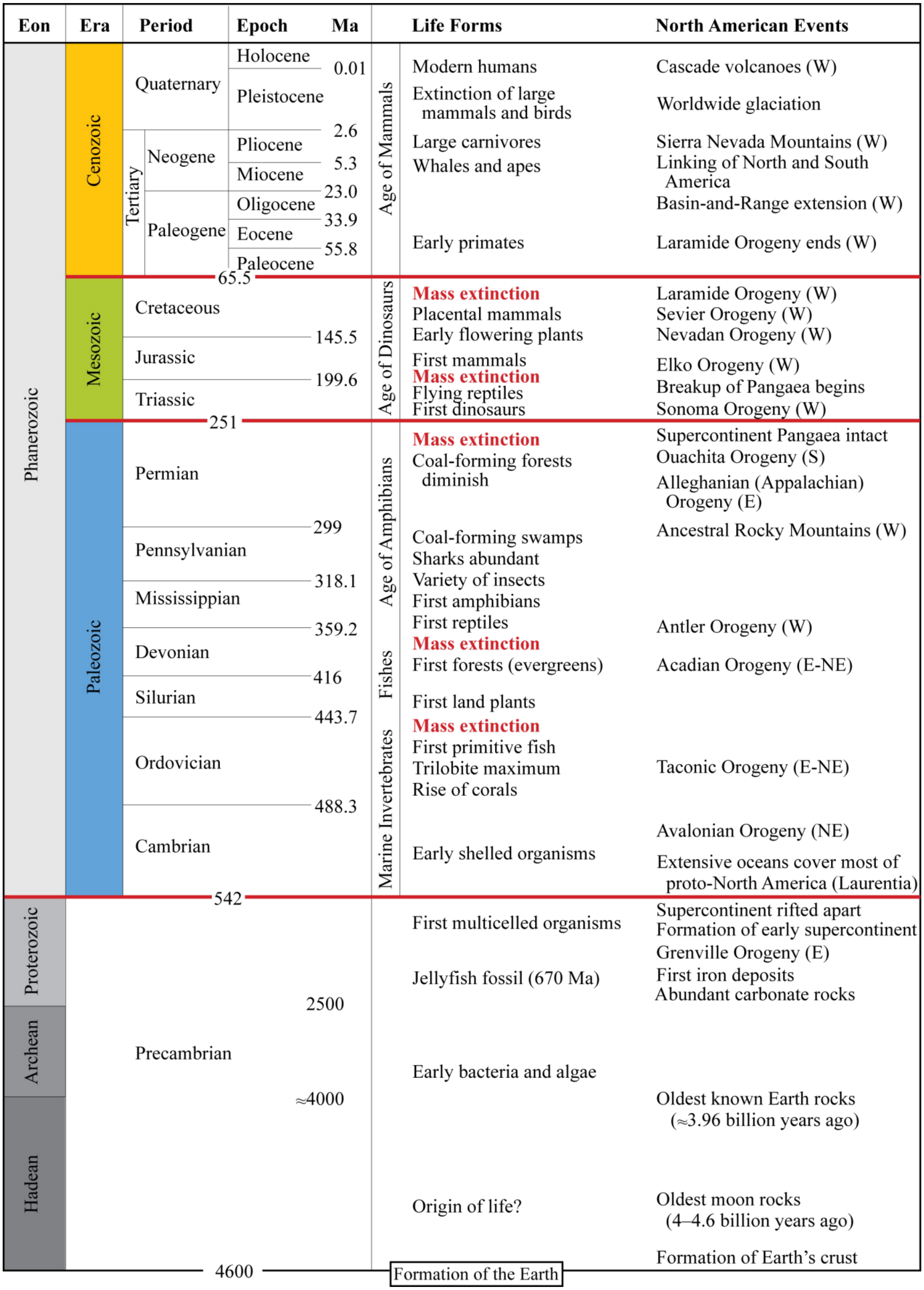

Figure 16. Geologic timescale. Included are major life-history and tectonic events occurring on the North American continent. Red lines indicate major boundaries between eras. Isotopic ages shown are in Ma. Compass directions in parentheses indicate the regional location of individual geologic events. Adapted from the U.S. Geological Survey (http://pubs.usgs.gov/fs/2007/3015/) with additional information from the International Commission on Stratigraphy (http://www.stratigraphy.org/view.php?id=25).

