World Geomorphological Landscapes

Casey D. Allen *Editor*

Landscapes and Landforms of the Lesser Antilles

Springer

World Geomorphological Landscapes

Series editor

Piotr Migoń, Wroclaw, Poland

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This Volume is dedicated to all peoples of the Lesser Antilles—past, present, and future. Your resilience and patriotism during even the most difficult times serves as an inspiration. May the Caribbean Sun continue to shine within you and your families.

Foreword

Lesser Antilles

The Lesser Antilles, which include the Leeward Islands, the Windward Islands, and the Leeward Antilles of the eastern Caribbean, were once described as “Edens of Delight,” and they certainly comprise some of the most striking and intriguing landscapes on Earth. Used in 1925 as a model by William Morris Davis for his cycle of island development, they have never, until now, been the subject of a comprehensive geomorphological appreciation. They extend from the Virgin Islands in the north to Trinidad and Tobago in the south, and 1140 km from Aruba in the west to Barbados in the east. Consisting of some six hundred tropical islands, in total they only cover a relatively modest land area (less than half the size of Albania), but they exemplify major, horseshoe-shaped island arcs, with numerous volcanic features, including stratovolcanoes, granitic plutons, and also carbonate formations (including reefs) on which numerous karst features have developed. This well-structured volume provides an analysis of the tectonic history of the area, a discussion of its climatic conditions, and a survey of the human influence and transformation of its diverse landscapes. Above all, it discusses the main island clusters, drawing attention to their spectacular landforms, their land use histories, their heritage concerns, and the geomorphological hazards (including tsunamis, earthquakes, landslides, and hurricanes) with which their inhabitants have to contend. As befits an area of such splendid geomorphological phenomena, it is also beautifully illustrated with plates and maps and will become the first port of call for all those interested in how the landscapes of the islands have evolved. Moreover, it will stimulate further research. It is also a very worthy new volume in a series of books—The *World Geomorphological Landscapes*—that are doing much to draw attention to the magnificence and significance of our planet’s major geomorphological regions.

Andrew Goudie
Emeritus Professor of Geography, University of Oxford, Oxford, UK
Past President of the International Association of Geomorphologists

Series Editor Preface

Landforms and landscapes vary enormously across the Earth, from high mountains to endless plains. At a smaller scale, Nature often surprises us creating shapes which look improbable. Many physical landscapes are so immensely beautiful that they received the highest possible recognition—they hold the status of World Heritage properties. Apart from often being immensely scenic, landscapes tell stories which not uncommonly can be traced back in time for tens of million years and include unique events. In addition, many landscapes owe their appearance and harmony not solely to the natural forces. Since centuries, or even millennia, they have been shaped by humans who modified hillslopes, river courses, and coastlines, and erected structures which often blend with the natural landforms to form inseparable entities.

These landscapes are studied by geomorphology—"the Science of Scenery"—a part of earth sciences that focuses on landforms, their assemblages, and surface and subsurface processes that molded them in the past and that change them today. Shapes of landforms and regularities of their spatial distribution, their origin, evolution, and ages are the subject of research. Geomorphology is also a science of considerable practical importance since many geomorphic processes occur so suddenly and unexpectedly, and with such a force, that they pose significant hazards to human populations and not uncommonly result in considerable damage or even casualties.

To show the importance of geomorphology in understanding the landscape, and to present the beauty and diversity of the geomorphological sceneries across the world, we have launched a new book series *World Geomorphological Landscapes*. It aims to be a scientific library of monographs that present and explain physical landscapes, focusing on both representative and uniquely spectacular examples. Each book will contain details on geomorphology of a particular country or a geographically coherent region. This volume introduces an area which is among the least familiar for world geomorphologists: The Lesser Antilles. While some islands occasionally headline the news—mainly when struck by natural disasters (Montserrat being the most recent example) and others provided key evidence of Quaternary sea-level change (Barbados)—the majority are largely under-researched and forgotten. And yet they are highly diverse geomorphologically, displaying an array of different landscapes ranging from volcanic and karstic to coastal and reef. Collectively, they tell the fascinating story of a (mostly) volcanic archipelago's geomorphic evolution, and this book undoubtedly helps in appreciating this understudied region's landscapes and landforms.

The *World Geomorphological Landscapes* series is produced under the scientific patronage of the International Association of Geomorphologists—a society that brings together geomorphologists from all around the world. The IAG was established in 1989 and is an independent scientific association affiliated with the International Geographical Union and the International Union of Geological Sciences. Among its main aims are to promote geomorphology and to foster dissemination of geomorphological knowledge. I believe that this lavishly illustrated series, which sticks to the scientific rigor, is the most appropriate means to fulfill these aims and to serve the geoscientific community. To this end, my great thanks go to the Editor, Dr. Casey D. Allen, for his initiative to produce the Lesser Antilles volume and his excellent coordination of work leading to a high degree of coherence between chapters. I am also most grateful to all individual contributors who agreed to add the task of writing chapters to their busy agendas and delivered high-quality final products.

Piotr Migoń

Acknowledgements

My most profound and generous thanks go to Kaelin Groom for her help with reviewing the early stages of the final manuscript, as well as her assistance with double-checking and editing the graphics (and a few other components) in this volume. Her keen eye and artistic abilities lay far beyond mine. She also graciously offered her cartographic prowess throughout the book, creating maps from scratch. I have the utmost respect for her as a colleague and greatly appreciate her companionship throughout the editing and writing process. Many thanks also go to the governments and people of each island in this volume, as several agencies and individuals helped to fill missing imagery gaps and confirm information. I would also like to sincerely acknowledge the chapter authors, especially those who submitted their chapters promptly and those who stepped-in at the last minute to help tidy-up and finish-off a few remaining chapters. I am grateful for your willingness to work on a sometimes extremely tight deadline. Finally, to Piotr Migoń, the Series Editor, for encouragement, support, and the tireless hours he puts into helping the *World Geomorphological Landscapes* series: thank you.

Washington, UT (USA) Casey D. Allen

Contents

Editor and Contributors

About the Editor

Casey D. Allen An award-winning Traditional Geographer *and* Educator recognized for research that spans the physical and social sciences as well as humanities, Dr. Allen maintains wide-ranging interests that coincide with his passion for fieldwork and peripatetics. For nearly 20 years, he has served in various capacities at several different universities (and other jobs), including a stint as instructor and coordinator of St. George's University's BS/MD program (Grenada), where he became enamored with the Caribbean. His current research focuses on validating the importance of experiential education through fieldwork—including his international field study programs, *Sustainability in the Caribbean* and *Geography by Rail®*—using the mediums of geomorphology and humanistic geography broadly speaking, and rock/cultural stone decay and landscape/sense of place more specifically. He also has expertise and keen interests in biological soil crusts, geo/digital humanities, and geoarchaeology. Check his website for updates (https://caseallen.com) and follow his eclectic tweets on Twitter: @caseallen.

Contributors

Jeanette C. Arkle is currently a Ph.D. geology candidate at the University of Cincinnati, Ohio, USA. She completed MS and BS geology degrees, and a BA geography degree from California State University, Fullerton. Her research focuses on crustal deformation, bedrock exhumation, and geomorphology of mountain belts. To investigate the evolution of landscapes and tectonic-surface process interactions, she uses low-temperature thermochronology, terrestrial cosmogenic nuclide dating, and optically stimulated luminescence dating, in tandem with GIS geomorphic analyses and field techniques. She has worked primarily in tectonically active mountain belts including southern Alaska, the northwest Himalaya, southern California and the southeast Caribbean.

Frederick Chambers is Associate Professor in the Department of Geography and Environmental Sciences at the University of Colorado Denver where he previously served as Department Chair and Director of the Master of Environmental Sciences program on two separate occasions. His current research interests are focused in four areas of concentration: (1) mineral weathering and micro-climatological interrelationships of basalt flows on the Big Island of Hawaii, (2) investigation of historical urban heat islands in both old mining towns and the "Rust Belt" of northeastern U.S., (3) continuing investigations into small glaciers in the western U.S. and their responses to climate change, (4) monitoring and assessing the glaciers in the Northern Patagonia Icefields. This research has been supported by the National Geographic Society, United States Geological Survey, National Park Service, and several internal grants from the University of Colorado Denver. Dr. Chambers is also an avid SCUBA diver with a burgeoning interest in the Caribbean.

Sean Chenoweth an Associate Professor of Geography at University of Louisiana at Monroe, USA, **Michael (Sean) Chenoweth** has been conducting research in the Caribbean since 1999. Much of Dr. Chenoweth's focus has been on karst geomorphology and human land use associated with these landscapes. Field work in the Jamaican Cockpit Country led him to seek out similar areas in the Caribbean for a cockpit karst correlation project he is currently pursuing. He also has a strong interest in geospatial technologies including GIS, remote sensing, GPS and applications involving unmanned aerial systems. Recently, he helped to create a non-profit organization dedicated to the preservation and enhancement of the Poverty Point World Heritage Site. Some of his hobbies are bicycling, photography, scuba diving and amateur radio.

Mick Day is an Emeritus Professor of Geography at the University of Wisconsin-Milwaukee, USA, specializing in karst landscapes, their geomorphology, land use and conservation. His regional focus is on the Caribbean, Central America and Southeast Asia.

Patti Day is a Lecturer in Geography at the University of Wisconsin-Milwaukee, USA, specializing in geographic information, its production, acquisition, curation and usage. She is particularly focused on legal issues pertaining to geographic information access, and has global interests extending beyond the Caribbean to North America, Europe and the Pacific.

Alison DeGraff Ollivierre is a geographer, certified geographic information systems (GIS) professional, and award-winning cartographer, who works for National Geographic Maps. **Alison DeGraff Ollivierre** has lived and worked in Saint Vincent and the Grenadines since 2011. Her initial research spanned both SVG and Grenada and focused on the facilitation of a participatory mapping project to develop a comprehensive local knowledge GIS database of important historical, cultural, and ecological heritage sites throughout the islands. Ollivierre additionally assisted with the development of a collaborative marine multi-use zoning plan for the Grenada Bank and is co-authoring and conducting research for an avian field guide for the transboundary Grenadines that highlights both scientific and local ecological knowledge. She holds a BA in Geography from Middlebury College (Vermont, USA) and an MSc in Geoinformatics from the University of the West Indies, St. Augustine (Trinidad and Tobago) where she completed her thesis research on the use of participatory mapping in Caribbean small island developing states to address climate change.

Susanna L. Diller completed her MS degree (Geography) at the University of New Mexico, Albuquerque, USA. She earned her BA degree (Geography) from the University of Colorado Denver, where her honors thesis was a GIS analysis of Twitter conversations about the boyband One Direction, which included extended field time in the UK. A traditional geographer with varied research interests that include geomorphology, cultural geography, sport geography, and GIS, her graduate studies focus on the social role of fountains in public space, particularly in semi-arid cities such as Albuquerque and Denver. Susanna currently works as part of the cyberinfrastructure team with New Mexico EPSCoR (Experimental Program to Stimulate Competitive Research), and has been increasing her regional expertise to include the Caribbean and Europe.

Russell Fielding earned his PhD in geography at Louisiana State University in 2010. He participated in the Canada-US Fulbright Program, spending a year researching and teaching with the Institute of Island Studies at the University of Prince Edward Island. As for research, Fielding is interested, broadly, in questions of subsistence, cultural tradition, and resource conservation. His current research projects focus on issues of food security with regard to the artisanal whaling operation in St. Vincent and local freshwater production through the incineration of municipal waste in St. Barthélemy.

W. Travis Garmon is a hydrogeochemist who completed a MS degree in Geology from the University of Arkansas, and BS degrees in both Geology and Geography from Western Kentucky University. His current research focuses on Mississippi Valley-Type ore deposits in KY and TN, with emphasis on determining the source region(s) of metals found within the deposits using bulk geochemistry and both stable and radiogenic isotopes. His previous research has included dye-tracing in karst aquifers in both south-central KY and south-eastern MN to determine aquifer dynamics and aid in tracking contaminant transport. He remains well-versed in tectonics, and has always held an interest in the Caribbean.

Kaelin M. Groom Fervently dedicated to fieldwork, discovery, and maintaining the delicate balance between historic preservation and educational experience/exposure, **Kaelin M. Groom** completed her PhD in Environmental Dynamics at the University of Arkansas (USA), where she also obtained an MA in Geography. She earned her BA, also in Geography, from the University of Colorado Denver. Her specialties include geomorphology, cartography, cultural resource management, and heritage tourism. With wide interests, Kaelin's current research includes analyzing cavernous rock decay (tafoni) formation and development, quantifying tangible impacts of tourism in culturally protected landscapes, and serving as an advocate for rapid and mixed methods field assessments in rock decay and heritage management. Professionally, she has worked as a research consultant with both domestic and international agencies such as the King Fahd Center for Middle East Studies, USAID's Middle East SCHEP team, US National Park Service, Grenada National Museum, and the Petra National Trust.

Ayumi Kuramae is finalizing her BSc thesis (Coastal Marine Management-Marine Biology) at the University of Applied Sciences Van-Hall Larenstein, Leeuwarden (Netherlands). She did an international study abroad program at Bangor University (School of Ocean Sciences) where she further specialized in marine ecosystems and processes, conservation, and exploitation. She has been collaborating on different tropical marine research projects—such as benthic mapping of Saba's coastal waters and distribution and population status of L. gigas in Anguilla—while also conducting volunteer work in the Dutch and British West Indies (Caribbean). She plans on continuing with her passion by expanding her knowledge and experience in (tropical) marine ecology by completing and MSc in marine biology, and her graduate studies focus on the evaluation of waste management and the possible impacts of solid waste and beach debris on St. Eustatius. Further research interests are coral reef ecology, ecosystem resilience, and regime shifts.

E. Arnold Modlin, Jr Ph.D. is the lone (but not lonely) geographer in the History and Interdisciplinary Studies Department at Norfolk State University in Norfolk, Virginia, USA. Arnold's research interests revolve around how people use landscapes to remember and forget painful pasts, particularly as they relate to issues such as slavery, colonialism, and civil rights. His main research focus over the last few years deals with how the memory of slavery is talked about contrarily in different places in the U.S. South and the Caribbean. Dr. Modlin believes that the struggle to remember difficult pasts connects linguistic, emotional, affective and sensorial expressions with geographies of racial, gendered, generational and economic difference and built and "natural" landscapes. Some of his work has been published in Tourism Studies: An International Journal, Southeastern Geographer, Journal of Heritage Tourism, and the edited volume Social Memory and Heritage Tourism Methodologies.

Elizabeth Nelson A Ph.D. candidate in geography at the University of South Carolina, **Elizabeth (Beth) Nelson** received her MA in geography from Arizona State University, and her baccalaureate (also Geography) from University of Nebraska Kearny. Her active research engages with human geography in the sociopolitical relationships involved in migratory patterns. Currently, her focus is specifically North African migrations to France and other colonial/postcolonial migratory conditions. During the course of her career, she has researched both physical and human geographic characteristics, many involving energy resources and human impacts on the environment. Ranging from hydrological and solar energy resources to political issues involving the extraction and use of fossil fuels, her varied research and careers have followed political engagements with various human-environment or human-political situations. Beth works hard to keep her passion, research topics, areas of expertise, and teaching in both physical and human geography up-to-date and relevant.

Lewis A. Owen received his PhD in geomorphology from the University of Leicester, U.K., in 1988. Before joining the University of Cincinnati in 2004, he held positions at the Hong Kong Baptist University, Royal Holloway—University of London, and the University of

California—Riverside. Professor Owen's research focuses on the Quaternary geology and geomorphology of tectonically active mountain belts and their forelands, particularly in the Himalayan–Tibetan orogen and the Cordilleras of North and South America. He has also undertaken research in other tectonically active regions, including the Caribbean, Red Sea margin in Yemen and the Atlas and Anti-Atlas Mountains of Morocco. In 2011, Professor Owen was awarded the Busk Medal from the Royal Geographic Society for his field research in Quaternary history and geomorphology in tectonically active areas.

Lauren Parkinson recently graduated cum laude from Kennesaw State University with an BA in Geography and a Minor in International Affairs. She was selected as the Department of Geography and Anthropology's 2015 Outstanding Student in Geography and the 2016 Outstanding Senior in Geography due to her involvement with Gamma Theta Upsilon, dedication to academic excellence, and her commitment to research. She will continue her education by studying natural resource management and sustainability in a graduate program in the near future.

Amy E. Potter an Assistant Professor of Geography in the Department of History at Armstrong State University in Savannah, Georgia, USA, **Amy E. Potter**, Ph.D., has research interests that center on the larger themes of cultural justice and the African Diaspora. She has conducted ethnographic fieldwork in the Caribbean and U.S. South. In the Caribbean, she examined how the island of Barbuda has transitioned, in part through the mechanism of migration, from an agriculture and grazing economy to that of tourism and the larger implications for the island's common property. Her current research, funded by the National Science Foundation, examines racialized southern heritage landscapes with a focus on plantation house museums. Some of her work has been published in the Journal of Cultural Geography, Historical Geography, Southeastern Geographer, Journal of Heritage Tourism, Island Studies Journal, and the edited volume Social Memory and Heritage Tourism Methodologies of which she is an editor.

Jennifer L. Rahn is an Associate Professor of Geography at Samford University in Birmingham, Alabama, USA. She first traveled to Saba in 1990 to learn how to scuba dive, and then spent two years as a dive master and tour guide on the island trails (before they were official trails). She has also spent significant time on Statia, and has explored 12 other Caribbean islands. Jennifer continued to visit Saba regularly and, in 2008, began teaching a study-abroad diving course in conjunction with Sea Saba Dive Center. Her coastal geomorphology research on Saba and Statia includes sub-aerial and sub-aqueous beach profile monitoring on sand and cobble beaches. On Saba specifically, her research also includes coral reef mapping and coral nursery implementation and monitoring, among other projects. She collaborates with and volunteers for the Saba Conservation Foundation and the Saba Marine Park whenever she is on island (about 3 months a year).

Richard Edward Arnold Robertson Originally from the island of St. Vincent, **Richard E. A. Robertson** is an experienced field researcher and academic who has been working in the Caribbean for over 25 years. He joined the staff at the Seismic Research Centre in Trinidad in 1993 where he now serves as Director. His research interests include volcano monitoring, hazard and risk assessment, crisis communications, risk perception and management, volcano geodesy and magma genesis. He has a keen interest in the dissemination of scientific information to vulnerable island communities and has published academic books, books chapters, and numerous refereed articles in his areas of expertise. He has worked on various projects including: the ongoing eruption of the Soufrière Hills Volcano on Montserrat, establishment of volcano monitoring networks, public education, and outreach programs throughout the Eastern Caribbean, and the lecturing and supervision of geoscience students. He is an advisor to disaster management organizations throughout the Eastern Caribbean.

Phillip P. Schmutz Ph.D. is an Assistant Professor in the Department of Earth and Environmental Sciences at the University of West Florida in Pensacola, Florida, USA. Phillip's research interests center on themes of environmental monitoring and modeling of coastal/beach/dune environments with an emphasis in beach hydrology. He has conducted fieldwork along the coast of Texas, Florida, North Carolina and Mexico as well as the island of Dominica. His doctoral research was funded by the National Science Foundation's Doctoral Dissertation Research Improvement (DDRI) award. He conducted his post-doctoral research at White Sands National Monument through a National Park Service grant. His work has been published in the Journal of Coastal Research, Aeolian Research, and Earth Surface Processes and Landforms.

Ryan Sincavage is currently a PhD candidate in Environmental Engineering at Vanderbilt University in Nashville, Tennessee, USA. He completed a B.S. degree in Earth Sciences from the Pennsylvania State University and a M.S. degree in Geology from the University of Colorado Boulder. His research focuses on sedimentology and stratigraphy of large fluvial systems and deltas, particularly the interactions of climate, tectonics, and autogenic processes on channel mobility, surface morphology, and preservation of sediments. Current active research focuses on the Holocene Brahmaputra River avulsion history of Sylhet Basin, a tectonically active sub-basin within the Ganges-Brahmaputra-Meghna Delta (GMBD) of Bangladesh, and the coupling of tectonic deformation and stratigraphic architecture in the Indo-Burman fold belt of eastern India. He primarily uses field observation of outcrops as well as laboratory analyses (grain size measurements and X-rayfluorescence) of sediments to quantitatively assess provenance and fluvial system behavior.

Vanessa Slinger-Friedman is an Associate Professor of Geography in the Department of Geography and Anthropology, and the Associate Director of Distance Education for the College of Humanities and Social Sciences at Kennesaw State University (USA). Originally from Trinidad, Dr. Slinger-Friedman obtained her MA in Latin American Studies and PhD in Geography from the University of Florida. Her work has included a World Bank sponsored study in Mexico and El Salvador of Vetiver grass technology for soil erosion control, the use of an agroforestry system for Amazonian urban resettlement in Acre, Brazil, and the use of ecotourism on Dominica, W.I. for economic development and nature preservation. Dr. Slinger-Friedman has a regional focus on Latin America, the Caribbean, and the SE United States, where she has researched ecotourism and the impact of Latino immigration respectively. Her other research interests include innovative pedagogy, online teaching, and intercultural competence related to study abroad.

Donald M. Thieme is a geomorphologist and soil scientist. Dr. Thieme studies the distributions and properties of sediments and soils to identify the direction and rate of landscape change. In addition to direct field examination, sampling, and laboratory analysis, he uses shallow geophysical methods for geological and archaeological research. His work includes studies of the effects of both climate change and human activities on soils. Dr. Thieme has only recently taken an interest in the landscapes of the Caribbean region, his previous field experience being confined to the continental United States and Mexico.

John C. Weber is a Professor of Geology at Grand Valley State University (USA) and also a regular summer field camp Instructor at the Yellowstone Bighorn Research Association facility for the University of Houston. In his research, he uses structural geology, GPS geodesy, thermochronology, and tectonic geomorphology to study plate and microplate motion and neotectonics in the SE Caribbean, northern Adriatic, and circum-Caucasus. He also interfaces with industry through teaching and consulting.

Tirzha Zabarauskas is a graduate student at University of Colorado Denver (USA) pursuing a Master of Arts in Applied Geography and Geospatial Science. She holds a BA in Geography with minors in geology and educational studies. She is a member of Phi Theta Kappa honor society and Philanthropic Education Organization. Tirzha spends her summers teaching STEM-focused camps to students in Boulder and Denver, Colorado. She is an avid photographer and traveler—having visited several Caribbean islands thus far in addition to other locales—and can be found doing either when not working. She lives with her husband and daughter in a suburb of Denver. Though she has burning interests in the Earth Sciences, her current research is focused on spatial literacy and education for primary school students.

1 Small Islands, Intriguing Landscapes

Casey D. Allen

Abstract

The Lesser Antilles comprises three main island groups: Leeward Islands, Windward Islands, and Leeward Antilles. Stretching from the Virgin Islands in the north to Trinidad and Tobago in the south and encompassing Aruba, Bonaire, and Curaçao to the east, the Lesser Antilles remain a geomorphologically and anthorpogenically diverse region. While this chapter introduces offers the reader a (very) brief overview of this fascinating and under-studied world region, its main focus rests in explaining this volume's structure and function, including notes regarding vernacular, historical accuracy, and the splendid cartography.