Map Unit Properties

This section identifies characteristics of map units that appear on the Geologic Resources Inventory digital geologic map of Virgin Islands National Park. The accompanying table is highly generalized and is provided for background purposes only. Ground-disturbing activities should not be permitted or denied on the basis of information in this table.

Geologic maps facilitate an understanding of Earth, its processes, and the geologic history responsible for its formation. Hence, the geologic map for Virgin Islands National Park provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report. Geologic maps are two-dimensional representations of complex three-dimensional relationships; their color coding illustrates the distribution of rocks and unconsolidated deposits. Bold lines that cross or separate the color patterns mark structures such as faults and folds. Point symbols indicate features such as dipping strata, sample localities, mines, wells, and cave openings.

Incorporation of geologic data into a Geographic Information System (GIS) increases the usefulness of geologic maps by revealing the spatial relationships among geologic features, other natural resources, and anthropogenic features. Geologic maps are indicators of water resources because they show which rock units are potential aquifers and are useful for finding seeps and springs. Geologic maps are not soil maps, and do not show soil types, but they do show parent material—a key factor in soil formation. Furthermore, resource managers have used geologic maps to make connections between geology and biology; for instance, geologic maps have served as tools for locating sensitive, threatened, and endangered plant species, which may prefer a particular rock unit.

Although geologic maps do not show where earthquakes will occur, the presence of a fault indicates past movement and possible future seismic activity. Similarly, map units show areas that have been susceptible to hazards such as landslides, rockfalls, and volcanic eruptions. Geologic maps do not show archaeological or cultural resources, but past peoples may have inhabited or been influenced by depicted geomorphic features. For example, alluvial terraces may have been preferred use areas and formerly inhabited alcoves may occur at the contact between two rock units.

The geologic units listed in the following table correspond to the accompanying digital geologic data. Map units are listed in the table from youngest to oldest. Please refer to the geologic timescale (fig. 16) for the age associated with each time period. The table highlights characteristics of map units such as: susceptibility to erosion and hazards; the occurrence of paleontological resources (fossils), cultural resources, mineral resources, and caves or karst; and suitability as habitat or for recreational use. Some information on the table is conjectural and meant to serve as suggestions for further investigation.

The GRI digital geologic maps reproduce essential elements of the source maps including the unit descriptions, legend, map notes, graphics, and report. The following reference is the source for the GRI digital geologic data for Virgin Islands National Park:

Rankin, D. W. 2002. Geology of St. John, U.S. Virgin Islands. Scale 1:24,000. Professional Paper 1631. U.S. Geological Survey, Reston, Virginia, USA.

The GRI team implements a geology-GIS data model that standardizes map deliverables. This data model dictates GIS data structure including data layer architecture, feature attribution, and data relationships within ESRI ArcGIS software, increasing the overall utility of the data. GRI digital geologic map products include data in ESRI shapefile and coverage GIS formats, Federal Geographic Data Committee (FGDC)-compliant metadata, a Windows help file that contains all of the ancillary map information and graphics, and an ESRI ArcMap map document file that easily displays the map with appropriate symbology. GRI digital geologic data are included on the attached CD and are available through the NPS Data Store at http://science.nature.nps.gov/nrdata/.

Map Unit Properties Table: Virgin Islands National Park

Gray-shaded units are not mapped within Virgin Islands National Park.

Age	Map Unit (Symbol)	Features and Description	Mineral Occurrence	Paleontological and Cultural Resources	Resistance to Erosion
QUATERNARY	Surficial deposits (Qs)	Alluvium, swamp deposits, beach deposits, beachrock, and artificial fill	None documented	Archaeological artifacts including Taino, Dutch, and African-slave cultural resources	Low—Coastal erosion will likely continue to damage anthropogenic structures and cultural artifacts located on various beaches
TERTIARY (PALEOGENE AND NEOGENE)	Red Hook Tonalite Porphyry (Tr)	Dikes and small hypabyssal intrusions of porphyritic tonalite with as much as 45% phenocrysts; characterized by quartz phenocrysts 1 cm (0.4 in) or larger; named for prominent dikes at Red Hook (Eastern St. Thomas quadrangle) where dikes are intruded along brittle faults	Quartz, biotite, hornblende, apatite, plagioclase, and vermiculite	None documented	High
	Explosion breccias (Te)	Mafic dike with 60% or more xenoliths; occurs only on east side of Dittlif Point where it spans about 20 m (66 ft) across an outcrop of Water Island Formation; cuts diabase dike that is interpreted to be unit Td but could be unit Kcm (gabbro) of Careen Hill Intrusive Suite; 15 to 20 cm (6 to 8 in) thick	Xenoliths include keratophyre, greenstone, gabbro, and tonalite	None documented	High
	Hornblende lamprophyre (Tl)	Dark, magnetite-bearing, aphanitic dikes with prominent hornblende phenocrysts; most Tl dikes are younger than dikes of unit Td, but some Td mafic dikes cut Tl	Hornblende, clinopyroxene, and plagioclase	None documented	High
	Biotite-hornblende tonalite (Tt)	Biotite-hornblende tonalite and minor gabbro, diorite, granite, and pegmatite; produces contact-metamorphic aureole as wide as 2 km (1.2 mi)	Quartz, plagioclase, biotite, chlorite, hornblende, orthoclase, zircon, clinopyroxene, apatite, pyrite, magnetite, diopside, sphene, allanite, and calcite	None documented	High
	Diabase, gabbro, and diorite (Td)	Nearly vertical dikes; chilled margins typical, columnar jointing not typical; dikes intrude all stratified units except surficial deposits and are intruded by tonalite (Tt); likely includes dikes of more than one age; some may be intrusive equivalents of extrusive rocks in enclosing or overlying stratified units, while others may be part of tonalite (Tt) intrusive cycle; a very few cut hornblende lamprophyre (Tl); most interpreted to be part of early Tertiary pre-tonalite (Tt) magmatic cycle (Donnelly et al. 1990)	Plagioclase, clinopyroxene, hornblende, magnetite, pyrite, quartz, amphibole, chlorite, and epidote	None documented	High
CRETACEOUS	Tutu Formation (Ktm, Ktmc, Ktml, Ktp, Ktpl)	Volcanic wacke, shale, sandstone, conglomerate, calcareous siltstone, limestone, marble, and rare basalt and andesite or their metamorphosed equivalents; all rocks are within contact aureole of tonalite (Tt); graded beds, slump folds, and disrupted slabs of metasandstone and metasiltstone in metaconglomerate indicate deposition by turbidity currents on an unstable slope, perhaps a trench wall; basal contact not exposed, but it is in apparent conformity with underlying Outer Brass Limestone (Ko) Includes Mandal Member (Ktm) with Congo Cay Limestone Lens (Ktmc) and marble, calc-silicate rock, and marble conglomerate (Ktml); as well as Picara Member (Ktp) with marble conglomerate and calc-silicate-rich beds north of Maho Point (Ktpl); overall the Mandal Member is finer grained than the Picara Member	Calc-silicate rocks contain combinations of calcite, quartz, plagioclase, tremolite, diopside, phlogopite, garnet, epidote, wollastonite, sphene, pyrite, and other sulfides	None documented	Moderate to high
	Outer Brass Limestone (Ko)	Thin-bedded (3-m [10-ft]) calc-silicate rock, with beds of white to blue-gray calcite marble (sulfurous odor when broken), and metamorphosed, matrix-supported cobble conglomerate with andesite clasts in carbonate matrix; total thickness about 100 m (330 ft)	Calcite, plagioclase, epidote, brown isotropic garnet, diopside, vesuvianite, and wollastonite	Possible Taino quarry source	Moderate to high
	Louisenhoj Formation (Kl)	Strongly cemented volcanic conglomerate, breccia, volcanic wacke, and shale in graded beds as thick as 6 m (20 ft); rare chert and limestone; minor pillow basalt and possible aa lava; basalt and andesite—both as the dominant clasts in the strata and as extrusive rocks—are characterized by about 20% prominent phenocrysts of stubby plagioclase and clinopyroxene; differences in clast populations suggest local sources; from central St. John to the north and east, most rocks are foliated; at least 1.5 km (0.9 mi) thick on west coast of St. John, and may be as thin as 0.5 km (0.3 mi) at Leinster Bay; overlies the Water Island Formation with apparent conformity Includes porphyritic, locally vesicular andesite lava (Kla) and porphyritic, locally amygdaloidal basalt and pillow basalt (Klb)	Clinopyroxene and plagioclase; biotite, pale amphibole and epidote may appear in andesite; epidote, hornblende and biotite may appear in basalt	Limestone clasts, some fossiliferous, on Rata and Ramgoat Cays	Moderate to high