Keywords

Lesser Antilles • Leeward Antilles • Windward Islands • Leeward Islands

1.1 Introduction

While often neglected geomorphologically in both study and literature, the Lesser Antilles islands in the Caribbean contain outstanding landscapes and landforms: granitic islands in the north, active and highly explosive volcanoes in the center, mostly extinct volcanics in the south, and a few (sometimes large) sedimentary uplift blocks scattered throughout the archipelago. Spatially, the Lesser Antilles consist of a vast territorial swath spanning about 940 km from the British and US Virgin Islands in the north to Trinidad and Tobago in the south, and approximately 1140 km from Aruba in the west to Barbados in the east (over 1,000,000 km^2, Fig. 1.1). In that otherwise watery expanse, the Lesser Antilles claim no less than 600 individuals yet mostly uninhabited islands, forming—with the exceptions of outlying Barbados and Aruba, Bonaire, and Curaçao (the ABCs)—an arcing boundary between the Caribbean Sea and the Atlantic Ocean. This positioning on Caribbean Plate's edge creates a landscape of volcanic features: from plutons and stratovolcanoes to geothermal springs and lava flows, as well as hazards associated with regular heavy precipitation, fire, volcanically induced tsunamis, hurricanes, and, somewhat paradoxically, drought. Additionally, geologic uplift and subsequent rock decay continue to occur, exposing sedimentary landforms such as coralline shelves and carbonate reefs, as well as general karst landscape features.

The Lesser Antilles' human occupance also played a role in shaping the islands' landscapes, and, in many instances, these actions (individually, say a landholder, or as a group, say a country) have influenced landforms. As Amerindians began settling the Islands, migrating northward from mainland South America or southward from larger islands such as Puerto Rico and Hispaniola, they brought with them various cultural traits, including agricultural practices. Some left records in the form of rock engravings (petroglyphs) and additional tangible artifacts, others intermarried with European colonists or African slaves, and their progenies still inhabit the islands today. These peoples made use of the landforms, as evinced by Lesser Antillean archaeological sites being found near freshwater rivers, along bays with coral reefs, and in caves. Evidence for pre-Columbian populations also exists in the form of numerous "worked stone" (*cupules* and/or grind stones) on several islands,

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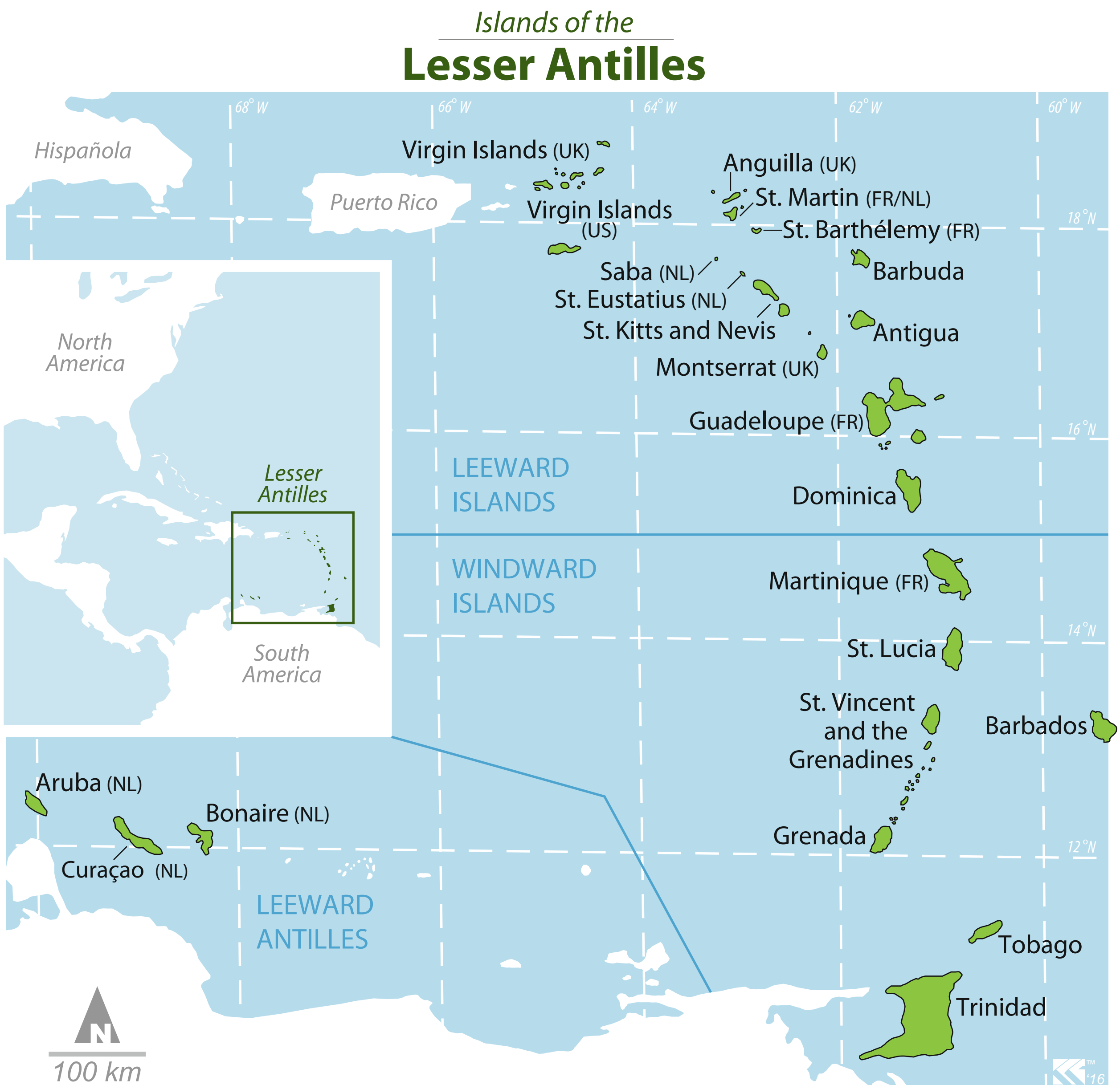

Fig. 1.1 General map of the Lesser Antilles identifying the three subregions—Leeward Islands, Windward Islands, and Leeward Antilles—as well as the primary islands/island groups that will be highlighted in this volume. Cartography by K.M. Groom

demonstrating that these peoples understood—if only subconsciously—at least the basics of how rock hardness and mineral grain size can interact to provide them with surfaces for grinding substances and creating tools and other implements (e.g., smooth, polished granitic rocks have been found at archaeological sites on islands where no granite is present).

After Columbus' "discovery" of the (then) New World, a different influence on Lesser Antillean landscapes and landforms began. Colonial settlements began appearing, slowly populating each island with a land tenure system that was sometimes sustainable, but mostly not. Plantations began to expand, and soon more labor was needed, sparking the Trans-Atlantic Slave Trade, where a majority of West African slaves ended up on plantations in the Caribbean. To this day, those slaves' *obeah* belief system survives on nearly every West Indian island in some form. Beyond human occupance, as landholdings expanded rapidly, island landscapes changed: Previously forested lands gave way to sugar, cotton, tobacco, and indigo fields, exposing precious (and often nutrient-rich) volcanic soils to the elements. Insect-infested lagoons were dredged, changing coastlines and depositional processes. Where encampments began, forts were built to protect interests, most using local stone and local limestone mortar, some of which still stand today.

Through the centuries after European "discovery," strong cash crop economies developed, necessitating the need for trade agreements and treaties, all while pirates and privateers continued to make some of the West Indies' small coves and ports infamous. As technology developed, so did economies and politics. Some islands sought (and subsequently won) independence from their colonial power—sometimes easily, but more often than not, with arduous struggle—while others remained part of the Commonwealth or colonial power. Toponymic remnants from these time periods can still be found throughout the Lesser Antilles. Still, it took until the latter part of the twentieth century (1960s–1980s) for islands to gain their independence, with some still struggling for their autonomy today (e.g., St. Kitts and Nevis) while other islands stay part of the original colonial power (e.g., Martinique, for example, where the official currency is the euro). Outside interferences, including non-colonial interests, have also influenced Lesser Antillean development. The infamous *Operation Urgent Fury* in 1983 led by American forces on the British Commonwealth Nation of Grenada, for example, highlighted perceived political turmoil of the region. While other industries occur—agricultural export, some fertilizer and salt production, and petroleum in the case of Trinidad and Tobago and the ABCs—the most common among the Lesser Antilles continues to be tourism, or at least the potential for it.

The Lesser Antilles of today represent a lively collection of economies, politics, cultures, and geomorphology. To showcase these vibrant characteristics, following this *Introduction*, the volume includes a general overview of regional tectonics and geology, landform evolution/geomorphology, and basic climate/climatic geomorphology. The tectonics and geomorphology discussions span from Eocene to the Quaternary (when island formation along the Lesser Antilles Arc began), while the climate component encompasses recent history to present. Then, this volume continues with separate and in-depth chapters on landscapes and landforms associated with individual islands (e.g., Dominica) or island sets (e.g., the Virgin Islands). Each chapter also contains two specific, yet geomorphologically applicable topics, especially for the Lesser Antilles: *Heritage and Tourism* and *Hazards*. A heritage and tourism component is included because, not unlike other regions of the world, each island has its own struggles with governmental regulations when it comes to tourism, and much of the tourism centers around geomorphic features and phenomena ("geotourism," e.g., beaches, reefs, rainforests, mountains, and even rock decay; see Dowling and Newsome 2006 for an overview), while also being (potentially) influenced by hazards. The Lesser Antilles are plagued not just by hurricanes and their associated risks, but also by volcanics, earthquakes, fire, landslides, and, interestingly, fire and drought. And each of these events—sometimes in tandem with others, sometimes solo—often plays a role in changing island geomorphology. Every chapter includes, at a minimum, the following topics:

- *Introduction*. A basic overview of the chapter's main points.
- *Setting*. Or sometimes being listed as "Geologic Setting," this section remains a short and concise overview of the island's or island set's formation 9 and sometimes geochronology), often including basic climate and other related information.
- *Landforms*. A discussion of major and minor landforms, including notable interior (e.g., mountain), coastal (e.g., bays, beaches), and offshore landforms (e.g., coral reefs), and sometimes geochronology.
- *Landscape*. Sometimes listed in specific chapters as "Environmental History and Landscape Change" or "Landscape and History", this section is meant to represent a bridge between geomorphology and culture. This often includes anthropogeomorphologic analyses or archeogeomorphologic discussions, for example, including both past and present peoples' histories and their link with the geomorphology.
- *Heritage and Tourism*. As a (the) main economic resource on each of the Lesser Antilles islands is usually tourism, this subsection represents a mostly concise review of impacts that heritage resources management and tourism have on the larger (geomorphic) landscape.
- *Hazards*. A review of past hazards and their geomorphic impacts, as well as evaluation of potential and future hazards, and what they could mean for the island's or island sets' (geomorphic) future.
- *Conclusion*. A concise review of the previous six topics, noting any potential future outlooks for the island or island set from a geomorphic point of view.

Finally, it should be noted that writing a chapter on a Caribbean island's landforms *and* landscapes remains a delicate endeavor. Some islands have adequate information to pen a chapter (though not necessarily in English), others less so. Indeed, the region remains rich with research opportunities, but with so much to do, authoring a chapter for an edited volume often takes a backseat to primary research agendas. Additionally, the author(s) must be part geomorphologist, part anthropologist, part political scientist, part historian, part hazard specialist—and more—and then be able to weave each together coherently. Chapter authors have striven for a balance between landforms and landscapes, although at times, one may seem to be heavier than the other. Still, when considering how little (current) research has been conducted throughout the Lesser Antilles compared to other locales, the fact that some semblance of balance can even exist remains, perhaps, a minor miracle. Sometimes finding a balance necessitates coauthors, while other times a person tackled "their" island solo, and this complex ability should not be ignored, nor should an author's claim that "their" island is the most beautiful, or most pristine, or most unspoiled, or has the best geomorphology in the Caribbean. These seemingly boastful comments are deemed allowable for this volume because the editor believes everyone should be afforded an opportunity to promote their passion for place. After being presented with evidence provided by these regional experts, the reader is invited to decide for themselves which island—which "… visually stunning …" and "… great landscape …" (Goudie 2002, 65)—they find most intriguing in this small, oft-understudied World Geomorphological Landscape.

1.2 A Few Notes About this Volume

1.2.1 Lesser Antilles Toponyms

Throughout the Lesser Antilles, colonialism shows itself most readily in place names (toponymy). The presence of local place names, usually never officially recorded or, at best, inaccurately recorded by the original scribe, further confuses Lesser Antillean toponymy. Often times, even with the best intentions, mistakes happened and, whether from misinterpretation of a local word, creolization, or faulty record keeping, the misspelling spread, sometimes making its way into vernacular. Even on islands that are still today an overseas territory of their once colonial power, toponymy can reveal much about an island's historical occupance. One common aspect rests in naming convention differences between European nations. The French, for example, tended to favor naming places based on physical features, and many of these survive throughout the Lesser Antilles: *Anse*, *La Soufriére*, *Morne*, and *Pitons*, for example. British colonists, on the other hand, favored naming places after famous leaders and people, giving the Lesser Antilles an abundance of George's, Mark's, and John's, as well as others. Similar linguistic influences can be found throughout the Caribbean for (former) Spanish, Dutch, and even Swedish colonies. That said, while some place names might be referred to differently on official records, this volume strives to offer the most recognized names associated with locations on each island, regardless of colonial influence, as these most often represent the local vernacular/convention.

1.2.2 Lesser Antilles Historical Accuracy

Most dating of pre-Columbian (i.e., pre-European contact) Lesser Antillean artifacts and occupational periods remain contextual. In the Lesser Antilles specifically, not all scientists agree on ages of rock art (petroglyphs) and other archaeological artifacts. Discrepancies arise because no precise technique has yet been devised to establish definitive dating in tropical regions, and most Amerindians left no (decipherable) written record. Each chapter in this volume, however, follows current research trends, with any deviation being specifically noted in that chapter. Similarly, the term *Amerindian* is used exclusively to refer to aboriginal/native peoples of the West Indies—those inhabitants prior to Columbus' "discovery"—as opposed to the (mostly) West African slave descendants that currently inhabit most islands, often referred to as *Afro-Caribbean* in the literature to denote the mixing between them and the original Amerindian population.

1.2.3 Lesser Antilles References

The reader may notice throughout this volume that some citations come from the internet (websites) and trade publications. Additionally, some chapters may continually reference only the same handful of peer-reviewed articles and/or books. While this is perhaps not normal academic practice, it remains warranted for this volume. It seems that in many cases throughout the Lesser Antilles, once a piece of (geomorphic) research has been completed, no one else continues or updates it, leaving many older references. Indeed, being a mostly under-researched region (the smaller islands in particular) means much of the data comes from either firsthand research experiences of the chapter author(s) themselves, a small cadre of researchers (sometimes several decades old and sometimes in a non-English language), and touristic paraphernalia—including Ministry of Tourism websites, guidebooks (online), and white papers. These types of references should not be seen as diminishing the quality of research presented in this volume, but instead should be taken as a call for more (field-based) academic research to be conducted in the region. Every effort has been made to verify the accuracy of Web-based references by the editor when peer-reviewed literature was unavailable.

1.2.4 Cartographers' Note

Maps in this volume are for informational and reference purposes only and are not prepared for legal, engineering, navigational, or surveying endeavors. The cartographic products herein have been created with the highest degree of accuracy possible, and the cartographer, editors, chapter authors, or publisher cannot be held responsible for any damages from omissions or misuse of maps contained in this volume. Depiction of boundaries is non-authoritative, and any misrepresentation of coastlines, features, cities, towns, etc., is not done with malicious intent, but most likely due to a paucity in reliable data or old information. For example, some islands may appear to be more topographically complex than their surrounding islands (e.g., Dominica), but this is not necessarily the case. These visual differences represent discrepancies among the precision of data available for each individual island/island set. The appearance of commercial establishments featured on these maps does not imply endorsement of them by either the cartographer, editors, chapter authors, or publisher, but simply reflects important locational features. All maps are copyrighted by the respective cartographer, and reproduction without legal consent may result in prosecution.

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2 Geologic and Tectonic Background of the Lesser Antilles

W. Travis Garmon, Casey D. Allen and Kaelin M. Groom

Abstract

A case study of the geomorphology of the Lesser Antilles island arc reveals, in its entirety, the influence of numerous geological forces and events. Most notably, these include the products of plate tectonics, volcanism, and carbonate marine reef formation. North of Dominica the island arc splits into two separate chains. The easternmost archipelago of these chains is largely comprised of extinct volcanoes that have since become the core of carbonate reef growth. The westernmost archipelago of the island arc and the southern half of the overall Lesser Antilles are still active volcanic complexes formed due to partial melting of subducting oceanic crust. Orogenic uplift due to transform plate tectonics and thrust faulting is observable in the southern Leeward Antilles.

Keywords

Caribbean • Lesser Antilles • Island arc • Tectonics • Archipelago

2.1 Introduction

The variety of distinctive geologic formations, from sedimentary to volcanic, separate the Lesser Antilles island arc into three distinctive island groups: the Leeward Islands, the Windward Islands, and the Leeward Antilles Islands (Fig. 2.1). Encompassing the northern section of the arc, the major Leeward Islands (and island sets) tend to be smaller in size than their Windward counterparts and include—from northwest to southeast—the US and British Virgin Islands, Anguilla, Saint Martin, Saint Barthelemy, Saba, Saint Eustatius, Saint Kitts, Nevis, Barbuda, Antigua, Montserrat, and Guadeloupe. Depending on sources, Dominica can be classified as either a Leeward or Windward Island. This volume follows the more recent literature that treats Dominica as the northernmost Windward Island—those larger West Indian islands that contain the southern arm of the Lesser Antilles island arc—followed in a southerly direction by Martinique, Saint Lucia, Barbados, Saint Vincent and the Grenadines, Grenada, Tobago, and Trinidad. Though not usually associated with the Lesser Antilles specifically, the Leeward Antilles—Aruba, Curaçao, and Bonaire off the northern coast of Venezuela (often called the "ABC islands" or "ABCs")—remain spatially and geologically distinct from the rest of the Lesser Antilles. Still, they are included in this volume for ease of reference, because no other volume contains an overarching review of their landscapes and landforms.

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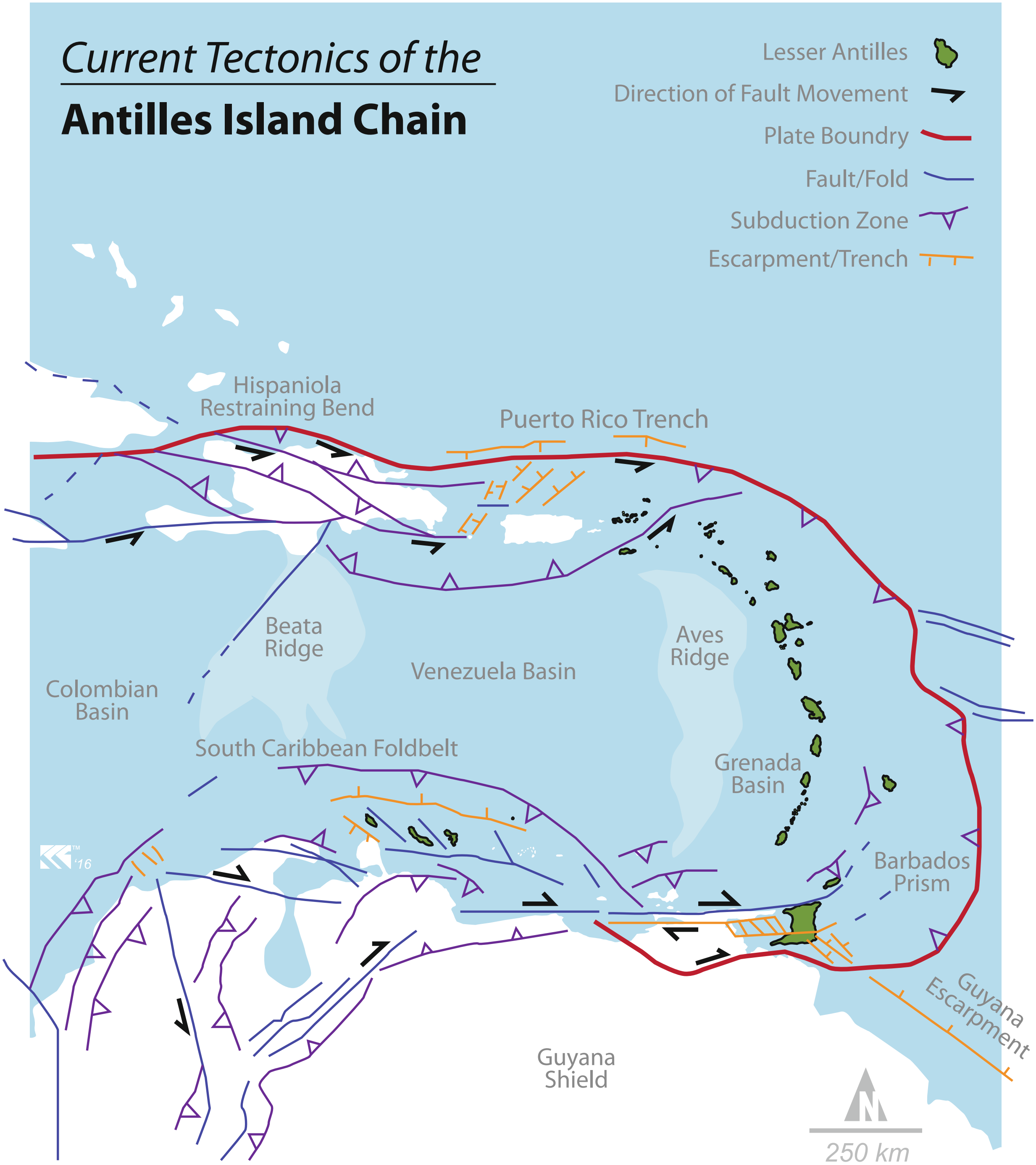

Fig. 2.1 Tectonics of the Antilles Island Chain, illustrating plate boundaries and fault zones surrounding and within the Caribbean Plate. Subduction zones along the eastern and northeastern margins have led to volcanism, which produced the Windward Islands, the inner arc of the Leeward Islands, and the cores of the outer arc of the Leeward Islands. Transform boundaries and folding along the southern extent of the Caribbean Plate have uplifted the sedimentary units that comprise the Leeward Antilles. The directions of plate movement and prominent tectonic features in the region in relation to the Lesser Antilles shown in green. Cartography by K.M. Groom

2.2 Geologic History and Formation of the Lesser Antilles

2.2.1 Tectonics of the Atlantic Basin and Caribbean Sea

The formation of the Atlantic Basin began with the separation of the supercontinent Pangaea roughly 175 million years ago during the Jurassic. Rifting between the former continents of Laurasia (modern-day Europe, Asia, Greenland, and North America) and Gondwana (modern-day Africa, South America, Australia, Antarctica, and India), initiated the formation of the northern Atlantic Ocean. At the turn of the Cretaceous, roughly 25 million years later, Gondwana began to separate into the continents we recognize today, forming the southern Atlantic. These two different rifting events, each forming and continuing to widen the Atlantic Ocean, are centered on the submarine mountain chain known as the Mid-Atlantic Ridge—the divergent boundary between the African and American plates. As these plates move apart, decompression melting in the upper mantle produces magma flows which cool to form basalt and gabbro, leading to new oceanic crust. Subduction of the Caribbean Plate under the South American Plate began around 80 million years ago during the Late Cretaceous (Bouysse 1988; Mann 1999; Macdonald et al. 2000), and 40 million years ago, volcanism began because of that subduction (Fig. 2.2; see also Smith et al. 1980; Bouysse 1988; Kerr et al. 1996; Kerr et al. 2003).