Age	Map Unit (Symbol)		Features and Description	Mineral Occurrence	Paleontological and Cultural Resources	Resistance to Erosion
CRETACEOUS	Lameshur Volcanic-Intrusive Complex (Klm)		Dominantly keratophyre and volcaniclastic rock derived from it; also includes basalt and basaltic andesite, trondhjemite, gabbro, and chert. Keratophyre occurs as lava flows, breccia, layered tuff, dikes, and small hypabyssal intrusive rock; several varieties of keratophyre are distinguished by the size and type of phenocrysts. Mafic rocks occur as pillow lava, pillow breccia, dikes, and rare small plutons. Local hydrothermal alteration may include boxwork texture and gossan. Named for Lameshur on the southern coast of St. John.	Quartz and plagioclase	None documented	Low to high
CRETACEOUS	Lameshur Volcanic-Intrusive Complex	Careen Hill Intrusive Suite (Kct, Kcc, Kcp, Kca, Kcf, Kcm, Kcsd)	Trondhjemite, keratophyre (intrusive equivalents of all keratophyre units of the Water Island Formation), and gabbro; distinct columnar jointing present on Leduck Island and in many dikes and sills; no sequence of intrusion recognized. Named from Careen Hill in Charlotte Amalie. Includes trondhjemite (Kct), coarsely porphyritic keratophyre (Kcc), porphyritic keratophyre (Kcp), phenocryst-poor keratophyre (Kca), plagioclase-phyric keratophyre (Kcf), gabbro (Kcm), and sheeted dike complex (Kcsd). Trondhjemite and keratophyre form sharp hills on the south coast of St. John.	None documented	None documented	Low to high
CRETACEOUS	Lameshur Volcanic-Intrusive Complex	Water Island Formation (Kwp, Kwa, Kwf, Kws, Kww, Kwr)	Dominantly extrusive keratophyres and volcaniclastics rocks derived from it; about 20% basaltic lava (mostly pillowed), breccia, and hyaloclastite; minor radiolarian chert; no through-going stratigraphic order recognized; extrusive equivalent of Careen Hill Intrusive Suite; ash-flow tuffs notably sparse; groundmass of keratophyre commonly spherulitic; excellent exposures of pillow breccias and hyaloclastites are found west of Ram Head Trail, on Harbor Point, and on the peninsulas of Turner and Dittlif points; base of the Water Island Formation not exposed but it was likely deposited on oceanic plateau crust Includes porphyritic keratophyre (Kwp) (superbly exposed in a series of cascades along Battery Gut), phenocryst-poor keratophyre (Kwa) (dominant unit of the Water Island Formation on St. John and well exposed along Fish Gut Bay), plagioclase-phyric keratophyre (Kwf), basalt and basaltic andesite (Kws), volcanic wacke and bedded tuff (Kww), and radiolarian chert (Kwr)	None documented	Radiolaria within bedded chert at Kiddel Point and Saltpond Bay	Moderate to high

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of Virgin Islands National Park, the environment in which those units were deposited, and the timing of geologic events that created the present landscape.

More than 100 million years of geologic history are exposed on the island of St. John. This history ranges from Lower Cretaceous submarine volcanic eruptions to modern-day surficial deposits that form the island's magnificent beaches.

Most of St. John is composed of volcanic rocks (e.g., keratophyres, basalt, and andesite) or sedimentary material derived from these rocks (Rankin 2002). Calcareous rocks and chert are also present in small amounts. Stratified rocks, except for recent deposits, are Cretaceous age. Dikes, sills, and batholiths of Tertiary (now officially called "Neogene;" International Commission on Stratigraphy 2009) age have intruded these rocks.

Lameshur Volcanic-Intrusive Complex

Excellent exposures of the oldest rocks in Virgin Islands National Park occur on southern and southeastern St. John. Renamed the Lameshur Volcanic-Intrusive Complex by Rankin (2002), these rocks are among the oldest in the Caribbean and predate the development of early island-arc volcanism in the Greater Antilles. Geologically, the Virgin Islands constitute the eastern extremity of the Greater Antilles and are part of the same magmatic arc (Rankin 2002). The complex of rocks is estimated to be at least 2 km (1.2 mi) thick (Rankin 2002); although the base is not visible, it is presumed to be underlain by oceanic crust (Donnelly 1989). The Lameshur Volcanic-Intrusive Complex includes both the Water Island Formation and the Careen Hill Intrusive Suite.

Keratophyres and volcaniclastic rocks account for more than 80% of the Water Island Formation, which represents quiet eruptions in relatively deep water (indicated by the presence of radiolarian chert) in an extensional (pulling apart) oceanic environment. Additionally, the formation contains basaltic lavas, breccias, and hyaloclastites.

The Careen Hill Intrusive Suite is the intrusive equivalent of the Water Island Formation; these rocks did not flow onto the ocean floor, rather they cooled below the ocean floor. This suite is composed mainly of trondhjemites, porphyritic keratophyres, and gabbros (Rankin 2002).

Louisehoj Formation

The Late Cretaceous Louisehoj Formation was deposited onto the Water Island Formation during development of an island arc. Subduction-related volcanism in shallow marine waters created more than 2,100 m (7,000 ft) of greenish-gray or grayish-blue green andesite ash beds and pyroclastic breccia. Graded bedding throughout the formation records submarine slides and slumps of volcanic material. The variety of clast compositions and sizes, particularly in the conglomeratic beds of the formation, suggests that numerous volcanic vents were located nearby.

The Louisenhoj Formation dominates the western half of St. John, including Cruz Bay, Trunk Bay, and Cinnamon Bay. Louisenhoj rock has inherent strength, creating difficulties during construction projects.

Outer Brass Limestone

During a time of volcanic quiescence, the Outer Brass Limestone was deposited on top of the Louisenhoj Formation in a quiet marine environment. Deposition of the limestone likely occurred on moderate slopes at a few hundred feet in depth. The Outer Brass Limestone is about 100 m (330 ft) thick on St. John and consists of thinly interlayered calc-silicate rock, white to blue-gray calcite marble, and calcareous-matrix andesite conglomerate. Contact metamorphism of the calcareous rocks by Neogene plutons produced an interesting assemblage of minerals, including tremolite, diopside, phlogopite, garnet, epidote, wollastonite, vesuvianite, sphene, pyrite, and other sulfides (Rankin 2002). The marble beds, which are up to 3 m (10 ft) thick, may be the source of Taino trading beads (figs. 17, 18). This unit forms a discontinuous belt extending from Maho Bay to Brown Bay, with excellent exposures at Annaberg Point on the north shore of St. John.

Although the Outer Brass Limestone is a thin, minor unit on St. John, it is useful for stratigraphically separating the conglomeratic Louisenhoj Formation from the lesser conglomeratic Tutu Formation (Rankin 2002).

Tutu Formation

After deposition of the Outer Brass Limestone, volcanism resumed and the Tutu Formation formed in an island-arc setting. Characterized by volcanic wacke, shale, conglomerate, calcareous siltstone, limestone, and rare basalt and andesite (or their metamorphic equivalents), most of the material seems to have been deposited by turbidity currents, suggesting deposition on an unstable slope such as a trench wall leading into an accretionary wedge (Rankin 2002). Volcaniclastic fragments within the Tutu Formation are generally sand and silt size, suggesting that the volcanic source was farther away than the Louisenhoj vents (Rankin 2002). Additionally, a distinct fining upward implies increasingly distant volcanic sources. The extrusive igneous rocks of the Tutu Formation are the last evidence of volcanism on St. John.

The Tutu Formation is divided into two components: the older Picara Member and the overlying, finer grained Mandal Member. A thin limestone lens referred to as the Congo Cay Limestone Lens is a subcomponent of the Mandal Member. The Tutu Formation extends from Whistting Cay to Leinster Point.

Dikes, Narrows Pluton, and Virgin Gorda Batholith

The Neogene Period on St. John is marked by intrusive activity that included a mafic dike swarm followed by plutons of biotite-hornblende tonalite and minor gabbro, diorite, granite, and pegmatite. The latter includes the Narrows pluton and the Virgin Gorda batholith, which produced a contact metamorphosed aureole as wide as 2 km (1.2 mi). Individual dikes range in thickness from a few centimeters to several meters.

Surficial Deposits

Today, Quaternary alluvium, swamp deposits, beach deposits, beachrock, bay mouth bars, playa deposits, boulder fields, and artificial fill compose the sand beaches and low-lying areas of Virgin Islands National Park (Rankin 2002).

Figure 17. Taino trading bead. The Taino used marble to create trading beads and jewelry. Beds of marble occur in the Outer Brass Limestone. Photograph by K. N. Hall.

Figure 18. Marble. Contact metamorphism transformed beds of the Outer Brass Limestone into marble. This figure shows a marble boulder near Annaberg Point. Note the folded beds, which are indicative of contact metamorphism. Photograph by K. N. Hall.