Oceanic crust increases in both thickness and density with age. As the plate edges drift further from the divergent zone from which they were produced, they cool, and additional mantle material is accreted onto the bottom of the plate as formerly plastic mantle rocks become more rigid due to a drop in temperature. Furthermore, a steady "rain" of pelagic sediments within the ocean water column falls onto submerged crust, leading to the subaqueous formation of layers of marine shales, limestones, and sandstones. The longer an oceanic plate exists, the thicker the buildup of sedimentary rock, and the heavier the plate becomes. Ultimately, older oceanic plate will be sufficiently heavier and denser than bordering younger oceanic or continental plates, initiating subduction of the older plate. For these reasons, most oceanic crust is relatively young compared to continental crust, which does not subduct except in very rare circumstances. The eastern boundary of Caribbean Plate, also known as the Lesser Antilles subduction zone, is one of these rare instances where the largely continental South American Plate is subducting under the mostly oceanic Caribbean Plate, initiating volcanism and tectonic uplift.

Additional plate boundaries and interactions in the region include several transform boundaries, when two plates slide

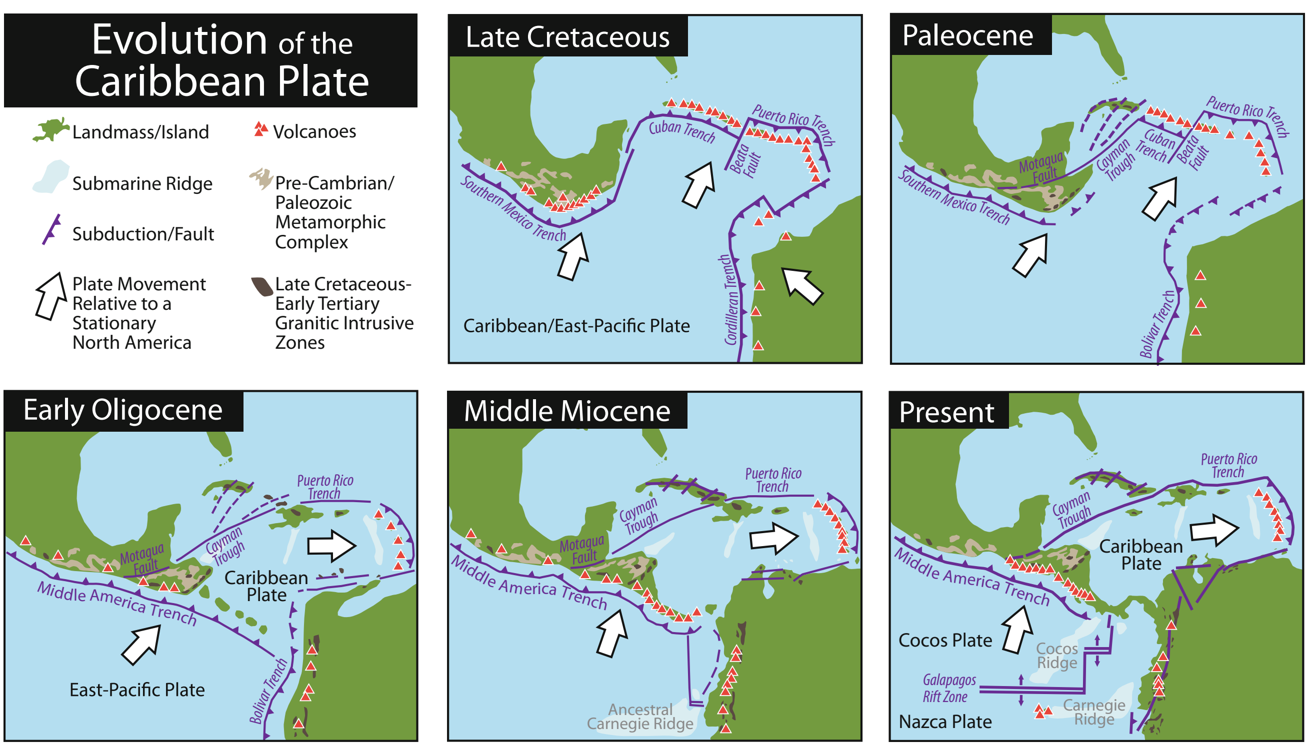

Fig. 2.2 Caribbean Plate Tectonic Evolution, including the Caribbean Plate's subduction under the South American Plate, beginning around 80 million years ago. Figure by K.M. Groom, modified from Malfait and Dinkleman 1972

past one another in opposite directions. Similar to (and often producing) strike-slip faults, these boundaries rarely produce orogenic events without additional deformational components. Brecciation and fracturing directly on the plate edge is a common feature at these locales. California's San Andreas Fault is a famous example of this sort of tectonic plate boundary, where the northward motion of the Pacific Plate relative to the North American Plate results in a massive right-lateral strike-slip fault. The relative motion of the adjoining plates defines left-lateral and right-lateral strike-slip faults. A similar mechanism to the San Andreas exists at multiple points throughout the Caribbean (Fig. 2.3; see also Edgar et al. 1971; Malfait and Dinkelman 1972). The southern margin of the Caribbean Plate expresses a right-lateral transform component relative to the South American Plate (the Caribbean Plate is moving eastward, relative to both the North and South American plates). In concert with subduction and transformational motion, slight compression along the southern margin has resulted in folding and thrust (steep reverse) faulting—yielding minor orogenic uplift to expose some of the Leeward Antilles, Barbados, Trinidad, and Tobago, along with many smaller islands (Fig. 2.1; see also Ave-Lallemant and Sisson 2005; Levander et al. 2006; Van der Lelij et al. 2007).

2.2.2 Lesser Antillean Volcanism

The Leeward Islands contain two distinct volcanic island arcs of different ages, resulting from a slight shift in plate interactions. The outer arc is the easternmost archipelago and, at 40 million years old, is the older of the two. This arc consists of extinct volcanic cores that have since decayed and developed marine reefs (Christman 1953; Malfait and Dinkelman 1972; Bouysse 1988; Bouysse et al. 1990; Marshall et al. 1997; Macdonald et al. 2000; Van der Lelij et al. 2007). The younger (20 million years) inner arc is still primarily active, marking the current site of the South American Plate and Caribbean Plate subduction zone (Malfait and Dinkelman 1972; Smith et al. 1980; Bouysse 1988; Bouysse et al. 1990; Macdonald et al. 2000; Robool and Smith 2004; García-Casco et al. 2011). Southward from Dominica, both the outer and inner arcs are superimposed, and many of the volcanoes are still active in the Windward Islands.

The geochemistry of volcanic eruptions (metal-rich effusive versus silica-rich explosive) determines the size and shape of the volcano itself. Effusive mafic eruptions result in shield volcanoes, which have a large surface and gentle slope due to the lower viscosity of mafic lavas. As the

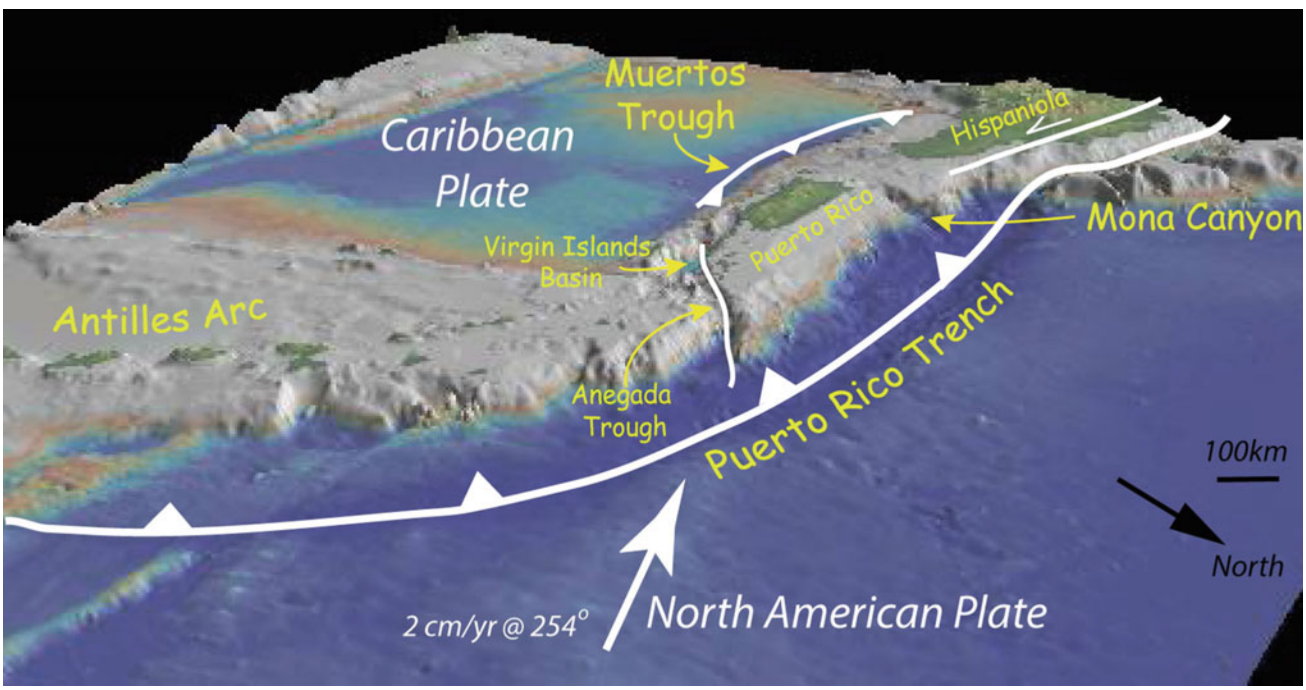

Fig. 2.3 A three-dimensional view of the Puerto Rico Trench (the Antilles Arc runs along its ridge). The northern boundary of the Caribbean Plate exhibits left-lateral strike-slip faulting along the North American Plate border to Puerto Rico, where the boundary transitions into a combination of transform and convergent (subduction) zones form the Puerto Rico Trench. Image courtesy of NOAA (http://oceanexplorer.noaa.gov/okeanos/explorations/ex1502/background/geology/welcome.html)

mafic lava is erupted, it can flow somewhat freely and thus spreads out in large, thin layers before cooling. Alternatively, high-viscosity felsic and intermediate lavas are more prone to the formation of stratovolcanoes, which have much steeper topography. Because of the felsic lava's high resistance to flow, the lava cools and solidifies before it has a chance to spread over a large geographical area. After multiple eruptions from the same vent, the igneous rocks form a steep mountain, and subsequent erupted material creeps down the sides of the volcano, forming igneous strata from each non-explosive event. Explosive events generate volcanic ash–molten rock and dust blasted into the atmosphere. Gravity soon overcomes the momentum of the erupted material, and the ash cloud collapses back to the surface of the Earth. When the collapse occurs quickly, it produces pyroclastic flows, which are effectively rivers of rapidly flowing superheated ash—an occurrence common in much of the Lesser Antilles (Sigurdsson et al. 1980). Occasionally, following a sudden purge of material within the magma chamber, the overlying volcanic complex can collapse in itself leaving a crater-like feature at the surface known as a caldera. Calderas are common on several islands throughout the Lesser Antilles, most notably on the isle of Dominica.

Nineteen active volcanic complexes are subaerially exposed throughout the Lesser Antilles, along with one active submarine volcano. The isle of Dominica is host to nine currently active volcanoes and was formed as multiple stratovolcanoes and calderas grew and overlapped one another. Volcanic complexes specific to Dominica include Morne Au Diable, Morne Diablotins, Morne Trois Pitons, Wotten Waven Caldera, Valley of Desolation, Watt Mountain, Morne Anglais, Grande Soufriere Hills, and Morne Plat Pays. Although all of the Dominican volcanoes are considered active and experience periodic minor eruptions, a substantial eruption has not been recorded on the island since Europeans first began exploring the Caribbean in the 1600s. Moving further south into the Windward Islands, active volcanoes are found on Martinique (Mt. Pelee), St. Lucia (Qualibou), St. Vincent (Soufriere), and Grenada (Mt. St. Catherine); however again, eruptions of these are rare occurrence, with geothermal activity (such as hot springs) being a main feature among them. An underwater active volcano named Kick 'em Jenny, north of the Grenada coast, has shown sign of rumbling as recent as August 2015.

Leeward Islands within the inner arc region are predominantly covered in Quaternary and Tertiary volcanic deposits. Most isles throughout the region are amalgamations of multiple stratovolcanoes. The compositions of most igneous rocks throughout the area range from mafic basalt to intermediate andesite (Kerr et al. 1996; Sinton et al. 1998; Macdonald et al. 2000; Robool and Smith 2004; García-Casco et al. 2011). Dominant minerals within the andesite regimes are biotite- and sodium-rich feldspars; with olivine, pyroxene, amphibole, and both sodium- and calcium-rich feldspars dominating the basaltic flows (Kerr et al. 1996; Robool and Smith 2004). The volcanic islands are littered with welded tuffs, pumice, tephra, and breccias, which are the product of pyroclastic flows typical of explosive eruptions (Kerr et al. 1996; Robool and Smith 2004). Basalt clasts (pieces of previously solidified basaltic lava flows preserved in a more recent flow that were not re-assimilated as melt) are noted within several of the non-explosive but still high-viscosity andesite eruptions, suggesting that intrusion of basaltic magma into andesitic magma chambers instigated several recent eruptions in the northern islands (Kerr et al. 1996; Robool and Smith 2004; Kerr and Tarney 2005; García-Casco et al. 2011). The andesitic chambers are proposed to have formed from the combined melt of oceanic basalt and gabbro with melted marine sediments during the subduction of the South American Plate (Malfait and Dinkelman 1972; Kerr et al. 1996; Robool and Smith 2004). Multiple dipping limestone beds of Oligocene age also outcrop on several of the inner arc islands, though were likely uplifted by a younger volcanic dome formation as opposed to a tectonic orogeny (Bouysse 1988; Mann 1999; Robool and Smith 2004; García-Casco et al. 2011).

The now-extinct outer arc of the Leeward Islands was first formed through Eocene volcanism and later modified by marine sedimentation from the Eocene to modern day. The limestones throughout the region require a subaqueous setting to be deposited, meaning the deposits are only formed in areas that were below sea level during their corresponding epoch of formation. Many forms of marine life precipitate an aragonite or calcite (both of which are polymorphs of calcium carbonate) shell throughout their life span. Upon their deaths, these shells fall to the bottom of the marine water column and accumulate on the seafloor, building layers of biogenic carbonate sediments which are later compacted and lithified to form limestone units. Coral and bryozoan reefs function in much the same manner—precipitating carbonate skeletons on existing structures. As these creatures die, they are covered in the carbonate frames of new reef-forming creatures, and the structure grows both outward and upward, provided it remains below sea level.

2.2.3 Lesser Antillean Unconformities

If a landscape transitions from subaqueous to subaerial, through uplift or sea-level change, marine carbonates can no longer be deposited. Once deposition of sediments ceases, a shift to an erosion-dominated environment often occurs, resulting in the removal of lithologic material. These periods of non-deposition and/or erosion are geologically represented by unconformities, where no record of natural events for a length of time is preserved in the stratigraphic column. Three primary types of unconformities exist, all of which are present in the Lesser Antilles. Nonconformities exist at the boundary between igneous and sedimentary rocks, such as those seen between the marine sediments and volcanic ash flows of the inner arc Leeward Islands. Disconformities describe gaps in rock deposition between relatively undeformed flat-lying sediments, observable on the sediment-dominated outer arc of the Leeward Islands and throughout the orogenically uplifted Leeward Antilles. Angular unconformities occur between flat-lying and inclined beds, in which a bed is uplifted/tilted, partially eroded, and then additional sediments are deposited in flat-lying strata above the remnants of the inclined beds, much like the volcanically inclined limestone beds on the isle of St. Eustatius.

Three regional unconformities are present in the Lesser Antilles. The first occurs between the Oligocene and Miocene volcanic and limestone deposits, the second at about 5.4 million years ago between Miocene and Pliocene volcanism, and the most recent at about 2.8 million years ago between the Pliocene and Quaternary volcanic ash flows. The earliest unconformity is most evident in the southern Windward Islands and the outer arc of the Leeward Islands, for example, the exposures on Antigua and Trinidad. The islands of Grenada and Tobago display examples of the Miocene–Pliocene unconformity in the Windward Islands, and the most recent Pliocene–Quaternary unconformity is observable in both the Windward Islands and the inner arc of the Leeward Islands at places such as Saba and Barbuda due to the active volcanism throughout both regions (Smith et al. 1980; Robool and Smith 2004). Fossil evidence suggests that these unconformities correspond with periods of relative sea-level drop in the region, which produced land bridges linking the island chain to the Greater Antilles to the north and to South America to the south (Marshall et al. 1997). While shifts in tectonic motion can cause changes in relative sea level, it is more likely the conditions necessary for these Lesser Antilles unconformities were the result of global climate change. Widespread evidence suggests periods when global sea levels have fallen in response to cooler global climates sequestering large volumes of water in ice at the poles as well as both alpine and continental glaciers (Marshall et al. 1997).

2.2.4 Leeward Antilles

Regionally and geomorphologically distinct, the Leeward Antilles—not to be confused with the Leeward Islands of the Lesser Antilles—are composed of the "ABCs" and several smaller islands owned by Venezuela and stretch along the southern extent of the Caribbean Plate just north of the South American coast. Unlike many of the Leeward and Windward Islands, the Leeward Antilles lack modern volcanism and consist of predominantly orogenically uplifted limestones (Levander et al. 2006; Van der Lelij et al. 2007). Transform faulting, reverse faulting, and minor subduction at the boundary with the South American Plate caused fold/thrust processes in portions of the South American Plate's continental shelf, bringing blocks of the seafloor upward to intersect the ocean's surface (Edgar et al. 1971; Levander et al. 2006; Van der Lelij et al. 2007; Viruete et al. 2008). Most of the islands within this region are merely exposed reefs and sandbars, although Bonaire is notable for being a reef uplifted due to volcanic activity (Van der Lelij et al. 2007). Exhumation of the Leeward Antilles was not a single geochronologically constrained event, as multiple uplifting periods brought the crustal blocks upward during the Cretaceous period, Paleocene, and Eocene epochs (Bouysse 1988; Van der Lelij et al. 2007).

2.3 A Brief Overview of Lesser Antillean Climate

Bounding the Caribbean Sea, and located roughly between latitudes of 10 and 19°N, the climate zone of the Lesser Antilles is easily identifiable as tropical. Although average rainfall varies from island to island, most precipitation throughout the region occurs during the latter half of the year—forming distinctive a "wet season." Year-round temperatures fluctuate very little, with approximate averages ranging from low of 22 °C to high of 29 °C (Chenoweth and Divine 2008). The summer and autumn hurricane season also brings substantial rainfall as hurricanes, tropical storms, and tropical depressions make landfall over the island arc. Though these data for the Lesser Antilles *as a region* are difficult to find, Jury et al. (2007) note that from the Virgin Islands to Barbados at least, a dominant midsummer to autumnal precipitation pattern generally occurs. Within the Lesser Antilles Arc, and including the ABCs, precipitation—and therefore climate—remained variable. For example, orographic uplift on the taller volcanic islands produces rainfall events as lifting unsaturated air parcels cool at the dry adiabatic lapse rate until saturation is achieved, inducing cloud formation and precipitation (Chenoweth and Divine 2008). Annual variations in subregional precipitation and storm frequency/intensity in the Lesser Antilles are also influenced by larger regional oscillations such as the North Atlantic Oscillation (NAO) and the El Niño Sothern Oscillation (ENSO), and even more so in the southern latitudes (Jury et al. 2007). For more specific information regarding climate in the Lesser Antilles, each subsequent chapter contains a basic climatological overview and, where significant, the climatic geomorphology is also discussed.

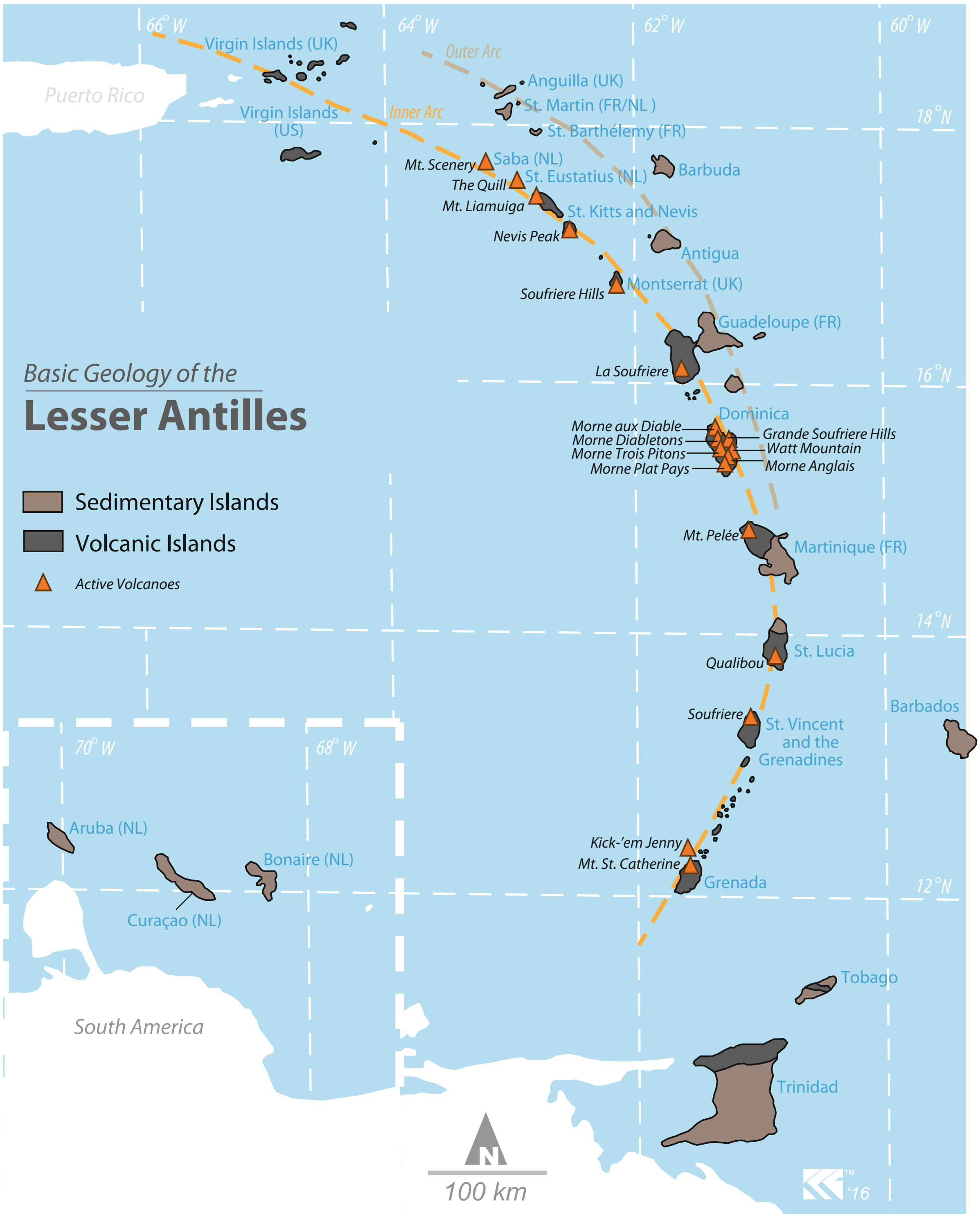

Fig. 2.4 Basic geology of the Lesser Antilles, illustrating dominant lithologies across the island chain. The outer Leeward Islands (outer arc) are the dominantly sedimentary islands of the northernmost arc, and the inner Leeward Islands (inner arc) are the dominantly igneous islands of the northernmost arc, converging at Dominica. Southward from Dominica, the Windward Islands have outcroppings of both igneous and sedimentary units. The Leeward Antilles, represented by the "ABC Islands," are composed of sedimentary units uplifted during orogenic events along the boundary between the Caribbean and South American plates. Cartography by K.M. Groom

Overall, Lesser Antillean climate may be somewhat consistent now, but other research suggests this may not always be the case—nor has it been in the past. For example, Hodell et al. (1991) performed a paleoclimatology study of the Caribbean using oxygen isotopes from sediment cores taken from Lake Miragoane, Haiti, and identified several changes in regional climate. Their study revealed a drier Caribbean climate from 10,500 to 10,000 years ago, with a shift to a wetter climate from 10,000 to 7000 years ago as the Earth transitioned from a glacial to interglacial period and sea levels rose. Another shift to a drier climatological regime occurred 3200 years ago. The authors of the study highlight the correspondence of their findings with similar studies performed across the globe that coincide with Milankovitch Cycles—periodic shifts in Earth's orbital and rotational properties caused by gravitational interactions with other objects in our solar system commonly attributed to affecting global climate patterns. Conversely, future climate model predictions, such as those presented by Hall et al. (2013) and Campbell et al. (2011), predict a general decrease in precipitation and regional drying in the coming centuries more likely due to anthropogenic forcing and not natural cycles.