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).

accretionary prism (or wedge). A wedge-shaped body of deformed rock consisting of material scraped off of subducting oceanic crust at a subduction zone. Accretionary prisms form in the same manner as a pile of snow in front of a snowplow.

allanite. A brownish-black silicate mineral of the epidote group. Found in igneous rocks, allanite contains a significant amount of rare earth elements.

amphibole. A common group of rock-forming silicate minerals. Hornblende is the most abundant type.

andesite. Volcanic rock commonly associated with subduction zone volcanoes. Named for the subduction zone volcanoes of the Andes Mountains.

apatite. A group of variously colored phosphate minerals. Tooth enamel and bones contain minerals from the apatite group.

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

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

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

batholith. A massive, discordant pluton, larger than 100 km^2 (40 mi^2), and often formed from multiple intrusions of magma.

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

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

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

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

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

biotite. A widely distributed and important rock-forming mineral of the mica group. Forms thin, flat sheets.

boxwork. Usually in caves; a network of resistant intersecting fins, usually of calcite, that project outward from the intervening, more deeply weathered bedrock.

breccia (volcanic). A coarse-grained, generally unsorted volcanic rock consisting of partially welded angular fragments of ejected material such as tuff or ash.

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

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

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

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

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]).

clinopyroxene. A group name for pyroxene minerals crystallizing in the monoclinic system. Important rock-forming minerals; common in igneous and metamorphic rocks.

columnar joints. Parallel, prismatic columns, polygonal in cross section, in basaltic flows and sometimes in other extrusive and intrusive rocks; they form as a result of contraction during cooling.

concordant. Strata with contacts parallel to the orientation of adjacent strata.

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.

deformation. A general term for the processes of faulting, folding, and shearing of rocks as a result of various Earth forces such as compression (pushing together) and extension (pulling apart).

dike. A narrow igneous intrusion that cuts across bedding planes or other geologic structures.

diopside. A mineral of the pyroxene group. Found in mafic, ultramafic igneous rocks and some areas of contact metamorphism.

diorite. A type of plutonic igneous rock. It is the approximate intrusive equivalent of andesite.

discordant. Describes contacts between strata that cut across or are set at an angle to the orientation of adjacent rocks.

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

eolian. Describes materials formed, eroded, or deposited by or related to the action of the wind. Also spelled "Aeolian."

epidote. A yellow-green, pistachio-green, or blackish-green mineral (calcium, aluminum, iron silicate). Common rock-forming mineral, found in metamorphic rocks.

extension. A type of strain resulting from forces "pulling apart." Opposite of compression.

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

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

feldspar. A group of abundant (more than 60% of Earth's crust), light-colored to translucent silicate minerals found in all types of rocks. Usually white and gray to pink. May contain potassium, sodium, calcium, barium, rubidium, and strontium along with aluminum, silica, and oxygen.

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

foliation. A preferred arrangement of crystal planes in minerals. In metamorphic rocks, the term commonly refers to a parallel orientation of planar minerals such as micas.

fracture. Irregular breakage of a mineral; also any break in a rock (e.g., crack, joint, or fault).

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

garnet. A hard mineral that has a glassy luster, often with well defined crystal faces, and a variety of colors, dark red being characteristic. Common in metamorphic rocks.

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

gossan. An iron-bearing weathered product overlying a sulfide deposit.

granite. An intrusive igneous (plutonic) rock composed primarily of quartz and feldspar. Mica and amphibole minerals are also common. Intrusive equivalent of rhyolite.

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

greenstone. A general term for any compact dark green altered or metamorphosed basic igneous rock owing its color to chlorite, actinolite, or epidote minerals.

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.

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").

hyaloclastite. A deposit formed by the flow or intrusion of lava or magma into water, ice, or water-saturated sediment, and its consequent shattering into small angular fragments.

hypabyssal. An igneous rock formed at a shallow depth.

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.

keratophyres. A term applied to salic (silicon or aluminum-rich minerals) or hypabyssal rocks.

landslide. Any process or landform resulting from rapid, gravity-driven mass movement.

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

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

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

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

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

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

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.

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

microplate. A small lithospheric plate.

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

monoclinic. One of the six crystal systems for classifying minerals.

mud flat. A relatively level area of fine silt along a shore, alternately covered and uncovered by the tide or covered by shallow water.