2.4 Summary

Ultimately, the formation of the Lesser Antilles island arc is the result of several significant geomorphologic events spanning millions of years. Following the divergence of the supercontinent Pangaea in the Jurassic, the Mid-Atlantic Ridge produced new oceanic crust on the margins of what would become North America, South American, and Africa. As the plates continued to diverge and a "new" oceanic crust continued to be produced, the older crust accumulated sediments from above and mantle material from below as the mafic crust cooled. During the Cretaceous and Tertiary, three periods of convergence between the northern margin of the South American and the Caribbean plates resulted in the thrust-fault-driven uplift of the Bonaire Block, which served as the igneous basement cores of what would become the Leeward Antilles on both plates, even as carbonate reefs grew on the now shallow basement (Malfait and Dinkelman 1972; Smith et al. 1980; Bouysse 1988; Bouysse et al. 1990; Ave-Lallemant and Sisson 2005; Kerr and Tarney 2005; García-Casco et al. 2011). 40 million years ago, that increased weight and density resulted in the onset of subduction of the South American Plate beneath the Caribbean Plate. This process resulted in Tertiary-aged volcanism, which gave rise to the Windward Islands and the outer arc of the Leeward Islands, both of which are products of intermediate and mafic stratovolcanic activity. The subsequent exposed island stratigraphy reveals frequent intermixed explosive and effusive andesitic eruptions, which are represented by vertical ash flows that have expanded laterally onto the island-arc shelves of Trinidad and Tobago (Robool and Smith 2004; Viruete et al. 2008). The outer arc Leeward Islands are dominated by marine limestone reef deposits of Miocene age and younger, which are built upon extinct volcanic cores that ceased erupting 20 million years ago following a shift in subduction angle and leading to the rise of the inner arc of the Leeward Islands (Bouysse 1988; Macdonald et al. 2000; Robool and Smith 2004). Additional volcanism in the Quaternary continued to build upon the Windward Islands and inner arc of the Leeward Islands. Subduction and volcanism resulted in plate thinning to the west of the Lesser Antilles, producing the Grenada Back-arc Basin (Bouysse 1988; Kerr and Tarney 2005; Levander et al. 2006; Van der Lelij et al. 2007; Viruete et al. 2008). At least twenty active volcanic complexes remain along the inner arc and the Windward Islands (one submarine, nineteen subaerially exposed), with carbonate reef formation continuing in the outer arc and Leeward Antilles, except where subaerial exposure and tectonic uplift have exposed dry land (Fig. 2.4).

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The Virgin Islands

3

Kaelin M. Groom, Ryan Sincavage and Frederick Chambers

Abstract

The Virgin Islands, politically divided between the UK and USA, are a widespread island grouping at the northernmost end of the Lesser Antilles. Spanning nearly 135 km^2, the Virgin Islands consist of eight primary islands including (from north to south) Anegada, Virgin Gorda, Jost van Dyke, Tortola, St. Thomas, St. John, Water Island, and St. Croix. In addition to these main islands, several other smaller surrounding islands and cays fall under the jurisdiction of the Virgin Islands. Despite, or perhaps due to, broader spatial distribution, the Virgin Islands host a myriad of unique landscapes and landforms including volcanoes, valleys, reefs, and geologic anomalies.

Keywords

Virgin Islands • Tourism • Geology • Geomorphology

3.1 Introduction

Serving as the gateway into the Lesser Antilles, the Virgin Islands are an unexpectedly diverse island group—geologically, spatially, and politically (Fig. 3.1). Scattered along an active fault boundary, the islands vary from volcanic to sedimentary, with the occasional intrusive outcrop dotting the landscape. The islands range in size from well over 200 km^2 to just barely large enough to breach the ocean surface. Some are more than 65 km from the rest of the island chain. Their key position in the Caribbean has made them a desirable outpost throughout both the colonial and modern times for several larger Western powers including Spain, Denmark, Britain, and the USA. Currently, the Virgin Islands are divided into two distinctly governed nations: the British Virgin Islands (sometimes abbreviated to BVI) to the north/east and the US Virgin Islands (often "US Virgin Islands" or USVI) to the south and west. Having been under some form of British jurisdiction since the late 1600s, the British Virgin Islands include the main Islands of Tortola, Virgin Gorda, Anegada, and Jost van Dyke, along with over 30 smaller islands (Fig. 3.2). The US Virgin Islands include St. Croix, St. Thomas, St. John, and Water Island, plus a collection of smaller surrounding islands (Fig. 3.3). The US Virgin Islands were ruled by the Danish Monarchy during the colonial era and were not sold to the USA until 1917, after century-long negotiations (Dookhan 1974). Although the Virgin Islands only cover 500 km^2 in total landmass—roughly the size of Long Island, NY—they contain remarkably varied landforms, landscapes, tourism ventures, and hazards.

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3.2 Setting

The Virgin Islands lie at the eastern end of the Greater Antilles and northern end of the Lesser Antilles, at the transition from active subduction of the Lesser Antilles Arc

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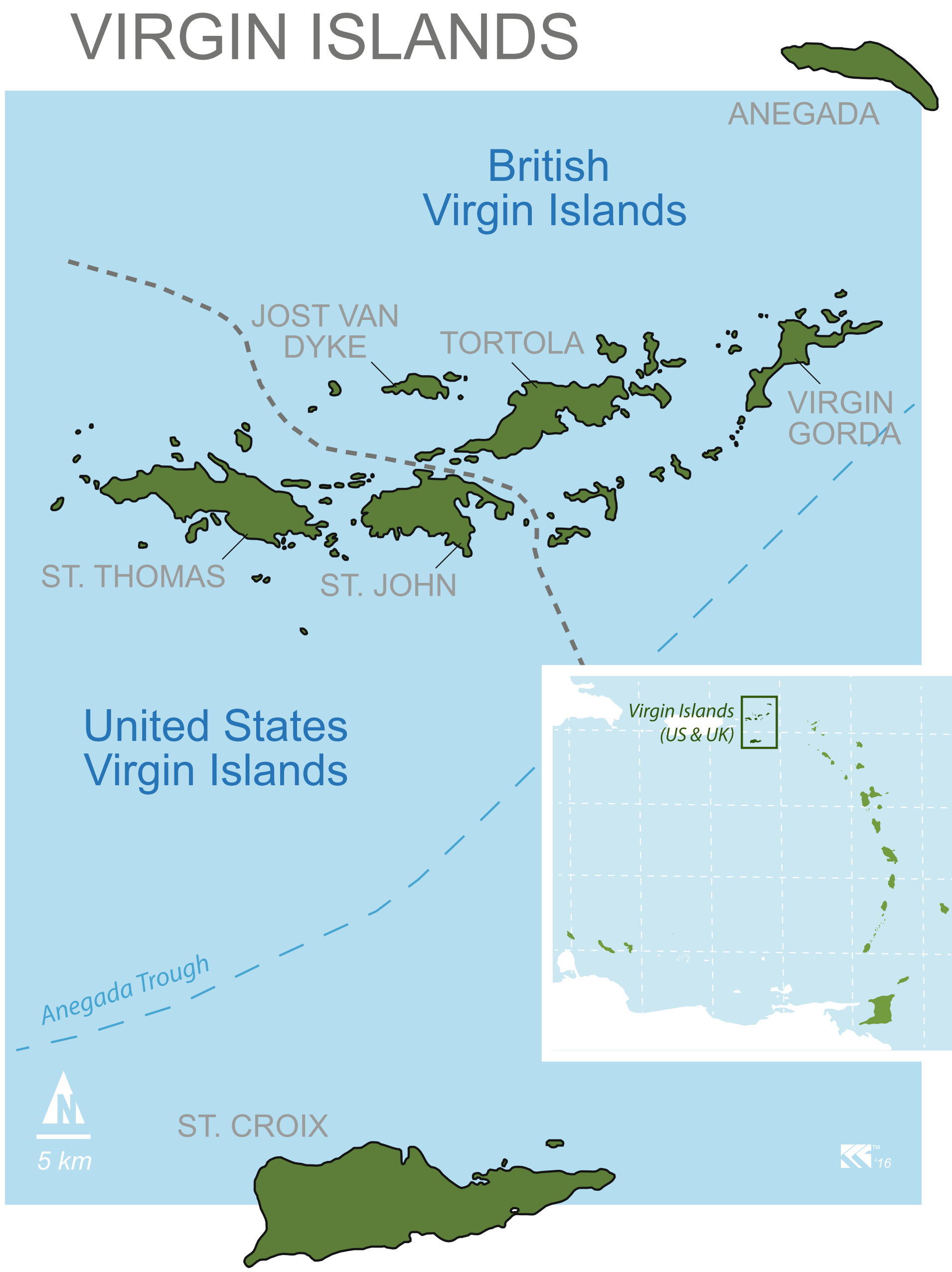

Fig. 3.1 Basic map of the Virgin Islands displaying spatial distribution, political affiliation, capital cities, the distance between St. Croix and Anegada from the rest of the Virgin Islands, as well as the Anegada Trough that separates St. Croix from the other islands. Cartography by K.M. Groom

and the strike-slip tectonic regime associated with the northern boundary of the Caribbean Plate (See Fig. 2.2). As described by Lewis and Draper (1990), the region can be divided into two east-northeast to west-southwest trending tectonic zones separated by the Anegada Trough, a ~50-km-wide extensional zone between the Caribbean Plate and the Puerto Rico-Virgin Islands microplate (Jany et al. 1990). The Northern Zone is essentially a continuation of Puerto Rico and contains the US Virgin Islands of St. Thomas and St. John and the British Virgin Islands of Tortola, Virgin Gorda, and Anegada. Structurally, the area is generally defined by beds dipping steeply to the north, likely associated with post-Eocene regional tectonics and not related to the intrusion of the Virgin Gorda batholith (Helsley 1971; Lewis and Draper 1990). The Southern Zone is geologically distinct from the Northern Zone, consisting of primarily sedimentary rocks (in contrast to the dominance of igneous rocks in the Northern Zone). It consists of a submarine ridge parallel to and south of the Anegada Trough, and the island of St. Croix, which offers the only exposures from which to describe the geology of this zone. Speed et al. (1979) described the structural complexities of St. Croix as having formed over three phases of deformation. In a general sense, the island consists of a graben structure at its center which hosted the accumulation of Tertiary sediments, surrounded on either side by horsts of Cretaceous-aged rocks.

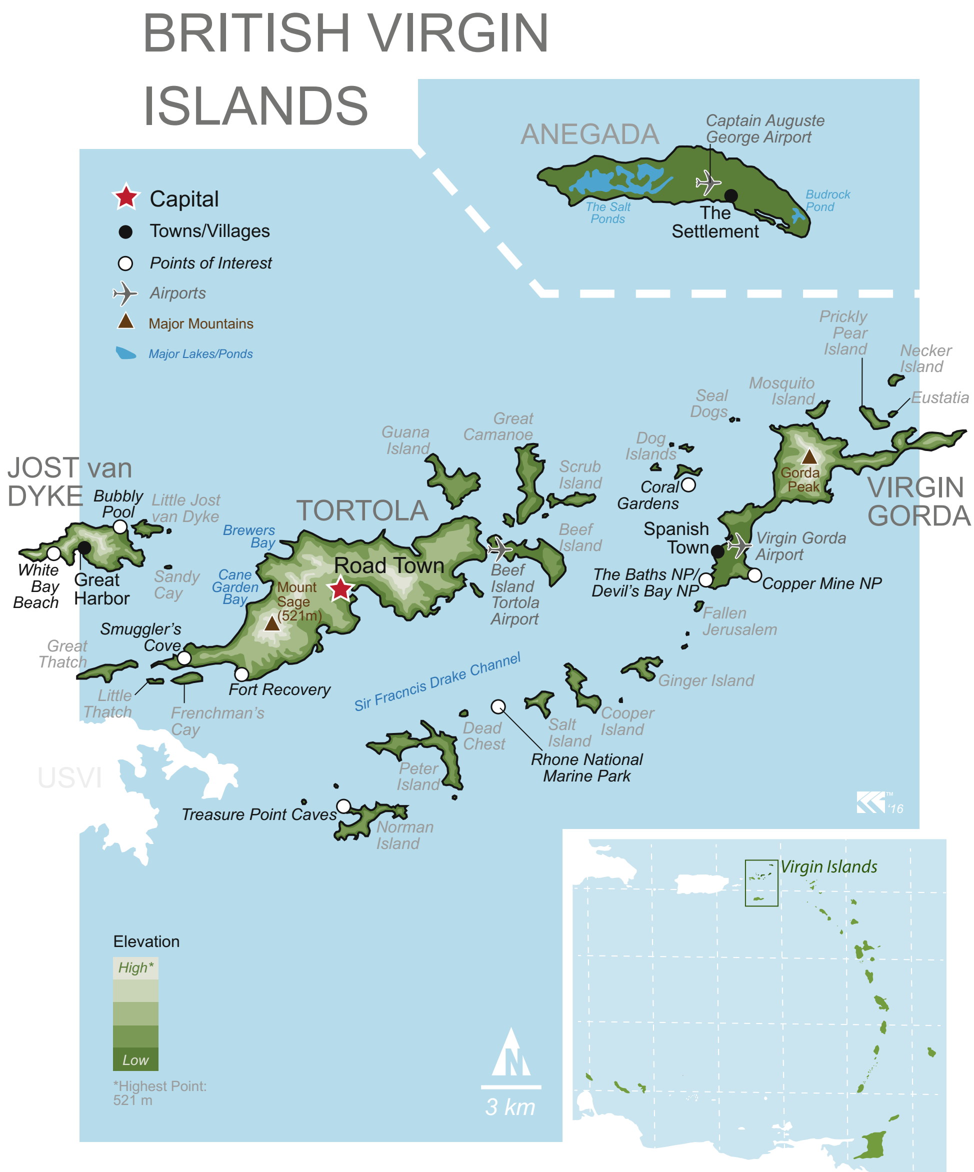

Fig. 3.2 General physiographic map of the primary British Virgin Islands and several of the larger surround islands showing political, physical, and cultural points of interest, as well as proximity to the USVI along the western border. Note the stark physiographic difference between Anegada and other main islands. Be aware that the actual distance between Anegada and the other BVI is larger than displayed on this map. The islands are shown closer to allow for more detailed representation of the islands' features. For a more accurate representation of distance, see Fig. 3.1. Cartography by K.M. Groom

The structure likely formed as the result of east-west extension in the Early Tertiary.

Despite the relatively small areal extent of the Virgin Islands, there are surprisingly diverse landforms along their interiors, coastlines, and offshore. Pioneering efforts at documenting the rich geomorphic variability of the US Virgin Islands were made by Meyerhoff (1926) and Cedarstrom (1941). As evidenced by the difference in tectonic regimes and geology of the Northern and Southern Zones of the Virgin Islands, there are similar differences in the physiography of the two regions. Islands in the Northern Zone are generally higher in elevation, with Mount Sage (521 m) on Tortola and Crown Mountain (473 m) on St. Thomas as the high points of the British and US Virgin Islands, respectively, whereas the high point of St. Croix (Mount Eagle) reaches an elevation of only 354 m. Much of the Northern Zone is contiguous with Puerto Rico as part of a submarine platform that was subaerially exposed during lowstands associated with Pleistocene glaciation (Rankin 2002). In both zones, the climate is considered tropical, but with a fair amount of variability across each individual island. Average precipitation values as high as 1000–1250 mm occur within the wettest areas of the islands,

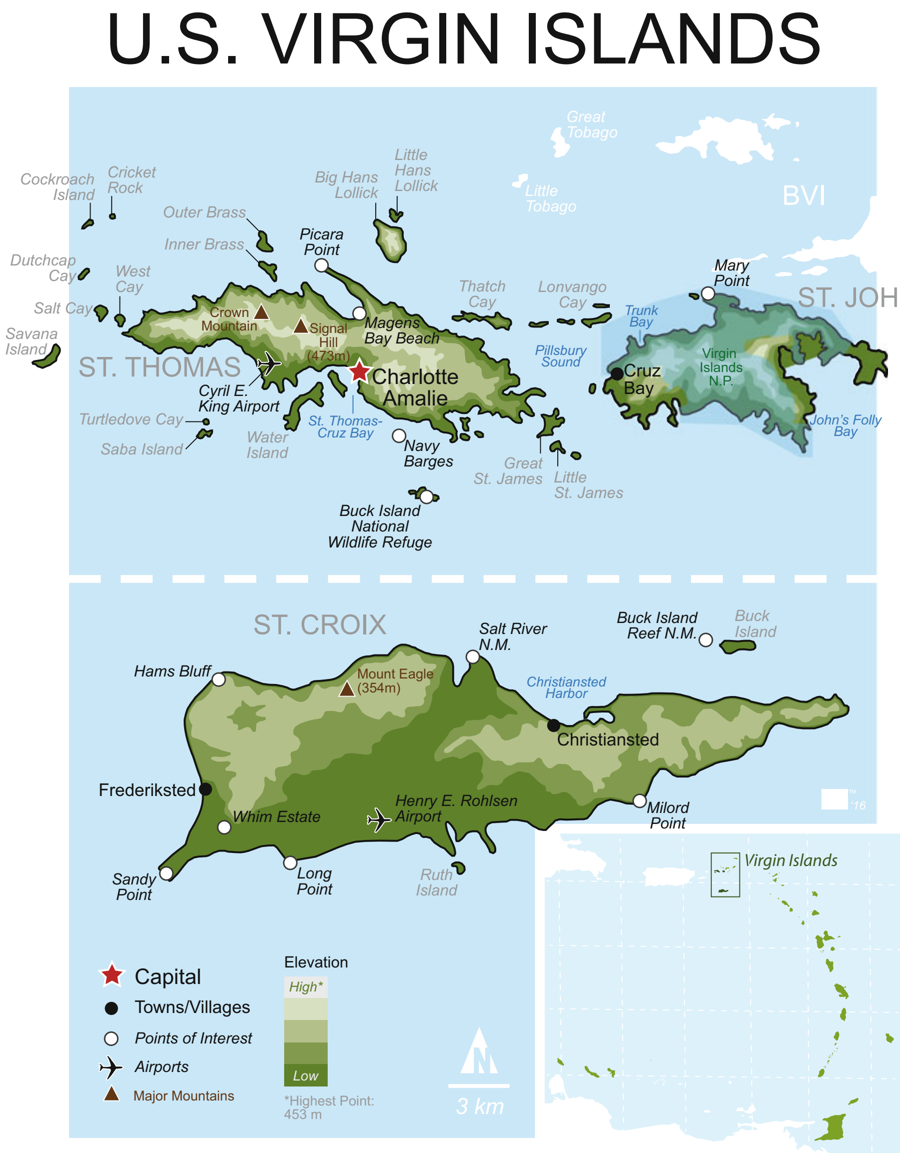

Fig. 3.3 General physiographic map of the primary US Virgin Islands with major surround islands displaying political, physical, and cultural points of interest, as well as proximity to the BVI along the eastern border. Notice the extent of the Virgin Islands National Park on St. John and the wide plains of St. Croix. Be aware that the actual distance between St. Croix and the other USVI is larger than displayed on this map. The islands are shown closer to allow for more detailed representation of the islands' features. For a more accurate representation of distance, see Fig. 3.1. Cartography by K.M. Groom

which in general are found on the western (windward) sides. Vegetation varies with average precipitation, with desert-like scrub brush in the dry regions and dense tropical forests found in the more humid areas (Fig. 3.4).

3.3 Geochronology and Landforms

The diverse geology of the Virgin Islands is reflected in the resultant landforms and geomorphology. In general, the ages of the rock bodies in the Virgin Islands become younger in a north to south direction, with igneous rocks as old as Aptian–Albian (Early Cretaceous) exposed on the US Virgin Islands and Early Miocene sedimentary rocks found on St. Croix. Table 3.1 is a general stratigraphic summary of the Northern and Southern Zones of Virgin Islands, with nomenclature compiled from the work of numerous authors (Donnely 1966; Whetten 1966; Helsley 1971; Rankin 2002).

3.3.1 Geochronology

The oldest rocks in the Northern Zone are the Early Cretaceous Lameshur Volcanic-Intrusive Complex (as named by Rankin 2002), which consist of the Water Island Formation and the Careen Hill Intrusive Suite. This complex is dominated (~80%) by intrusive and extrusive igneous rocks of varying composition, particularly keratophyre (including lava flows, breccias, and dikes), with lesser amounts (~20%) of basalt and gabbro, and minor (1% or less)

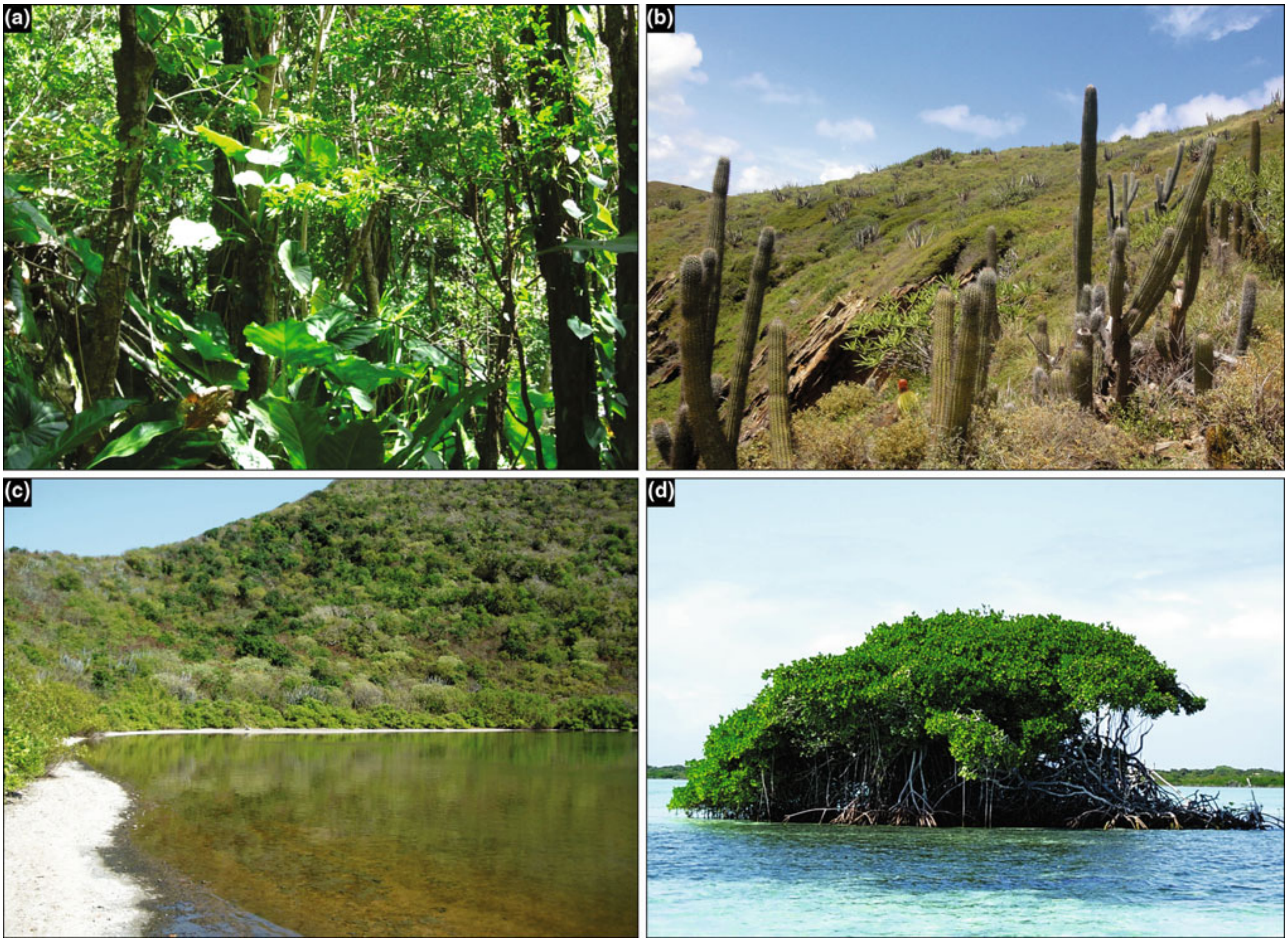

Fig. 3.4 Examples of the diverse vegetation regimes found in the Virgin Islands. **a** Lush rainforest vegetation on Sage Mountain, Tortola. **b** Dry cactus vegetation, including *Stenocereus fimbriatus* and *Melocactus intortus*, on the Dead Chest National Park, BVI. **c** Caribbean dry forest surrounding a salt pond on Ginger Island, BVI. **d** Red mangroves, *Rhizophora mangle*, along the south east coast of Anegada. Photographs by Nancy Pascoe courtesy of the National Parks Trust of the Virgin Islands

amounts of radiolarian chert. The Lameshur Volcanic-Intrusive Complex is overlain by the Late Cretaceous Louisenhoj Formation, up to 4000 m of volcaniclastic materials, followed conformably by the Outer Brass Formation, a thin limestone unit containing planktonic foraminifera yielding Turonian to Santonian (Early- to mid-Late Cretaceous) ages. The Tutu Formation, conformably overlying the Outer Brass Formation, consists of the Picara Member, a conglomerate consisting of clasts of the underlying Louisenhoj Formation, a thin limestone lens known as the Congo Cay Member, and the overlying Mandal Member, consisting of thinner, finer-grained materials than the Picara Member. The Eocene Tortola and Necker Formations unconformably overly the Tutu Formation and represent the youngest stratified units in the Northern Zone. These units consist of more volcaniclastic debris, as well as occasional foraminifera-bearing limestone units that aided in age determination.

All the above stratified units are to some extent crosscut by mid- to late-Eocene intrusions. The two largest intrusive bodies are known as the Virgin Gorda batholith (located underneath the northeastern regions of the British Virgin Islands) and the Narrows batholith (located in the straits between St. John and Tortola). The composition of these plutonic bodies is predominantly tonalite, and there are excellent exposures of the Narrows batholith intruding the Mandal Member of the Tutu Formation along the north shore of Mary Point (Rankin 2002). Associated with these batholiths are many dikes, ranging from a few centimeters to 10s of meters in thickness. These features vary in composition from diabase to diorite, and contact metamorphism of the Eocene layers is not uncommon. While a detailed chronology of these bodies has not been undertaken, they have all been determined to be of approximately the same age, although it is likely that they did not all form synchronously.

Table 3.1 Basic stratigraphic table for the Virgin Islands based on various geologic studies and resources

Age	Group	Formation	Member	General lithology
Eocene	Virgin Island group			Mixture of volcaniclastic debris and limestone units
		Necker formation		
		Tortola formation		
Cretaceous	*Unconformity*			
		Tutu formation		
			Mandal member	Thinly bedded, fine-grained sandstone
			Congo bay member	Limestone lens
			Picara member	Conglomerate with clasts of Louisenhoj formation
		Outer brass formation		Thin limestone unit
		Louisenhoj formation		Volcaniclastic materials
	Unconformity			
	Lameshur volcanic intrusive complex			Complex mixture of lava flows, dikes, and chert
		Water Island formation		
		Careen hill intrusive suite		

3.3.2 Landforms

The interior landforms of Northern Zone are dominated by steep slopes covering much of each island's landmass, with 80% of the island of St. John consisting of slopes steeper than 30% (Anderson 1994). These ridges are typically incised by deep cuts (locally called ghauts) that often are focused on the near-vertical dikes prevalent throughout the region (Rankin 2002). Colluvium is common on most slopes, and virtually, all valleys contain alluvium of varying thickness. Large boulders that appear to be in place are common on the ridge tops. Their origins have been interpreted to be the result of subtropical rock decay—selective rock decay, differentiation of the rock mass into corestones and saprolite, and subsequent removal of loose saprolite. Many of the ghauts are also filled with boulders and exhibit a lack of vegetation, presumably the result of frequent flash flooding (Rankin 1984).

In contrast to the prevalence of igneous rocks in the Northern Zone of the Virgin Islands, most of the exposures in the Southern Zone consist of sedimentary rocks, and they are primarily found on the island of St. Croix. The Caledonia Formation, potentially as old as Cenomanian (Early to Late Cretaceous), consists of alternating bands of centimeter scale mudstones with abundant microfossils and graded sandstone and conglomerate beds with clasts of volcanic origin. This formation has been interpreted as distal turbidite deposits originating from a volcanic island (Speed et al. 1979). Complex interfingering relationships exist between the Caledonia Formation and the formations it grades into laterally and vertically, including the tuffaceous sandstones known as the Allandale Formation and the Judith Fancy Formation and the turbidites of the Cane Valley Formation. The youngest sedimentary rock bodies in the region are of Late Oligocene to Middle Miocene in age and are found in the central graben valley of St. Croix. The Jealousy Formation has limited outcrop exposures, but has been described as mainly mudstone with some interbedded conglomerates (Whetten 1966). Conformably overlying the Jealousy Formation is the Kingshill Formation, a flat-lying to gently folded fossil-rich limestone with abundant foraminifera and gastropods, indicative of a fossil coral reef that was later uplifted.

St. Croix's interior geomorphology can be subdivided into three zones: the Northside Range, the coastal plain, and the East End Range (Whetten 1966). The Northside Range is found on the northwestern side of the island and trends toward the east, gradually narrowing and merging with the coastal plain. Similarities exist between the topography of this range and the predominant topography of the Northern Zone, with deeply dissected ridges containing steep-walled, V-shaped valleys filled with alluvium. The highest elevations of the Northside Range create a rolling ridgeline that Meyerhoff (1926) correlated with similar surfaces in Puerto Rico and the northern Virgin Islands as a "peneplain," but this interpretation has generally been dismissed as unrealistic for such a small number of relatively low-discharge streams (Whetten 1966). The coastal plain consists of a relatively flat surface on the western side of the island that gradually grades into hillier terrain to the east as it converges with the East End Range. This range has similar characteristics and elevations to the Northside Range, and combining these two ranges represents the uplifted horsts surrounding the down-dropped graben of the coastal plain.

Both tectonic zones of the Virgin Islands contain similar coastal and offshore landforms. Due to the rugged topography and resistant underlying bedrock, sea cliffs are common features along most islands within the system. These rocky headlands serve as a barrier separating the thin beaches that surround the islands, often framing a protected cove or bay (Fig. 3.5). Fringing many of the islands are extensive coral reefs, many of which experienced massive losses in recent years due to increased sedimentation associated with island development, increases in macroalgae triggered by the death of coral species that fed on them, disease, and frequency and intensity of Atlantic Basin hurricanes. The health of the coral reefs, specifically as it relates to increased sediment flux, will be explored in more detail in the hazards section later in this chapter.

3.4 Landscape

When broadening the view of the Virgin Islands to include historical and cultural components, the imposing and lasting influence of Imperial Colonialism on the people and landscapes of the Virgin Islands becomes evident. The islands' proximity to historic trade routes between Europe and North

Fig. 3.5 Coastal landforms on St. Thomas and examples of modern utilization of those features. **a** The famous Magens Bay Beach (lower right of the image), St. Thomas, from Hull Bay Road. The bay is protected by large jutting headlands visible in the background and foreground. The island of Big Hans Lollick can be seen in the upper right behind the headlands. **b** Celebrity Cruise ship docked at Havensight Point, along with several yachts and sail boats (foreground and lower right side of the image) in a St. Thomas Harbor. While the naturally deep and protective harbor now hosts a myriad of pleasure/tourist ships, it was similarly attractive for trade and piracy centuries earlier. Photographs by B.J. Barnes

America and central location in the Caribbean gives them unique strategic importance. Dookhan (1974, p. 2) even goes as far as to say the Virgin Islands "occupy the keystone of the West Indies arch." This has led them to be initially coveted not only for their economic potential but also, and perhaps more importantly, for their military value. European "discovery" was by way of Columbus' voyages in 1493. The indigenous peoples of the islands were comprised of Ciboney, Caribs, and Arawaks—representative of most native populations in the Caribbean (Dookhan 1974)—and they left behind numerous rock carvings and petroglyphs, mainly on St. John and St. Croix (Haviser and Strecker 2006). The 1600s saw various European countries competing in attempts to colonize the region, focusing primarily on the efforts of Spain, England, France, and Denmark. Ultimately, by the mid-1700s, the Danes and British had prevailed in establishing lasting colonies on what are now recognized as the Virgin Islands. The British Virgin Islands became a cohesive entity following the British takeover of Tortola in 1672 and annexation of Anegada and Virgin Gorda in 1680. At about the same time, the Danish West India Guinea Company was establishing permanent settlements on St. Thomas and St. Johns. St. Croix was purchased from the French in 1733, thereby unifying the three islands as the Danish West Indies, sometimes referred to as the Danish Antilles, later falling under the direct rule of the Denmark–Norway Monarchy a few decades later (Dookhan 1974).

These political transitions were far from peaceful—violent conflicts between locals and foreigners, competing colonial forces, and rampant piracy—and this left a lasting impression on the landscapes of the Virgin Islands. Large stone fortresses were erected along the coasts of the primary islands, such as Fort Christian on St. Thomas and Fort Burt on Tortola. These not only created a protective component in the landscapes themselves, but also required intensive stone quarrying and extraction of natural resources on the islands—making the way for modern quarry businesses such as Aggregate Inc. on St. Croix. These forts were erected to deter political competition, but also to protect the main port cities from pirates and buccaneers. In fact, much of piracy's "Golden Age" (1690–1730) took place in the North Atlantic and Caribbean Sea (Hallwood and Miceli 2015). The unique features of the Virgin Islands that attracted colonial powers also made them prime targets for piracy, such as the natural deepwater harbors, central location, and continuous regional trade, as well as the numerous surrounding islands and coves that could serve as hideouts. Many of the smaller islands in the Virgin Islands still have feature names that reflect their dubious past: Dead Chest Island, Treasure Point Caves, Deadman's Bay, to name a few.

Once colonial powers were fully established by the end of the eighteenth century, there were two primary and complementary economies on the islands of the region: sugar and slave trade. Sugar plantations were a dominant economic venture during much of the colonial years, and slave trade from Africa was used both to supply labor for the cane fields and also as a commodity unto itself (Armstrong 2003). The central location of the Virgin Islands encouraged the development of both enterprises with notable success. Both the British and Danes employed the largely profitable, and equally popular, triangular trade model: European products were sold for slaves along West African coast, and the slaves were brought to the Caribbean to work plantations, which, in turn, supplied sugar and rum for trade back in Europe (Hall and Higman 1992). With the triangular trade in full effect, thousands of African slaves were transported to the Virgin Islands, replacing indentured employees, such as poor or criminal deportees from Europe, who had been working the fields to that point (Armstrong 2003).

The massive influx of slaves had such an impact on the islands that one scholar stated: "One of the most important aspects of the History of the British Virgin Islands is slavery" (Pickering 1987, p. 45). St. Croix, in particular, was especially profitable during this time due to its unique topography: The fertile coastal plain is constantly fed by water sourced from both northern and eastern highlands, making it ideal for intensive agriculture. Even the prevailing northeast trade winds powered the large windmills crushing sugarcane (Dookhan 1974). While sugar plantations were established on most colonized Caribbean Islands, very few were as productive as those on St. Croix (Macpherson 1973). Cotton farming was also attempted in the Danish West Indies, but it proved too taxing on the soils and the efforts were abandoned for far more lucrative sugarcane crops (Tyson 1992).

After several slave revolts and pressure from Europe, the British Empire abolished slavery in 1834, followed by Danish abolition in 1848, and the Virgin Islands began the long and difficult process of gaining self-governance. While most freed slaves stayed on the plantations to work for minimal compensation, a large portion moved to economic centers such as the port cites of Charlotte Amalie, St. Thomas and Christiansted and Frederiksted, St. Croix to work at the docks (Hall 1985). In fact, St. Thomas is said to have some of the best natural deepwater harbors in the Caribbean (CIA: Virgin Islands 2016). These natural harbors and strategic trade cites of the Virgin Islands allowed steady trade of goods throughout the region as an economic alternative, as sugarcane production gradually declined following the abolition of slavery, increased production of sugar beets in Europe and USA, and a series of devastating hurricanes (Dookhan 1974). Around the turn of the twentieth century, property values on the British Virgin Islands were so low that freed slaves could purchase land of their own—inspiring renewed national pride. Around the same time, the USA brokered a deal with Denmark to purchase the Danish West Indies for $25,000,000 in gold and renamed them the US

Virgin Islands (Dookhan 1974). The US valuation of the islands was primarily one of the military nature. World War I was winding down, and the area was viewed as having strategic importance to long-term US geopolitical interests in the region.

Today, the US Virgin Islands are an unincorporated organized territory of the US and the British Virgin Islands are a self-governing member of the Commonwealth of Nations, otherwise known as the British Commonwealth, after gaining autonomy in the 1960s. Despite the now revitalized economies and national identity, the lasting effects of colonialism, slavery, and plantation occupation can still be seen in the landscapes throughout the islands. Many of the lavish plantation houses and defensive forts erected during imperial rule remain reminders of the islands' turbulent and, to many, painful history. However, some of that history is now being repurposed as a resource to further economic development by means of heritage/historical tourism—such as the conversion of plantation homes into interpretive museums and/or memorials—one of the Virgin Islands' many tourism outlets.

3.5 Heritage and Tourism

As with many of the islands of the Lesser Antilles, tourism is the primary economic industry in the Virgin Islands (both for US and the UK). As per the CIA World Fact Book, tourism accounts for nearly 45% of the national income in the British Virgin Islands and almost 60% in the US Virgin Islands (CIA: Virgin Islands 2016). Despite being such small islands, they offer a wide variety of tourism resources and support several different specialties of the tourism sector: heritage, resort, relaxation/spa, adventure, aquatic, natural/ecotourism, and more. These interrelating branches of tourism often incorporate elements of the built landscape, such as Fort Burt on Tortola and the Annaberg Sugar Plantation on St. John, but also rely heavily on natural landforms and environments for context, advertising, and as attractions in and of themselves. In other words, certain elements of the physical landscapes facilitate tourism, such as the natural harbor of St. Thomas-Cruz Bay once promoting colonial trade now docking cruise ships, while others actively draw and attract tourism, such as Magens Bay Beach on St. Thomas, famous for its gentle waters protected by large peninsulas on either side of the half-mile stretch of sand. The natural beauty and diversity of the Virgin Islands provide unique tourism assets but also incorporate potentially fragile natural heritage, which is managed differently between the US and British governments.

On the British Virgin Islands, areas of significant value, whether historic and/or natural, marine and/or terrestrial, are designated as national parks and managed by the BVI National Parks Trust, established in 1961 under the Ministry of Natural Resources and Labour. The Trust currently manages over 20 different parks and protected areas that include geologic anomalies to the region, such as the Baths and the Bubbly Pool, as well as iconic and picturesque landscapes, such as Sage Mountain or Sandy Cay (Fig. 3.6). The Baths National Park, located adjacent to Devil's Bay National Park on the southern tip of Virgin Gorda, consists of scattered massive spheroidally decayed granite boulders creating stunning sea pools and secluded caves along the sandy shoreline. For something a bit more exciting, the Bubbly Pool—which used to be a "locals' secret" before becoming a national park—is a small alcove on the northern shore of Jost van Dyke surrounded by large boulders. When the tide changes, large swells from the Atlantic Ocean break over the protective boulders letting only sea foam and white waters rush into the pool, creating what some call a "natural Jacuzzi"—thus the name "Bubbly Pool" (Jost van Dyke 2013). Established in 1964 and covering 64 acres of central Tortola, Sage Mountain National Park was the first National Park in the British Virgin Islands and is the highest point in all the Virgin Islands. Not only does the park protect a thriving forest of white cedar and mahogany trees, but it also represents the beginning of nature conservation and natural resource management in the British Virgin Islands (Sage Mountain National Park 2016). Equally as iconic, the small and uninhabited island of Sandy Cay situated between Jost van Dyke and Tortola consists of nothing but soft sandy beaches, crystal clear water, a small salt pond at its center, and green-hued rocks from significant copper ore deposits in the area (Sandy Cay: BVI 2012). Sandy Cay is a relatively new addition to the National Park system being transferred to the trust by the Laurence Rockefeller Estate in 2008 and represents one of the most intact dry tropical forests in the world (Zaluski 2014).

Since the US Virgin Islands are an unincorporated territory of the USA, instead of an autonomous nation like the British Virgin Islands, the establishment and management of protected areas are slightly different. There are a few nationally protected areas governed by the US National Park Service (NPS), but nowhere near as many as the British Virgin Islands. The only full park is the Virgin Islands National Park that covers most of St. John. Additional properties include the alleged landing site of Christopher Columbus at the Salt River National Historic Park on St. Croix, Buck Island Reef National Monument off the northeast coast of St. Croix (not to be confused with the Buck Island National Wildlife Reserve just south of St. Thomas), and the three-mile-long Virgin Islands Coral Reef National Monument along the southern coast of St. John (Virgin Island: Parks 2016) (Fig. 3.7). While there are relatively few nationally protected assets, they are quite large. For example, Virgin Islands National Park is well over 7000 acres and Buck Island with its surrounding reefs total over 19,000 acres of protected land (Virgin Islands: Parks 2016). The US

Fig. 3.6 Examples of National Parks and geologic points of interest in the British Virgin Islands. **a** Aerial view of the uninhabited Sandy Cay Habitat Management Area off the coast of Jost van Dyke. Photograph by I. Bahadoor courtesy of the National Parks Trust of the Virgin Islands. **b** Dry vegetation along the steep cliffs at the Dead Chest National Park. Photograph by N. Pascoe courtesy of the National Parks Trust of the Virgin Islands. **c** One of the large covered pools at the Baths National Park on the southwest tip of Virgin Gorda. Photograph by S. Estes. **d** An external view of the monolithic granite outcrop and surrounding beaches of the Baths National Park. Photograph by N. Pascoe courtesy of the National Parks Trust of the Virgin Islands

Virgin Islands also have a collection of local governed "Territory Protected Areas"—though these are mostly marine zones—which are popular tourism destinations.

Beyond the terrestrial landscapes, both the US and British Virgin Islands boast an array of beaches, reefs, and other marine heritage/tourism assets. Some of the most famous beaches include Trunk Bay (part of the Virgin Islands National Park on St. John) and Sandy Point on St. Croix (which is the longest beach in the USVI.); nearly, all of Anegada's shoreline is one continuous beach. Offshore, the Virgin Islands have several well-established reef systems that are popular for snorkeling and scuba diving, much like those found in the Salt River Canyon, featuring a 300 m plummet to the sea floor, off St. Croix's north coast (St. Croix Diving 2016). Other popular dive sites showcase more anomalous geologic features, unique to the Virgin Islands, such as Blond Rock, an incomplete seamount between Salt and Dead Chest Islands rising from nearly 20 m at the sea floor to a mere 4.5 m from the water's surface (Bulter 2007), or the Tunnels of Thatch, a series of submerged volcanic tubes and trenches running under Thatch Cay to the northwest of St. Thomas. Recently, both the US and British Virgin Islands have been creating several artificial reefs, such as the two decommissioned WWII Navy Barges purposely submerged off the coast of St. Thomas and the sunken 360 Shorts Airplane in the Coral Gardens of Great Dog Island, to boost coral growth and revitalize marine habitats damaged by over-use, storms, or other forms of environmental stress.

3.6 Hazards

Being situated in an area of complex tectonics, in an open ocean basin, with a burgeoning population, it is not surprising that the Virgin Islands are subjected to a vast array of natural hazards. The steep slopes combined with tropical moisture make the threats of mass wasting events ever present. Seismic hazards associated with the numerous

Fig. 3.7 Landscapes and landforms on St. John, USVI. **a** Landscape view of Coral Harbor and the town of Coral Bay (*center*) from Centerline Road on St. John, looking to the south. The land on the *left side* of the photograph is the East End of St. John. Norman Island may be seen on the *horizon* on the *left*. **b** The picturesque John's Folly Bay and the Sabbat Channel between St. John and Leduck Island (just visible in the far *right* of the image). Fringing the Virgin Islands National Park, John's Folly (both the village and bay) on the southeastern coast is one of the few areas on St. John not managed by the US NPS. Tortola (*Left*) and Peter Island (*Right*) can be seen on the horizon in the background. **c** Looking northwest on a secluded beach with snorkeling between Long Bay and Pelican Rock on the East End of St. John. Photographs by C.M. Fielding

interacting plates and microplates are a constant threat. Tropical storms and hurricanes frequently carve a path of destruction through the region. It is not only these hazards in and of themselves that cause concerns for the inhabitants of the Virgin Islands, but also the side effects of these factors that can wreak havoc.

Using an extensive network of GPS data, Jansma et al. (2000) demonstrated that Puerto Rico and the northern islands of the Virgin Islands are actually part of a smaller microplate associated with the larger Caribbean Plate. As the North American plate moves west relative to the microplate associated with the Virgin Islands, a left-lateral strike-slip fault zone comparable to some of the largest and well-known systems of the world (e.g., the San Andreas in California) is created. While a study of historical earthquakes indicated that the release of energy in events within the Virgin Islands has been orders of magnitude lower than those within Puerto Rico (Doser et al. 2005), there is sedimentologic and stratigraphic evidence to suggest a major tsunami has hit the island of Anegada in the British Islands over the past several hundred years (Atwater et al. 2012). Despite the relatively low population of the Virgin Islands in comparison with the neighboring countries such as Puerto Rico, Cuba, and the Dominican Republic, because of the small size of the islands, the population density is high. Furthermore, the steep slopes of the islands are prone to mass wasting during energy release in a seismic event, and many of the houses are built with substandard construction materials and techniques. Seismic risk for the Virgin Islands is considered high due to these combinations of physical and human factors.