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

parent rock. Rock from which soil, sediments, or other rocks are derived.

pebble. Generally, small rounded rock particles from 4 to 64 mm (0.16 to 2.52 in) in diameter.
pegmatite. An exceptionally coarse-grained intrusive igneous rock, with interlocking crystals, usually found in irregular dikes, lenses, and veins, especially at the margins of batholiths.
phenocryst. A coarse (large) crystal in a porphyritic igneous rock.
phlogopite. A magnesium-rich mineral of the mica group.
plastic. Capable of being deformed permanently without rupture.
plateau. A broad, flat-topped topographic high (terrestrial or marine) of great extent and elevation above the surrounding plains, canyons, or valleys.
plagioclase. A group of feldspars and common rock-forming mineral.
playa (coastal). A small generally sandy land area at the mouth of a stream or along the shore of a bay.
plume. A persistent, pipe-like body of hot material moving upward from Earth's mantle into the crust.
pluton (plutonic). A body of intrusive igneous rock that crystallized at some depth beneath Earth's surface.
porphyry. An igneous rock consisting of abundant coarse crystals in a fine-grained matrix.
pyrite. A common, pale-bronze or brass-yellow, cubic mineral.
radiolarian. Occurring from the Cambrian Period to the present, radiolarians are zooplankton that occurs throughout the ocean; their skeletal remains (often siliceous) cover large portion of the ocean bottom.
radiolarian chert. A well-bedded, microcrystalline rock composed primarily of Radiolaria with well-developed siliceous cement or groundmass.
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.
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.
shale. A clastic sedimentary rock made of clay-sized particles that exhibit parallel splitting properties.
silicate. A compound whose crystal structure contains the SiO_4 tetrahedra.
sill. An igneous intrusion that is of the same orientation as the surrounding rock.
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.
skarn. Calcium-bearing silicates derived from nearly pure limestone and dolomite with the introduction of large amounts of silica, aluminum, iron, and magnesium.
slope. The inclined surface of any geomorphic feature or measurement thereof. Synonymous with "gradient."
slump. A generally large, coherent mass movement with a concave-up failure surface and subsequent backward rotation relative to the slope.
spherulitic. Volcanic igneous texture dominated by spherical bodies of radiating mineral fibers.
strata. Tabular or sheetlike masses or distinct layers of rock.
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.
sulfide. A mineral compound characterized by the linkage of sulfur with a metal or semimetal such a galena or pyrite.
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.
tonalite. A type of plutonic (intrusive) rock.
topography. The general morphology of Earth's surface, including relief and locations of natural and anthropogenic features.
transform boundary. A type of plate boundary at which lithosphere is neither created or destroyed, and plates slide past each other on a strike-slip fault.
tremolite. A white to dark-gray monoclinic mineral of the amphibole group.
triclinic. One of the six crystal systems for classifying minerals.
tuff. Generally fine-grained, igneous rock formed of consolidated volcanic ash.
turbidite. A sediment or rock deposited from a turbidity current.
turbidity current. A density current in water, air, or other fluid, caused by different amounts of matter in suspension; specifically a bottom-flowing current laden with sediment, moving swiftly under the influence of gravity down a subaqueous slope and spreading horizontally on the floor of a body of water.
vent. An opening at Earth's surface where volcanic materials emerge.
vermiculite. A group of mica-rich clay minerals related to chlorite and montmorillonite.
vesuvianite. A dense, brittle mineral, usually brown, yellow, or green, commonly found in contact-metamorphosed limestone.
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.
wollastonite. A mineral ($CaSiO_3$) found in contact-metamorphism limestone; it may be white, gray, brown, red, or yellow.
xenolith. A rock particle, formed elsewhere, entrained in magma as an inclusion.

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Additional References

This section lists additional references, resources, and Web sites that may be of use to resource managers.

Climate Change Information

Global change impacts in the United States (report): http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts

NPS Climate Change Response Program: http://www.nature.nps.gov/climatechange/index.cfm

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

U.S. Geological Survey Geology of National Parks (includes 3D photographs). http://3dparks.wr.usgs.gov/

Harris, A. G., E. Tuttle, and S. D. Tuttle. 2003. Geology of National Parks. Sixth Edition. Kendall/Hunt Publishing Co., Dubuque, Iowa, USA.

Kiver, E. P. and D. V. Harris. 1999. Geology of U.S. parklands. John Wiley and Sons, Inc., New York, New York, USA.

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.

[Web site under development]. Contact the Geologic Resources Division to obtain a copy.

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

Geological Survey Web Sites

Oregon Department of Geology and Mineral Industries (DOGAMI): http://www.oregongeology.org/sub/default.htm

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

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”).