Another coupled human–environment hazard is the production and transport of sediment delivered to the marine ecosystems surrounding these islands. As development increases in the Virgin Islands, so does the density of roads (paved and unpaved) that dissect the islands. Regional studies (MacDonald et al. 2001; Ramos-Scharron and MacDonald 2007) have demonstrated that unpaved roads are the primary source of sediment for coastal waters, and that relatively minor precipitation events can generate disproportionately large volumes of sediment. Coral reef cover in the Caribbean has been in decline for at least the last 30 years, and increased sediment flux is considered a major factor in the health of corals adjacent to small islands (Gardner et al. 2003). As development and populations continue to increase in the Virgin Islands, it will become increasingly important to consider the significance of sediment production and transport in the design of infrastructure and control structures.

3.7 Conclusion

Boasting celebrated beaches, serene waters, emerald green mountains, and some of the best Scuba diving in the world (Bulter 2007), the Virgin Islands seem to have it all. Even elements of the islands' tumultuous past have been transformed by the local population, such as the conversion of the Whim Estate on St. Croix, a large sugar plantation, into a museum that not only commemorates the hardships of slavery but also celebrates their resilience and transition into free Crucians—people of St. Croix (Estate Whim Museum 2016). Indeed, even those quintessential deserted islands with nothing but beaches and a single palm tree that can only be reached by boat featured in countless travel magazines and tour brochures can be found in the Virgin Islands. An impressive myriad of unique geologic structures including soaring pinnacles, underwater lava tubes, colossal granite outcrops (i.e., the Baths, see Sect. 3.5), and towering volcanic peaks also sprinkle the islands. This is not to say the inhabitants of the islands are without their challenges, but the fact that all these features—alongside distinctive thriving cultures and histories—exist within a terrestrial area no larger than Long Island, NY, is a humbling reminder that there are more to landscapes than sheer size.

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Anguilla

4

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Abstract

Located east of the US Virgin Islands and 8 km north of Saint Martin, Anguilla is a low-lying Limestone Caribbee with no permanent standing water other than brackish salt ponds. With a volcanic historic long since passed, Anguilla has no mountainous features. Its limestone composition resulted in the formation of numerous caves, some of which are home to unique Amerindian religious sites. Anguilla's lack of soil coverage resulted in a relative lack of historic and modern plantation agriculture, and the island relied heavily on the export of salt and lobster until a tourism industry developed around the 33 public beaches that ring the island. Currently, tourism is the leading industry on Anguilla and has impacted both the environment and local awareness of environmental health.

Keywords

Anguilla • Beaches • Limestone • Erosion • Tourism

4.1 Introduction

Anguilla is one of the most northerly Leeward Islands in the Lesser Antilles, located east of the US Virgin Islands and 8 km north of Saint Martin/Sint Maarten (Fig. 4.1). Despite evidence of volcanic activity in the far past, Anguilla is a Limestone Caribbee—an island with limestone-dominant rock type. Because of this, Anguilla is a homogenously low-lying island with little relief (Bruce 2000), the highest point being Crocus Hill (65 m). Anguilla's water supply comes from rain and desalination plants, as the island has no permanent standing water other than salt ponds (Pan 2007). These salt ponds represent feeding grounds for several bird species and provide protection against flooding of living areas, businesses and roads (Anguilla 2008). Other than the salt ponds, the most dominant features on Anguilla are the caves, most notably Pitch Apple Hole, Cavanaugh Cave (alternately Cavannah or Kavanaugh), and Fountain Cavern, the latter of which is a national park that has been nominated for UNESCO recognition (Rogers 2010).

Anguilla is 26 km long by 5 km at the widest point, and this oblong shape led to its current name, which means "eel-shaped," while the original Amerindian name, *Malliouhana,* means "arrow-shaped" (Cambridge 2012b). Though some have suggested the first European to see Anguilla was Christopher Columbus, there is no evidence to that effect, and the first European contact was generally attributed to the French in 1565. After that, there was limited European exposure until the English, coming from St. Kitts, colonized the island in 1650. Despite a few French attempts at invasion, the British successfully retained control of the island

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Fig. 4.1 General physiographic map of Anguilla with surrounding islands and cays. Despite its fairly rocky topography, especially in the center of the island, the highest point of Anguilla is only 65 m. The Anguilla Channel to the south separates Anguilla from nearby St. Martin. The close proximity allows for a regular ferry service between St. Martin, Anguilla, Dog Island, and Scrub Island. Cartography by K. M. Groom

(Martin 1839; Staff 2015). In 1967, England oversaw the unified dependency of St. Kitts-Nevis-Anguilla, a move that most Anguillian opposed. The island revolted, and in 1971, they were returned to full British control. In 1980, Anguilla formally seceded from the unified dependency and has remained a British Overseas Territory since then (Staff 2015).

With a total land area of 90 km^2 and 61 km of coastline peppered with beautiful bays, Anguilla has come to be viewed by some as the best beach destination in the Caribbean (Tisdall 2010). Tourism remains Anguilla's number one industry, spurred on by more than 33 beaches, all of which are open to the public. The cays and islands found off the coast also serve as tourist attractions, with larger cays such as Scilly Cay and Prickly Pear Cay, and islands such as Scrub Island and Dog Island easily accessible from the main island. Along with the cays and islands, coral reefs ring the coast, most notably an extensive barrier reef to the north of the island. The reef systems are important for preventing beach erosion and helping mitigate damage from hurricanes, but coral health has reportedly declined in recent years. This has impacted offshore fisheries, a significant issue as fishing is one of Anguilla's main industries, employing 20% of the population (Hodge 2011). Anguilla has additionally developed a reputation as a tax haven, and offshore banking services are the second largest industry.

4.2 Setting

4.2.1 Geology

The island of Anguilla, along with St. Martin/Sint Maarten, St. Barthélemy, and the Sombrero and Dog islets, sits atop approximately 4500 km^2 of raised seafloor called the St. Barthélemy-Anguilla platform (Bouysse 1979, 1983, 1986). The platform slopes gradually to the southwest but has a much steeper eastern slope with submarine rock outcrops of early Tertiary age or older (Bouysse 1986).

The Lesser Antilles are divided into Limestone or Volcanic Caribbees, and Anguilla is one of the former (Quinn 2015: 415). On most of the Limestone Caribbees, limestone and other sedimentary material on the island's surface covers older volcanic arc remnants or metamorphic rocks. Topographically, Anguilla and the other Limestone Caribbees have less relief and fewer volcanic or tectonic landforms than the islands created by recent volcanic eruptions. Even among the Caribbees, Anguilla is particularly flat and low-lying, as are most of the small cays which occur on islets to the north and west of the main island (Hamylton 2013). On the main island, relief is greatest along the north shore of Anguilla, where the highest elevation occurs at the cliff overlooking Crocus Bay at 65 m above sea level (Bouysse 1986; Christman 1953; Mitchell (n. d.a); Stanley 2009; Smith 2013).

Geologically, Anguilla itself represents a textbook example of a Limestone Caribbee (Quinn 2015). Beneath the main sedimentary formations, the island consists of igneous basement rock dating to the middle Eocene, 56–41 million years ago (Ma). This is the remnant of a lava platform resulting from volcanic activity on nearby Saint Martin (Bruce 2000; Hamylton 2013). The basalt from the middle Eocene is most prominent on the northern end of the island and is visually distinct from the overlying limestone. In addition to the basalt, tuff and breccia from the middle to late Eocene (41–33 Ma) are also found around Anguilla and are visible along Crocus Bay on the north side of the island (Smith 2013; Wynne 2013). Above the basement rock, two layers of limestone form the body of Anguilla. The first is a blend of marly limestone and black shale originating in the Oligocene (33–23 Ma); the second is cavernous limestone laid down in the early Miocene (23–15 Ma). This layer comprises the visible cliffs on Anguilla and is riddled with fossils of a wide variety of fauna (Smith 2013).

Where limestone is visible at the surface or is overlain by only a thin veneer of sand, the topography is characterized by dolines and other karst features (Stanley 2009). Active collapse or subsidence has occurred even in some of the most developed areas such as The Valley, Anguilla's capital. Underground caverns occur in the limestones of Miocene and Oligocene ages, and these have been explored and utilized as sites for habitation as well as ritual use extending back many thousands of years (Crock 2008).

4.2.2 Climate

Anguilla is characterized as an "arid" island by Mitchell (n. d.a) with a hot and dry climate (Stanley 2009: 5) including a mean annual temperature of 28 °C (82.4 °F) and mean annual rainfall of 1017 mm (40 inches). At least 60% of Anguilla's land surface is exposed rock. Where the limestone has decayed to soil, it does successfully support crops. Because of the limited soil, the island's vegetation mainly consists of small trees and low scrub inland and sea grape and palm trees along the coasts. The limestone does not support water retention well, and though there are some wells on the island, most rainwater escapes back to the sea (Bruce 2000). The only wetlands are the salt ponds found throughout the island. These ponds are remnants of higher sea levels and are primarily brackish.

4.2.3 Reefs

Anguilla is noted for its spectacular and ecologically important coral reefs and beaches. In the shallow water off the north coast of Anguilla, 14,600 hectares of sublittoral substrate provides what should be ideal conditions for coral (Wynne 2013). The 17-km-long reef along the north coast is considered to be one of the most important reefs in the eastern Caribbean both because it helps protect against beach erosion and because it is host to many endangered and ecologically important marine life, such as spotted eagle rays, turtles, and the commercially fished queen conchs (Hodge 2011; Putney 1982). Living and fossil coral occur within the surf zone of the active shoreline on the north side of the island while "fringing" reefs a bit further offshore predominate to the south (Stanley 2009; Wynne 2013). Though coral conditions have been poorly monitored in Anguilla until more recently, experts from the Anguilla Department of Fisheries and Marine Resources find coral coverage and health have deteriorated since the 1990s. Most notably, coral reef coverage in the previously mentioned shallow water substrate declined from 14% in 1990 to 4% in 2009 (Wynne 2013).

4.3 Landforms

Because of Anguilla's low-relief limestone composition, it is without some of the dramatic mountainous features found on other Caribbean islands. What Anguilla lacks in the way of volcanic peaks, however, it makes up for with beautiful public beaches, an array of limestone caves, and various cays and islands offshore. The most practically important landforms on Anguilla are the salt ponds, the island's only permanent wetlands. There are 25 salt ponds on Anguilla, 22 of which are natural and formed thousands of years ago. The other three were created as part of more recent landscaping efforts. Along with serving a variety of ecosystems services such as flood mitigation during heavy rainfall, coastal protection during storm surges, and sediment trapping that catch contaminants coming off the mainland, these ponds provide a habitat for 130 species of birds, some 25% of which are endangered or threatened species (Anguilla 2008; Hodge 2011).

Despite the importance of the salt ponds, Anguilla is best known for its beautiful beaches. While the standard picture of an Anguillian beach is white sand stretching along the open coast, there are also cliffs in the north which enclose bays with smaller, more secluded beaches. Little Bay is one of the most famous enclosed beaches on Anguilla. It is surrounded to the west and east by cliffs and caves, and about 100 meters offshore from Little Bay there are substantial sea grass beds (Fig. 4.2). These mainly consist of *Syringodium* spp. which attracts marine turtles that come to feed on the sea grass (Hoggarth 2001). A two-mile-long white sand beach on the northeastern face of the island, Shoal Bay East (not be confused with Shoal Bay Beach), is widely considered the best beach in Anguilla (Jamason 2014; Staff 2011).

Anguilla's two national parks, Big Spring and Fountain Cavern, are both centered around limestone caves. Big Spring, located on the northeast end of the island, provided freshwater to the local residents until 1995, when contamination by Hurricane Luis rendered the water undrinkable. Fountain Cavern, on the same side of the island as Big Spring but further to the west near Shoal Bay, covers approximately six hectares and contains a limestone cave located 20 m underground (Anguillian 2015; Staff n.d.).

Aside from these notable examples, other limestone caves are found throughout the island. Cavanaugh Cave, located between North Hill and Katouche Bay, is the safest cave in Anguilla to explore. It was mined for phosphate through the nineteenth century and widely considered to be the site where fossils of *Amblyrhiza Inundata*, a large, extinct rodent were discovered (Green 1998). Despite the historic significance and enduring stability of Cavanaugh Cave, arguably the most famous cave in Anguilla is the archaeologically important Pitch Apple Hole, located in Katouche Bay on the north side of the island (Biknevicus et al. 1993). The cave gets its name for the Pitch Apple Tree whose roots extend far to the bottom of the cave, creating an open ceiling in the cave. Katouche Bay leads into one of Anguilla's only true valleys, Katouche Valley. Located between Crocus Hill and North Hill, Katouche Valley is the location of the only natural rain forest area on the island (Connor 2013). In addition to caves, there are other limestone formations found around the island. These include the natural arches such as the one found in Blolly Ham Bay. These are typically found on the west side of Anguilla and form due to erosion by wind, rain, and waves along the coast (Fig. 4.3).

Offshore, various islands and cays provide additional beach real estate and snorkeling opportunities. Cays are small islands that form on the surface of coral reef. When currents slow or shift, sediment builds up on the reef until it breaks the surface, gradually forming a stable surface (Editors 2016). There are many cays around Anguilla, with varying amounts of vegetation or habitable space. Scilly Cay is a tiny coral island located to the northeast of Anguilla. The cay has little vegetation with a few palm trees and a small sand beach. It is surrounded by waters with patch reefs, sea grass, and algal beds (Fig. 4.4). The Prickly Pear Cays, comprised of an east and west island, remain divided by a narrow channel on the Anguilla Bank. The West Cay is narrow and rocky, with no place to land a boat safely, while the East Cay is longer and easier to access (Blunt 1863). Prickly Pear Reef, which hosts an underwater canyon around the cays that ranges in depth from 12 to 21 m—including an underwater chimney formation, ledges, and caves—is part of why the cays have such a draw for snorkelers (Huber 2014).

Fig. 4.2 A beach enclosed by limestone cliffs and cave at the outer end of Little Bay, a smaller bay in the nook of Crocus Bay. Usually, the beach is exposed with calm seas, ground seas inundates the beach reaching the cliffs. The cliffs are dominated with dry scrubs (e.g., *Rondeletia anguillensis*) and cacti species. Photograph by A.K. Izioka

Of Anguilla's islands, one of the most prominent is Dog Island, an uninhabited island located 13 km NW off Anguilla. The island has a surface area of 207 ha with a rocky landscape formed by low cliffs that alternate with sandy beaches. It has a salt pond to the south and three small cays off the west and north coasts. Dog Island, like many of the islands of Anguilla, is classified as an Important Bird Area (Soanes et al. 2015, 2016), as it is home to three globally important bird colonies: Brown boobies, Masked boobies, and Frigate birds. The island's landscape structure and low relief provide the perfect nesting grounds for these birds (Soanes et al. 2015).

Another of Anguilla's relatively larger islands is Sombrero Island. Sombrero Island is important for many birds, just like Dog Island; however, it is also important for marine animals such as marine turtles (Kuramae Izioka nd). Sombrero Island is 1.6 by 6 km, with a total area of 38 ha. It got its name from its odd shape, which loosely resembles a sombrero hat from above. The vegetation on the island is very scarce, though Lazell (1964) noted some cactus species (*Opuntia antillana*) and Norton (1989) encountered more species such as *Sesuvium portulacastrum, Euphorbia serpens*, *E. mesembriathemifolia*, *Heliotropium curassavacum*, *Portulaca oleracca*, *and Fimbristylis cymosa.* The island also hosts a lighthouse which passing ships often use as a landmark (Lazell 1964).

Sandy Island is off Anguilla's northwestern coast and is made up of fine sand and surrounded by shallow reefs. Forces of nature such as hurricanes, tropical storms, and severe wave action renew and reshape the island every year, occasionally stripping all vegetation from the island. This is part of why Sand Island has only limited vegetation. Except for some palm trees, all the vegetation is small growth plants (Fig. 4.5).

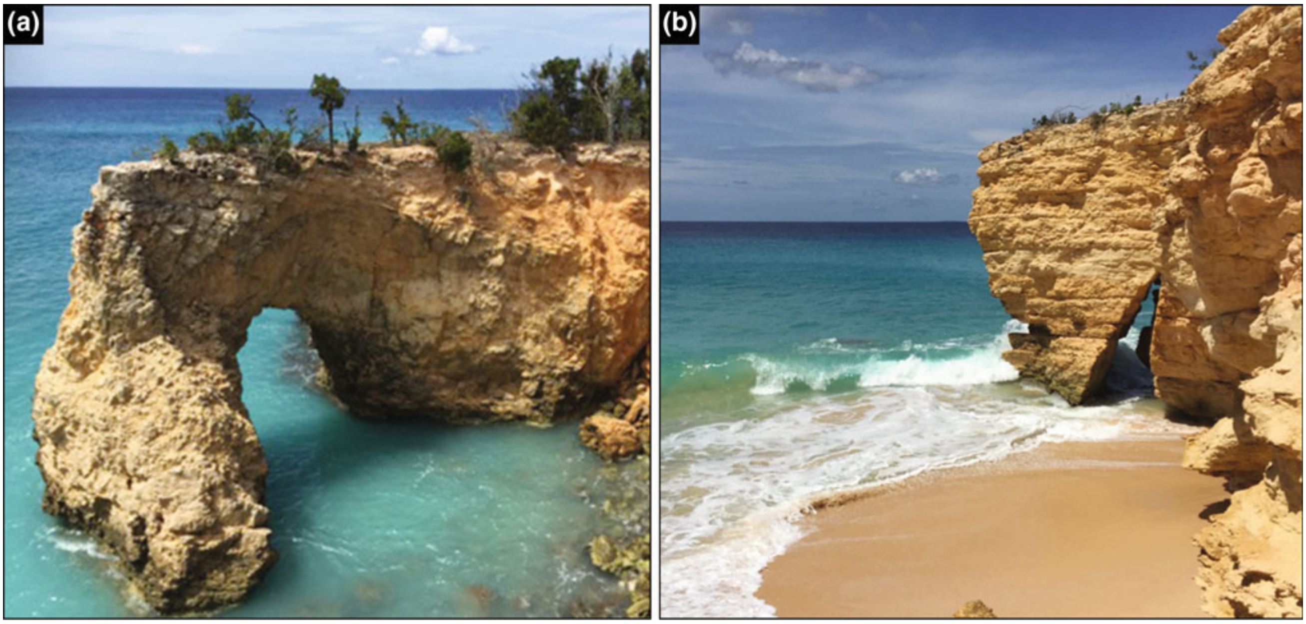

Fig. 4.3 Examples of coastal landforms on Anguilla. (**a**) Natural arch in the West-End of Anguilla. The arch is formed by erosion of currents, salt, and rain during ground seas. Vegetation of dry bush dominates this area, with some Aloe (*bottom left*) and cacti growing here and there. (**b**) A second natural arch at the same location with less vegetation growing on *top*. This arch is mainly formed by wave action and erosion exacerbating existing fractures in the sea cliff. Photographs by A.K. Izioka

Anguilla also hosts a few other small islands off its coast that should be noted here. Scrub Island has a unique mixture of coral and scrub. It has some rough coastal areas, particularly along the eastern side where the coastline primarily consists of low cliff formations. In the northern and southern parts of the island, the coast is made up of sandy beaches that slope into the sea. The beaches are important for marine turtles as breeding areas. Nesting activity has been recorded several times by Green Turtles and Hawksbills. The nearby Little Scrub Island is rough and rocky around the whole island. The waters surrounding Little Scrub are choppy and have impacted the island's inhospitable shoreline.

Seal Island is a small, narrow island between Dog Island and Anguilla. Perhaps more eel-shaped than Anguilla itself, Seal Island is sometimes hard to access because of the 8 km reef that runs between it and Anguilla. The reef, and its proximity to Anguilla, makes Seal Island a popular location for divers. The Flirt Rocks are two small islands, located about 6 km northwest of the Prickly Pear Cays. Both Great Flirt, which stands to a height of 6 m above sea level, and Little Flirt, which reaches 2.4 m above sea level, are rocky and unwelcoming (Blunt 1863). Anguillita is the southernmost feature of Anguilla. It is located off the southwestern coast and is primarily accessible via sea kayak. It is little known compared to features like Scrub Island, and most often frequented by divers who visit the coral reefs 5–20 m below the surface, and underwater caves, both of which host a variety of marine species (Hoggarth 2001; Wynne 2013).

4.4 Landscape and History

While Anguilla has so little relief that it went undetected by Europeans for much longer than some other Caribbean islands, its landscape has been shaped just as much by the features *not* found on the island as those that are. When Anguilla was first settled by the Arawak people, they were drawn to the island not for the verdant forests and lush farmland, but for the fertile fishing its coral reefs fostered, although the small quantities of soil on Anguilla were sufficient for the subsistence farming efforts the Arawak undertook. The two main caverns on the island, Fountain and Big Spring, which are a product of the island's limestone composition, became sacred sites for the Arawak (Rogers 2010).

Despite the importance of these caverns in the Arawak culture and the island's long Arawak and subsequent Carib history, there are virtually no remaining place-names on the island of Amerindian origin. One exception is Zemi Beach, which takes its name from the religious artifacts found nearby. Many of the current place names are slightly ironic. The Valley, for example, is the capital city on an island whose highest point is a mere 65 m above sea level. Others are descriptive: Shoal Bay or North Valley, and still others reference residents of the island: Cauls Pond or Hughes' Estate. Though many of these name origins are not known for certain, it is clear they are all from the period of European occupation. Interestingly, there are no names of African

Fig. 4.4 View of the southern end of Scilly Cay looking north from Anguilla. Scilly Cay is a coral island located on the East-End of Anguilla with low-lying vegetation. The northern side often experiences large waves during rough weather, but offshore coral reefs help protect against coastal erosion. The small island houses a large restaurant and enjoying a meal on Scilly Island has become one of Anguilla's most famous tourist attractions. Photograph by A.K. Izioka

origin or influence, even though the British did bring slaves to Anguilla (Mitchell 2010).

When the British first arrived on Anguilla, they realized that the soil would support crops of tobacco, corn, and cotton, the last of which had previously been cultivated by the Arawak and was already growing on the island (Mitchell n.d.b; Halstead n.d.). These first crops supported the initial British settlement, but were destroyed by a group of Caribs invading from nearby islands. The settlement itself was never eradicated, and the invasion was beaten back. The British subsequently attempted the same kind of plantation agriculture found throughout the Caribbean. Large numbers of slaves were imported from Africa, which became a problem when it became apparent that the soil conditions and arid climate were not conducive to large plantation operations on Anguilla. Though some sugarcane, rum, mahogany, cotton, and rum were all produced and exported from Anguilla, the plantations were small and low volume. This resulted in many of the slaves working on personal subsistence plots rather than the plantations, until the Emancipation Act passed in 1834 (Countries n.d.).

Today, the consensus is that only 13% of Anguilla's land cover is arable. The crops grown now are almost exclusively for domestic consumption, typically grown on plots of less than one-quarter hectare (Meditz 1987). The scrub plant cover on much of the island is more suited to grazing than agriculture; cattle, goats, sheep, and pigs are all raised for both domestic consumption and export, though these animals in turn have contributed to further deforestation (Mitchell n.d.b). All traditional agricultural practices undertaken on Anguilla are made possible by British investment in desalination plants, which help mitigate the absence of permanent freshwater, one of the island's most notable features. Anguilla's only permanent wetlands, the salt ponds, provided a steady export product until the 1970s, when a combination of overmining and significant hurricanes compromised the salt supply. Anguilla primarily exports through the Caribbean, with

Fig. 4.5 Sandy Island north of Road Bay, Anguilla. Similar to Scilly Cay, Sandy Island is composed of fine sand and coral and is protected by surrounding shallow reefs. There is no freshwater present on the island so vegetation is limited to a few palm trees and low-lying vegetation. The forested hills of Anguilla are visible in the background. Photograph by A.K. Izioka

virtually no exports going to America or Europe. When the salt supply dropped, Anguilla's export markets turned elsewhere (Meditz 1987).

The inability to develop significant land-based exports has pushed Anguilla to explore other avenues of income. These include offshore banking services, but the fishing and tourism industries have had a greater impact on the landscape. Along with other fish, lobster is one of Anguilla's primary exports, though sustained overfishing has now greatly depleted the local marine population. Anguilla never developed a tourist draw related to sport fishing, but visitors to the island find some of the most highly regarded seafood cuisine in the Caribbean. Tourists mostly visit the island for the beaches, which are an increasing concern for the government, as awareness of coastal erosion and reef health increase (Hoggarth 2001). Despite its low relief, the island still hosts points of interest. In addition to the caves, unique ecozones like Katouche Valley, and the offshore cays and islands, there are numerous sites around Anguilla where scuba and snorkeling are popular, including a fully underwater marine park and extensive coral reefs (Jamason 2014). Anguilla does not cater to cruise lines, and while some Caribbean cruises will stop at the island for a few hours, the island is largely protected from the massive population fluctuations that accompany cruise tourism (Swanson 2014). The increasing economic impact of tourism may lead to a revision of current policies regarding cruise ships, but for now Anguilla does well relying on the draw of some of the most beautiful beaches in the Caribbean (Fig. 4.6).

4.5 Heritage and Tourism

Heritage tourism has not yet been fully realized on Anguilla, but opportunity for expansion exists. There are 42 known Arawak sites on Anguilla, some of which have been dated back as far as 1500 CE, others as recently as 600 CE (Cambridge 2012b). The most significant heritage site on Anguilla, Fountain Cavern, displays a deep religious significance. Inside the cavern, the top of a five-meter-long stalagmite has been carved into what experts say is a representation of the *Jochahu*, the spirit of fertility. Fountain Cavern (and Big Spring) also contain numerous petroglyphs, and many Zemis, three-pointed stones thought to ward off evil, were found in the cave (Cambridge 2012a). Fountain Cavern used to be open to the public, and although it remains part of one of Anguilla's two national parks, the cave itself is now closed for

Fig. 4.6 The Four Seasons Resort and Residences Anguilla, located on the north side of the main island's far eastern edge. Notice the pristine white sand beaches lining the coast in both directions. The island mountains of St. Martin separated by the Anguilla channel are visible in the background. Image from the Four Seasons Web site (http://www.fourseasons.com/anguilla/)

preservation. It was nominated for UNESCO status, with overtures of ultimately turning it into a show cave, but has yet to receive that recognition (Rogers 2010).

In many ways, Anguilla's environmental conditions have served as a buffer against conflicts that plague other Caribbean islands. For example, though its location was in a politically desirable location for the purpose of securing safe trade routes, it lacked natural resources that would have made it a target of exploitation. Anguilla was attacked once in 1688 by some 300 Irish colonists who had been deported from the French-controlled St. Christopher. They caused significant damage and are today referred to as the "wild Irish," but these colonists ultimately settled peacefully and integrated into the local community (Mitchell, n.d.c). Two other significant points of early conflict were the attempted French invasions in 1745 and 1796, neither of which resulted in a lasting power exchange between France and England (Halstead, n.d.). Unlike some Caribbean islands, which saw multiple power exchanges between two or more countries throughout their formative years, Anguilla was relatively even-keeled politically.

The lack of natural resources also kept expansive plantation agriculture from taking hold, which prevented class stratification from developing as rigidly as it did on other islands. During the economic downturn following emancipation, many former slave owners left Anguilla, seeking better fortune elsewhere in the Caribbean or returning to Europe. This left a majority African population on the island, and today the minority white population is well integrated (Halstead n.d.). It has been argued that Anguilla's continued status as a British Dependency has limited its growth, but the only significant social conflict in Anguilla's history came from the population seeking direct British governance (Countries n.d.).

The absence of agricultural resources has not proven to be a deterrent to tourism, however, as tourism on Anguilla has historically been based on the appeal of its picturesque beaches. The island's more than 33 public beaches remain mostly undeveloped and nearly always uncrowded (Tourism 2016). Few other geomorphic points of interest that would serve as a tourist draw exist on the island, though there are many opportunities around the island for snorkeling, diving, or short boat trips to the surrounding cays and islands. Aside from a few low years, tourism in Anguilla seems to be on the rise. While potentially a good thing for locals, a growing concern surrounding tourism impacts continues, especially the need to conserve its primary tourist attraction: beaches. One primary concern about tourism rests in direct damage to reefs by snorkeling, diving, and/or boating. Increased tourism has also resulted in greater stress on fisheries, for both recreational fishing and restaurant demand (Hoggarth 2001).

On the other hand, tourism has contributed to growing community awareness surrounding the overall state of coral reef health, which has been degrading for a variety of reasons not directly related to tourism in the past decades, including coastal development and unregulated discharge. Hurricane Luis in 1995 first brought to the foreground concerns about beach erosion, but tourism has turned those concerns into more of a pressing issue. If the beaches were to degrade significantly, the resulting drop in tourism could devastate Anguilla's economy. While gradually adopting more proactive conservation policies for both heritage and the environment, little of the island is formally protected. Some of the outlying islands are designated as important bird areas, and the habitat value of these islands and the salt ponds on the mainland is increasingly recognized, but official protection remains haphazard at best (Anguilla 2008).

4.6 Hazards

Compared to other islands of the Lesser Antilles, Anguilla faces relatively few hazards. Because of the absence of volcanic activity and subsequent low relief on the island, there is no danger of either volcanic eruption or landslides. The latter element is doubly important, because Anguilla's lack of permanent water means that flood events resulting from periods of intense rainfall could be compounded if Anguilla had greater altitudinal variation. Currently, Anguilla's primary hazards center around hurricanes, earthquakes, tsunamis, and floods. Though flood events often coincide with hurricane activity, they are not restricted to these times, and can be significant and damaging from concentrated rainfall events. November 2011, for example, saw a 30-year storm drop 150 mm of rain in less than 12 hours. Following a period of consistent but seasonally normative rain (and fully saturated soil), increasing runoff led to flash floods that caused property damage across low-lying parts of the island (Admin 2011).

Anguilla has not experienced a recent tsunami (though it has been subject to storm surges directly related to hurricanes), but in December of 2011 it became the first non-US territory in the Caribbean to be certified as Tsunami Ready. This certification requires development of a hazard mitigation plan, emergency management plan, public notification system, and tsunami warning plan. Emergency managers on the island also conducted training scenarios and completed a public outreach program relating to the new warning system. Since Anguilla is considered at serious risk for earthquake activity, development of a tsunami response plan was a wise precaution. Earthquakes are frequent near Anguilla, though most occurrences are typically minor. Buildings should ideally be designed with earthquake preparedness in mind, but this can come at substantial initial cost and requires importing often-costly materials to the island. This has not been standard practice in the past, but the Government of Anguilla recently adopted a building code with stricter standards. It may take time for consistent implementation, but it demonstrates a commitment to building safety (Gibbs 1998).

These new building standards are as concerned with structural stability in a hurricane as an earthquake—a challenge since the components that make a building hurricane resistant are often opposite of the elements that are earthquake resistant (Gibbs 1998). Hurricanes are a more significant recurring hazard to Anguilla, however, and have far-reaching implications for the entire island. Hurricane Luis, a Category 4 storm in 1995, was one of the most significant hurricanes to make landfall in Anguilla's recent history. Luis caused significant reef damage, inundating at least one cay, and eroding measured beaches by 40%. While the beaches gained back an average 75% of the sand area over the next several years, the actual shoreline receded inland 8.7 m (Hoggarth 2001; Cambers 1996).

Hurricane Luis also served the unfortunate double function of increasing hurricane awareness in Anguilla. Since the last hurricane of comparable strength had been Hurricane Donna, a Category 5 in 1960, residents of Anguilla anticipated they had a few decades before another similar storm hit (Rappaport 1995). It took only four years before the next analogous storm hit: Hurricane Lenny, in 1999. Hitting the island after Hurricanes Georges (in 1998) and Jose (early in 1999), Hurricane Lenny made landfall as a Category 4 (Cambers 1999). Lenny caused flooding up to 4.3 m deep in The Valley, resulting in $65.8 million in damages (Pan 2007). Hurricane Earl, a Category 3 storm in 2010 took out the power on Anguilla and caused $4.3 million in damage, but no loss of life (Caribbean 2014). Most recently, Hurricane Gonzalo (in 2014), a Category 1 storm, caused flood damage in the amount of $500,000 (Anguillian 2014).

Anguilla's hurricane frequency is standard for Caribbean islands, but remains a cause for concern, particularly for an island whose beaches are the primary attraction. Beach monitoring stations installed in 1992 help keep track of erosion, and Anguilla has implemented beach stabilizing fences to some effect (Cambers 2007, 2009; UNESCO 2003). These measures help mitigate the damage caused by hurricanes, but are ultimately only slowing the changes that rising sea levels and storm impacts are inflicting on the coastline (IPCC 2007). More substantial measures may become necessary in future years, and hopefully the government will take a proactive stance on developing a plan for future beach management.

4.7 Conclusion

It would be easy to look at Anguilla, a flat body of land with little relief, and say it lacks the drama or variety of the surrounding islands. To do so would be to miss a special place with a range of features to offer residents and visitors alike. Anguilla is an amalgam of distinctive elements that set it apart from other island nations in the Lesser Antilles. The salt ponds that form its only permanent wetlands provided a unique export for an island that lacked other natural resources typically produced on islands in the area. Now, those same ponds play ecological roles by protecting the coast and providing habitat for an abundance of bird species. The cays and coral reefs that litter the coast around the island extend Anguilla's habitat areas, while offering exposure to a variety of marine life for snorkelers and scuba divers.

Tourists have been a blessing and a curse for Anguilla. While undoubtedly important, as tourism represents the number one industry on the island, increased tourism has negatively impacted reef health and overall environmental quality. Yet tourism has also raised local awareness of beach erosion and a range of reef health issues, leading to multiple avenues of governmental reform. Erosion management efforts are timely, as the area has entered a cyclical period of increased hurricane activity that will continue to alter the coastlines.

Some things have changed significantly on Anguilla since it was inhabited by the Arawak people who relied heavily on the sea for food, growing only light vegetable crops and cotton, and relying on Big Spring for freshwater. Now, desalination plants provide drinking water to the island. But there is still only minimal agriculture, mostly subsistence farming done in backyard plots. The limestone caverns that the Amerindians revered as sacred sites are still present, unique heritage sites that offer a glimpse into the long pre-European history of the island. And the beaches remain, pristine, quiet expanses of sand on an island that has not yet embraced the intense tourist experience of cruise ships.

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Saint Martin/Sint Maarten and Saint Barthélemy

5

Russell Fielding

Abstract

St. Barthélemy and St. Martin are small islands among the northernmost of the outer, coralline Lesser Antilles arc and are separated from one another by a narrow channel. Both islands are characterized by undulating coastlines with cove-like white and golden sand beaches and impounded salt ponds, offshore islets, dry landscapes (though the higher peaks on St. Martin do support slightly more rain-dependent vegetation), and landforms combining ancient volcanics with more recent sedimentary geology. St. Barthélemy and the northern part of St. Martin are culturally and politically connected to France, while the southern part of St. Martin (known as Sint Maarten) is linked to the Netherlands. Both islands are hilly, and while St. Martin's larger size affords it some space for coastal plains, St. Barthélemy has significantly less flat land. Both islands are popular tourist destinations with St. Martin attracting more cruise ships and resort-based tourists and St. Barthélemy focusing on a smaller-scale, luxury tourism niche. Tropical cyclones occasionally threaten these islands, but the greatest hazards may be droughts and any disruption to the energy system since rainwater catchment and desalination provide the majority of the freshwater to both islands.

Keywords

Arid • Binational • Coralline • Mountainous • Tourism

A Toponymic Note

In this chapter, both islands will be referred to by shorthand names: Saint Barthélemy will be called "St. Barth" (read with a silent 'h'). This island is also frequently referred to in the literature as "St. Bart's" or "St. Barts," and less frequently in modern times as "St. Bartholomew," though this toponym is used in certain historical texts and maps. With regard to Saint Martin/Sint Maarten, following Benoît (2008) and other authors, distinct names for the two parts of the island, for the island as a whole, and during explicit discussion of the divided nature of the island will be used. The island of Saint Martin/Sint Maarten will be designated as simply "St. Martin." When discussing the distinct sides, the Dutch side will explicitly be referred to with the toponym "Sint Maarten," while the French side will be referred to as "Saint Martin", with no abbreviation of the word "Saint". When discussing the divided political geography of the island itself, both names will be used, separated by the virgule (i.e. "Saint Martin/Sint Maarten").

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5.1 Introduction

5.1.1 Orientation

Saint Martin/Sint Maarten (Fig. 5.1) and Saint Barthélemy (Fig. 5.2) are two small islands (87 and 21 km^2, respectively) located near the northern limit of the Lesser Antilles archipelago. Only Anguilla and the Virgin Islands reach further north. Politically, Saint Barthélemy is an overseas collectivity (*collectivité d'outre-mer*) of France, having achieved that status with independence from Guadeloupe in 2007. Saint Martin/Sint Maarten is a binational island, as its dual names indicate, divided by a roughly east–west border separating the French and Dutch sides of the rather triangular island. The larger (53 km^2), northern, French side is called Saint Martin, and the smaller (34 km^2),

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southern, Dutch side is called Sint Maarten. Saint Martin, like St. Barthélemy, is an overseas collectivity of France. Sint Maarten was a part of the Netherlands Antilles until that union's dissolution in 2010, after which Sint Maarten became an autonomous country within the Kingdom of the Netherlands.

The islands of St. Barth and St. Martin evoke landscapes and seascapes that come as close to the stereotypical image of "tropical paradise" as exist anywhere. Beaches of soft white or golden sand and warm, electric-blue water are backed by thickly vegetated mountains, alive with fruit trees, tropical birds, land snails, tortoises, and iguanas. Of course, as with other islands in the Caribbean, human activity, from subsistence agriculture to slave-based industries to international tourism, has altered the landscape on each island in its own way, both historically and today.

5.1.2 Previous Work

The most detailed, accurate, and influential early academic work on the landscapes and landforms of these two islands is the 1950 Ph.D. dissertation by Christman, later condensed and published as a journal article by the same author (1953). Christman's *Geologic Map of Saint Bartholomew* (Fig. 5.3) remains the standard some sixty-five years after its creation, although a 1983 map by Westercamp and Andreieff is more recent and technically superior. Christman's, however, remains popular owing perhaps to its sepia-tinted, monochromatic beauty, and English legend and accompanying text. The most accurate and functional colonial-era cartography of St. Martin, St. Barth, and several other islands in the region was done by Samuel Fahlberg in the eighteenth century (Reinhartz 2012).

In addition to the foundational work by Christman, notable earlier research into the geology, geography, and physical landforms of St. Martin and St. Barth includes Cleve's (1871) work, Spencer's (1901) report, and Vaughan's extensive work throughout the region, conducted throughout much of the first third of the twentieth century (e.g., 1918, 1926).

More recent work has focused upon specific questions of volcanism, tectonics, sedimentary geology, caverns, and biogeography. In addition to their geological interest, each island—but primarily St. Barth—has been the subject of anthropological and linguistic studies (Benoist 1964; Maher 2013), focusing upon its isolation, both as a function of its insularity and as exhibited within the island itself, owing both to topography and settlement patterns.

5.2 Setting

Previous literature on the Lesser Antilles region has failed to establish agreement regarding the island arc to which St. Barth and St. Martin belong. Fink and Fairbridge (1975) place both within the outer, "limestone" arc, while Cambers (2010) places St. Barth in the inner, "volcanic" arc and leaves St. Martin in the outer, "coralline" arc. Standing on the islands, evidence of their volcanic origins, especially in contrast to the nearby low and sandy Anguilla, remains apparent. These volcanic features, however, are not geologically recent and are in many places overlain by Miocene or later sedimentary rock. The islands in the inner, recent-volcanic arc, however, often show basaltic or pyroclastic geology at or near the surface. Many have erupted within historical time, including the most recent major eruption in the region—that of the Soufrière Hills volcano on Montserrat in 1995. By contrast, most of the rocks of volcanic origin on St. Martin and St. Barth date primarily from the Eocene to the Oligocene (Tomblin 1975). For this reason, this chapter places both islands firmly within the outer arc, while noting that the two arcs do indeed converge in the immediate vicinity, closing the gap that separates, for example, St. Vincent from Barbados or even Antigua from Barbuda. Only at Guadeloupe, where the two arcs are close enough to converge within one island, is the gap narrower.

The island of St. Martin lies between 18.0° and 18.1° North latitude and between 63.2° and 63.0° West longitude. Shaped roughly like an equilateral triangle leaning to the right, this island contains the point of highest elevation within the broad undersea plateau, called the Anguilla Bank, from which both islands rise. St. Martin is an island of hills, valleys, and impounded bays. The coastline is irregular in both morphology and topography, with sandy beaches, spits, and bars, alternating with rocky coasts, themselves comprised of limestones, marls, basalts, and porphyrites (Vroman 1968). The beaches consist of white to golden coralline sand, not the dark, volcanic sand of the geologically younger, volcanic islands to the south. The basement rocks on St. Martin are comprised of the ancient, silicified volcanic tuffs common to the other islands in the region (St. Barth and Anguilla especially), some of which remain exposed, forming the island's mountainous areas (Schwartz 2010). On St. Martin, these tuffs form the Pointe Blanche formation, named for the cape at the island's southernmost point, an area where the formation is most visible (Sypkens-Smit 1995). On St. Barth, rocks of the same age and provenance are referred to as the St. Bartholomew formation (Christman 1950).

Fig. 5.1 General physiographic map of St. Martin and surrounding islands. The island is separated into the French Saint Martin and the Dutch Sint Maarten. Place names and the descriptions of physiographic features such as rivers, lakes, and mountains reflect this political division (e.g., river vs. ravine). While the island officially has two separate place names, the more popular "St. Martin" is cartographically used to represent both nations. Cartography by K.M. Groom

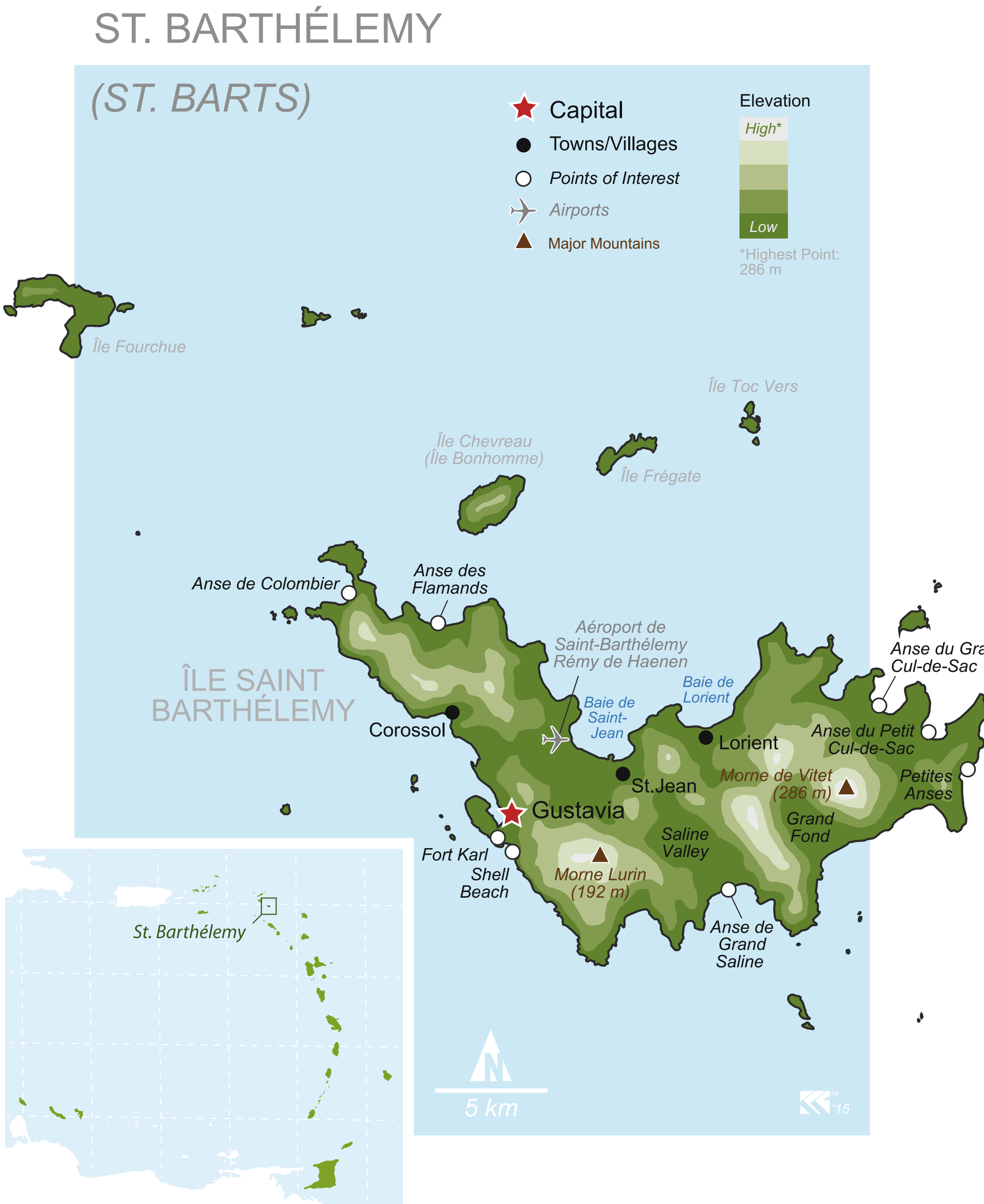

Fig. 5.2 General physiographic map of St. Barthélemy, colloquially known as St. Barts with surrounding islands. French place names and physical descriptions signify the islands political affiliation with France. Cartography by K.M. Groom

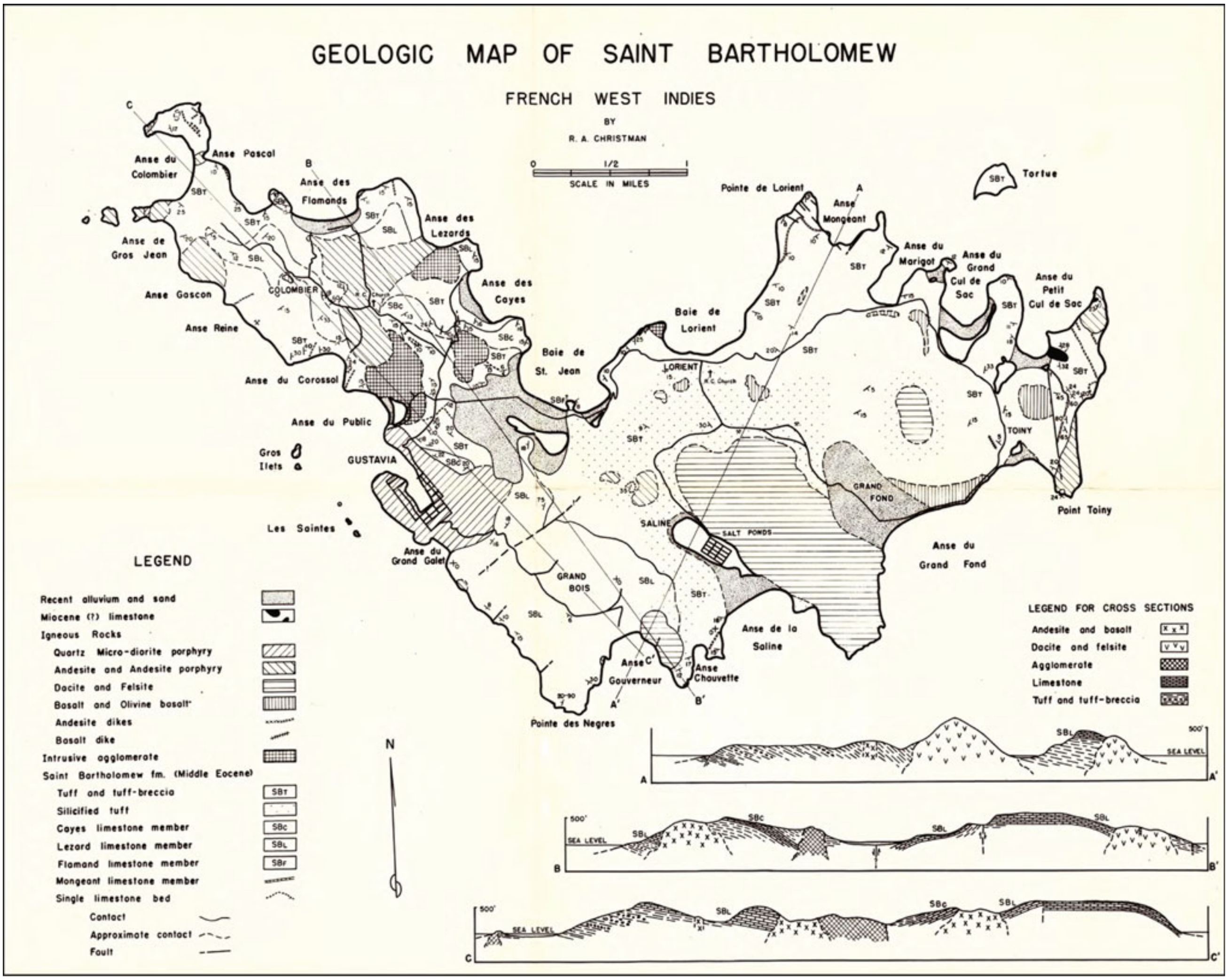

Fig. 5.3 "Geologic Map of Saint Bartholomew" by R.A. Christman, published in 1953. The detailed regional categorization, three cross sections running along the northwest–southeast and northeast–southwest diagonals, and pleasant aesthetic enhance the popularity of this map

St. Barth lies at 17.9° North latitude and between 62.9° and 62.8° West longitude. The island is shaped like a crescent opening north, or, if one is so inclined, like a smirking smile. The rolling coastline alternates between rocky shores and embayed coves, most of which feature sandy beaches at their landward extents. Like St. Martin, the structure of St. Barth is primarily composed of ancient volcanics overlain by Eocene limestones. Westercamp and Andreieff (1983) found evidence for three separate phases of volcanism, the first two occurring below sea level and coincident with the sedimentation processes that led to the limestone layers. According to these researchers, the volcanic center that produced the tuffs found on both St. Barth and St. Martin is thought to have been located near St. Barth's present north coast and offshore near the present islets of Île Chevreau (also called Île Bonhomme) and Île Frégate.