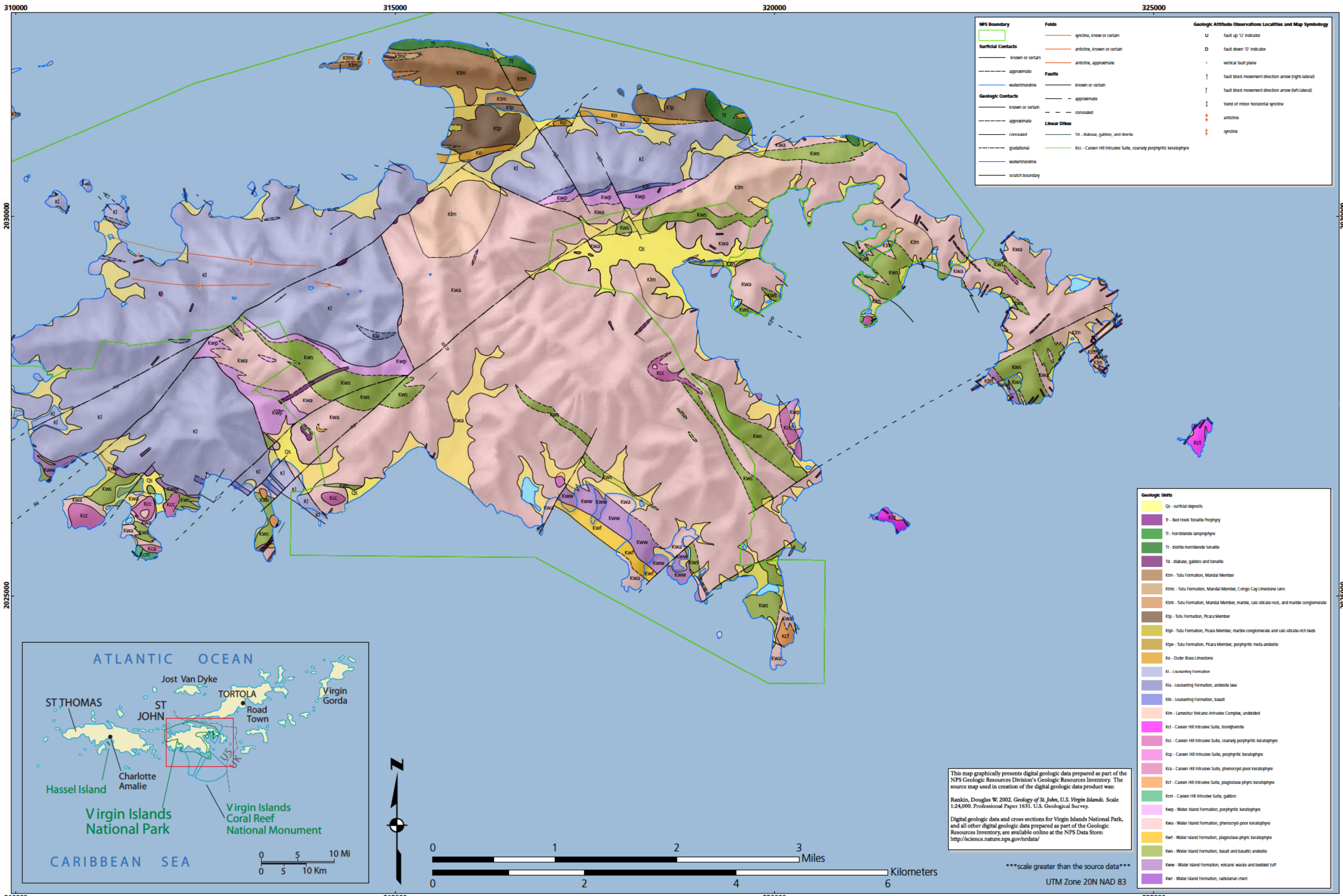
U.S. Geological Survey Publications Warehouse (many USGS publications are available online): http://pubs.usgs.gov

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

Appendix A: Overview of Digital Geologic Data

The following page is an overview of the digital geologic data for Virgin Islands National Park. For a poster-size PDF of this overview and complete digital data, please see the included CD or visit the Geologic Resources Inventory publications web site: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

Overview of Digital Geologic Data for Virgin Islands National Park



Appendix B: Scoping Meeting Participants

The following is a list of participants from the GRI scoping session for Virgin Islands National Park, held on April 7–9, 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 web site: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

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