Both islands experience a climate marked by stable temperatures and seasonally variable precipitation. Average monthly temperatures range from 25 to 28 °C throughout the year. Diurnal temperature variation is more extreme than seasonal variation, ranging by about 5 °C from day to night. Monthly rainfall varies throughout the year, with a marked shift from rainy to dry seasons. On both islands, rainfall peaks at about 130 mm in October and is at a minimum, about 45 mm, in February. St. Martin's more mountainous interior does afford that island slightly more rainfall at higher elevations than St. Barth receives.

The soils of St. Barth are thin, rocky, dry, and relatively infertile. The native flora is largely xerophytic and agriculture has long been challenging. On St. Martin, owing to the higher elevations and the precipitation that this topography captures, soil layers are thicker and ephemeral streams leave deep, dry "ghauts" in some valleys, a feature mostly absent from the St. Barth landscape.

5.3 Landforms

5.3.1 General Landscapes

Rather than being dominated by a single volcano, as are several of the islands in the Lesser Antilles (e.g., Saba or Nevis), both St. Martin and St. Barth are characterized by numerous peaks, valleys, and—especially in the case of St. Martin—low coastal plains. Christman (1950) identified two separate mountain chains traversing St. Martin: the larger of which is roughly geographically central on the island, extending from Koolbaai Berg (Cole Bay Hill) in the south to Mount O'Reilly in the north (though perhaps a better origin is at Cay Bay Hill, slightly further south than Cole Bay Hill). This cordillera includes Pic Paradis, the island's highest point of elevation (424 m). Christman's second mountain range is a smaller, southeastern chain stretching from the island's southernmost point, Pointe Blanche, to Les Deux Frères, the two hills that stand behind the southern shore of the Baie de l'Embouchure, on the island's east coast.

Between these mountain chains lies the major valley on St. Martin, which extends from Philipsburg in the south to Baie Orientale in the northeast, then makes a westward traverse of the island, broken only by low hills, across to Grand Case, on the northwestern coast. This western extension of the valley is where the smaller, French side airport is located.

The other major valley on St. Martin begins at the Great Salt Pond and Little Bay on the island's south coast and trends northward. This valley is enclosed on three sides by ridges that converge at the international boundary to form the island's larger mountain chain. The valley, which is located entirely within the Dutch side, contains the villages of Cul-de-Sac and St. Peters.

The Terres Basses peninsula, as the name suggests (at least to Francophiles), is a low-lying area, punctuated by a single rise—Morne Rouge at 52 m. This peninsula, which Schwartz (2010, 303) describes as a "double tombolo," but which could also be seen as a single, large tombolo with a flooded interior, encloses Simpson Bay Lagoon (sometimes spelled *Simson*), the island's largest inland water body (Fig. 5.4). The two isthmuses that frame the bay are low, narrow, and predominantly sandy, though limestone terraces and cliffs may be found on the southern isthmus from Cupecoy to Maho Bay (Fig. 5.5) and on Terres Basses proper from Point Plum to Pointe du Bluff. The cliffs can reach heights of up to six meters, though most are much lower, and occasionally contain erosional features such as arches. The island's international airport is located on the southern spit.

St. Barth is a V-shaped island—others, beginning with Christman (1953, 67) have understandably likened it to a "boomerang"—with three main mountainous areas containing two major valleys and numerous small coastal plains. The westernmost mountainous area is the northwestern, leeward side of the island where peaks remain lower than 200 m but drop precipitously toward the beaches at Flamands, Colombier, and, to some extent, Corossol. The central mountains are found in the south of the island—the point of the V—and form a single complex constituting the foothills of Morne Lurin (192 m), this region's highest peak. The eastern mountains form a semicircle on the island's windward side, hemming in the Grand Fond Valley (Fig. 5.6), which faces the predominant wind and waves of the island's southeast coast. In the eastern portion of this semicircle of peaks is found Morne de Vitet, the summit of which, at 286 m, is St. Barth's highest point.

Between the central and eastern mountainous areas lies the Saline valley, the location of St. Barth's largest site for salt making, now defunct. Between the foothills of Morne Lurin and the mountains on the island's leeward side lies a saddle, the northern slope of which is the site for the island's airport. The airport itself has attained a certain degree of infamy as one of the more difficult landings, certainly in the Caribbean, perhaps in the world. The 650-m runway, short by almost any standard, slopes downhill[1] toward St. Jean Beach, where it terminates mere meters from the waterline (Fig. 5.7).

Around this mountainous skeleton, the island's deeply embayed coastline spreads like a fringe (Fig. 5.8). Eroded tongues of ancient lava flows, shaped by prevailing currents and capped in some places by cemented sediments, laid bare in others, circumscribe the island with an undulating ring of bays and headlands that trap coastal sediment, forming discrete beaches and imbuing a sense of place to each as its own entity.

The St. Barthélemy Channel separates St. Martin to the north and St. Barth to the south by a distance just less than 20 km at its narrowest point. Numerous islets, rocks, and reefs dot this channel, creating convenient anchorages or dangerous hazards, depending upon the attentiveness of the sailor. Two of these islets, Fourchue and Tintamarre, feature interesting geologies and human histories.

Fourchue is a small (roughly 0.5 km^2), uninhabited islet in the St. Barthélemy Channel belonging to St. Barth. This islet is rocky and denuded—the former quality an example

[1]The slope is downhill on the most common approach. Sometimes, though, owing to wind conditions, controllers opt to bring pilots in over the beach, in which case the runway slopes uphill from the perspective of those aboard the landing plane and terminates below a hilltop traffic roundabout on a busy stretch of road.

Fig. 5.4 Aerial view looking north toward Simpson Bay Lagoon, center, framed by its twin isthmuses. Mainland St. Martin is to the *right*; the Terres Basses peninsula is out of the frame to the *left*. The low island in the background is Anguilla. Photograph by D. Fielding

Fig. 5.5 Limestone terraces at Cupecoy on St. Martin. Photograph by R. Fielding

of the region's volcanic history and the latter owing to its resident herd of goats—and is a popular destination for yachters and snorkelers. Historically, the islet has been associated with both pirates and slave traders and occupies a rather liminal space within the historical political geography of St. Barth. As islands often do, Fourchue became a sort of unofficial entrepôt for illicit commodities—including human cargo—that would otherwise have been forbidden (Maher 2013).

Île Tintamarre is a small (0.9 km^2), flat island located 3 km off St. Martin. Politically, it is a part of Saint Martin. Currently uninhabited, Tintamarre is a popular day-trip destination for tourists, who come for its beaches, reefs, and mud bath. The island was once home to a population of more than 100 people and even supported an international airline, the *Compagnie Aerienne Antillaise*, run by the late Rémy de Haenen, a celebrated resident and local official on St. Barth (Casius 2005).

Fig. 5.6 The Grand Fond valley on St. Barthélemy. Photograph by R. Fielding

Fig. 5.7 The runway at Aéroport St-Jean-Gustav III (SBH), recently renamed for Rémy de Haenen, on St. Barthélemy, as seen from an airplane making the most common approach. Baie de Saint-Jean is visible at the end of the runway. Image from Fielding (2014)

According to one mid-twentieth century historian, St. Barth "lacks almost all natural advantages except an excellent harbor" (Ekman 1964a, 17). Indeed, Gustavia does represent one of the best natural harbors in the region (Fig. 5.9), provided the vessel's draft is not too deep. This natural harbor is framed by *La Pointe*, the peninsula on the south, which adjoins the main island at a low saddle beneath the 34-m hill on which Fort Karl formerly stood. The saddle gives way to Shell Beach, one of the more unique beaches on St. Barth.

Shell Beach (*Anse de Grand Galet*) is not made up of pebbles as the French name would imply, but of bivalve and mollusk shells, deposited on the beach by waves after having been dredged from Gustavia harbor. This beach also features large (up to 4 m diameter) boulders of sedimentary rock. Some of this beachrock contains shells that retain their natural color and shape, an indication to one researcher of their young age (Vroman 1968).

The eastern coast of St. Barth, and to a lesser extent, Lorient Bay, exhibits an interesting example of coral

Fig. 5.8 Northeastern view of the undulating St. Barthélemy coastline, including the rocky Petite Anse, Anse des Flamands, and in the distance, Baie de Saint-Jean. Also visible are three offshore islets, from left: Île Chevreau (also called Île Bonhomme), Île Frégate, and Île Toc Vers. The sargassum raft barely shown at the bottom of the image was part of an island-wide presence during the winter of 2014–15 and continuing to the time of this writing (see Hazards section). Photograph by R. Fielding

pavement. The attached reef has colonized nearly the entirety of two bays—Anse de Grand Cul-de-Sac and Anse de Petit Cul-de-Sac, as well as the nearly beachless east-facing coast known as Petites Anses.

5.3.2 Salt Ponds, Baymouth Bars, and Piscines Naturelles

Both islands display several variations of inland saltwater features, both natural and anthropogenic. When circumnavigating St. Martin, one notices the abundance of baymouth bars and salt lagoons contained therein. Perhaps the most prominent are Simpson Bay Lagoon—contained within the isthmuses that connect the main island to the Terres Basses peninsula—and the Great Salt Pond, held back by the baymouth bar upon which the town of Philipsburg, the capital of Sint Maarten, is situated (Fig. 5.10).

On St. Barth, the large salt pond near the eponymous *Anse de Grand Saline* is no longer in operation but stands as a landscape of remembrance to one of the island's major historical industries—salt making (Fig. 5.11). The dryness of this island limited its agricultural potential (and challenges its present, seemingly-insatiable development for tourism) but made it an ideal site for evaporation ponds. The island government has recently begun efforts toward environmental restoration at the site of the former salt pond.

In at least two locations on St. Barth, ancient coastward lava flows have formed natural pools, replenished by breaking waves but otherwise separated from the sea. These sites are known as the Washing Machine, owing to the turbulence caused when large waves enter, and, simply, *Le Piscine Naturelle*, or the natural swimming pool (Fig. 5.12). Both are popular with swimmers, though the former is more accessible than the latter owing to a walking path that does not require the hiker to cross private property.

5.3.3 Caverns

Both islands feature caverns in places where the soft limestone is exposed and susceptible to erosion. Sypkens-Smit (1995) refers to, and includes photographic plates and schematic maps of, caverns at several locations along the Terres Basses peninsula of St. Martin. These caves have yielded important findings related to the paleofauna

Fig. 5.9 Aerial view, facing southeast, of Gustavia, St. Barth, showcasing the natural harbor. Photograph by D. Fielding

Fig. 5.10 Aerial view, looking north, of Philipsburg, Sint Maarten, situated between the Great Salt Pond (Groote Zoutpan) behind the town and Great Bay (Groote Baai) in the foreground. Photograph by D. Fielding

(McFarlane 2013) and human prehistory (Haviser 1991) of the region. Sadly, from the perspective of science, and inexcusably from the perspective of national heritage, one of the more artifact-rich caves on St. Martin was "definitively ruined some hours after the discovery by using explosives and pouring in concrete" by a hotel construction team (Dubelaar 1985: 171). On St. Barth, no artifacts or significant fossils have been reported, but Lenoble et al. (2012) have documented and charted numerous caverns and rock overhangs. These tend to be clustered in the south and east of the island with the greatest concentration among the foothills of Morne Lurin and near the coasts at their bases.

Fig. 5.11 The salt ponds at Saline on St. Barth. Saline Beach (Anse de Grande Saline) is visible between the mountains in the background. Photograph by R. Fielding

Fig. 5.12 The “Washing Machine” on St. Barth. Photograph by R. Fielding

5.4 Heritage and Tourism

5.4.1 History

The standard history of St. Martin is contained in the straightforwardly titled, *History of Sint Maarten and Saint Martin* (Hartog 1981). While dated, this text addresses much of the history of the island before mass tourism began to flourish there, though it does so from a decidedly Eurocentric perspective. Another valuable, locally flavored history is *Beyond the Tourist Trap: A Study of St. Maarten Culture* (Sypkens-Smit 1995), which is, as the name implies, primarily focused on the island's Dutch side.

The best locally produced (and certainly locally flavored) history of St. Barth is Bourdin's *Histoire de St. Barthélemy* (1978), published originally in French with side-by-side English translation. Maher's (2013) text on the linguistic geography of St. Barth provides a surprisingly thorough account of the history of the region, including not only St. Barth and St. Martin, but also St. Kitts, Guadeloupe, and islands further afield. Maher relies heavily upon the work of Per Tingbrand for information about the Swedish period of St. Barth's history.

5.4.2 Colonialism and Politics

Saint Martin/Sint Maarten is famously the "world's smallest binational island" (Schwartz 2010: 302). In response to frequent disputes between the French and Dutch settlements on the island, the 1648 Treaty of Concordia established the first border—altered several times later—between the two sides. While the existence of a border has led to the diverging political structures on the island, the actual border poses no barrier to travel, whatsoever. One would only stop to take a souvenir photograph—never to show a passport. At each point where the road crosses the border, a small marker stands with the French and Dutch flags on either side. The border, of course, does not separate regions of physical geographical difference, nor are the human geographies noticeably different on either side, except in a few minor ways. English is more prevalent on the Dutch side than on the French, but neither side is difficult for a monolingual Anglophone traveler.

St. Barth has been referred to as "history's shuttlecock" (Maher 2013: 29), owing to its back-and-forth transfer, first between the French and British and later between the French and Swedish colonial governments. This volley was not unique to St. Barth, of course, and could describe any number of islands throughout the Lesser Antilles. The near-century of Swedish colonial rule (1784–1878) gave St. Barth the name of its capital, Gustavia (previously known as *le carénage*, simply, "the place where boats are hauled out of the water"[2]), as well as an enduring cultural affinity for the Scandinavian country. St. Barth stands alone as a formerly Swedish Caribbean possession.

5.4.3 Tourism

St. Martin has embraced tourism, to the nearly full exclusion of other industries, since the 1956 economic development plan initiated by the Technical Economic Council of the Netherlands Antilles. According to Hartog (1981), it was this plan that rejected agriculture, livestock, fishing, mining, and industry as viable parts of St. Martin's economic future. During the next decade, the 1960s, several projects were started with the goal of developing the island's infrastructure for tourism. The specific focus was on the airport, water and electricity supplies, roads, and hotels. Today Sint Maarten—and to a lesser extent, Saint Martin—widely embraces tourism. The port in Philipsburg is equipped to handle multiple large cruise ships simultaneously. Princess Juliana International Airport is one of the busiest in the region and one of the few that can accommodate large, long-haul jets. The island hosts over one million visitors per year and offers resorts, casinos, tours, and watersports for activity-seeking tourists.

Tourism on St. Barth is of a different character than tourism on St. Martin. While the industry has its start at roughly the same time period, the mid-twentieth century, the current status is quite different. Maher (2013) traces the beginning of tourism there to the arrival of David Rockefeller in 1958. After Rockefeller bought property on the

[2]Technically speaking, the town is called Gustavia and the port was called *le carénage*. The earliest evidence of the distinct identities of the port and the town is from a March 24, 1788, report to Stockholm from Johan Norderling, a Swedish judiciary, who wrote, "The Carénage (one portion of the harbor of Gustavia) is above all else unceasingly beautiful; I never refrain from admiring it" (cited in Ekman 1964b: 8). There remains some confusion about the Le Carénage/Gustavia distinction within the popular press today. For example, one tourist book states that "the town of Carénage was renamed Gustavia in honor of the Swedish king" (Didcott and Didcott 1997: 7). The actual situation seems to be that there was no proper town near the port until Sweden took possession of St. Barth and built up the harbor area. Thus, the name *Gustavia* and the town itself emerged simultaneously at or near the site of the port, which had been—and for a while continued to be—known simply by its descriptor, *le carénage*. Maher's (2013) history supports this interpretation, as do certain earlier documents, for example, a periodical from 1800, which first refers to "Le Carenage, near which stands Gustavia, the sole town in the colony," and later states that "Le Carenage had no town belonging to it before the island was in possession of Sweden" (Anonymous 1800: 68). Today, the port is officially called the Port of Gustavia (*Port de Gustavia*) and still "looks as if it had been drawn by a child asked to sketch an ideal harbor" (Ekman 1964a: 224).

island and built a vacation home, other wealthy foreigners—first Americans, then Europeans—began to follow suit. By the end of the 1970s, the economy of St. Barth had been thoroughly transformed from the agrarian and maritime character of the past to one wholly focused upon tourism. Despite the single focus on one sector, tourism development has been strictly regulated on St. Barth. While many environmental activists, scholars, and journalists decry the saturation of the island's roadways with cars, its slips with yachts, and its beaches with villas and guesthouses, the trend in St. Barth remains one focused on luxury, rather than mass, tourism. Hotels remain small, both in physical size and number of guest rooms allowed in each. Prices remain high, compared to other Caribbean islands, and the port in Gustavia cannot accommodate large cruise ships (although ships do occasionally anchor offshore and transport tourists to St. Barth via tender). The wealthy clientele whose presence on St. Barth precipitated the island's tourism development have continued to constitute its target market even as the island is "discovered" by a more middle- to upper-middle-class tourist set. Still, according to Cousin and Chavin (2013: 188), the touristic appeal of St. Barth continues to be based upon its "insular exclusiveness, tropical exoticism, French refinement, and Euro-American cosmopolitanism."

5.5 Hazards

Both islands are vulnerable to hazards that might cut off their supply of imported resources. St. Barth, especially, is dependent upon imports for much of its subsistence. With no fresh surface water or groundwater, St. Barth has long been vulnerable to drought. Despite the waste-to-energy powered desalination plant, in operation since 2001, fresh water on St. Barth remains in short supply (Fielding 2014). Additionally, the fuel for the incinerator—municipal and industrial solid waste—is primarily obtained through imports in the form of consumer goods and packaging. Any hazard, such as a hurricane, that disrupts the importation of these goods would also threaten the fuel supply for the desalination plant.

5.5.1 Hurricanes

The location of St. Martin and St. Barth in the northern Lesser Antilles places the islands within the path of tropical cyclones. According to analysis by Caron (2011, 192), both islands have been "flooded" by five storm surge waves, produced by Category 4 or 5 hurricanes since 1851. The eye of a storm need not pass directly overhead to cause substantial damage. Hurricane Omar, as cited by Caron (2011), passed 100 km north of St. Barth—thus, at least 70 km north of St. Martin—and still resulted in major damages to both islands. Damage from hurricanes includes both the destruction of infrastructure and the erosion of coastlines.

5.5.2 Earthquakes and Tsunamis

While neither St. Martin nor St. Barth sits on a known fault line, the nearby seismic zones off Puerto Rico and further south, in the Windward Islands, are known to produce earthquakes that can cause tsunamis. Caribbean volcanoes are also rarely, but powerfully, tsunamigenic. Despite the multitude of potential causal events, such as earthquakes, terrestrial volcanic eruptions, submarine volcanic eruptions, and landslides, both in the region and further afield, tsunamis in the Caribbean are rare. One team of researchers analyzed the data and historical descriptions related to 91 extreme wave events that occurred throughout the Caribbean region between 1498 and 2000 and determined that between 27 and 36 of these wave events represented true tsunamis (Lander et al. 2002). Of these, only one is definitively known to have caused damage on St. Barth and St. Martin: the November 18, 1867, tsunami caused by a 7.5-magnitude earthquake with an epicenter located between St. Croix and St. Thomas in the Danish West Indies—now the US Virgin Islands (Zahibo and Pelinovsky 2001). An earlier teletsunami, generated across the Atlantic in 1755 by an earthquake near Lisbon, Portugal, caused a 4.5-m wave on St. Martin. Though no specific effects were recorded from this tsunami, one author states that "lowlands on most other French islands were inundated," indicating the possibility of flooding and damage on both St. Barth and St. Martin (Lander et al. 2002, 64).

5.5.3 Nearshore Development

Both islands display frequent tourism-oriented development in close proximity to the shore. Perhaps this is best epitomized by Princess Juliana International Airport (SXM) and the famous Maho Beach on Sint Maarten. This west-facing, 320-m-long beach is situated directly across a two-lane street from the base of the airport's only runway. Because of SXM's role as a regional hub—one of the few airports in the Lesser Antilles that receives trans-Atlantic flights—large airliners regularly approach low over the beach, which is open to the public. The low-flying jumbo jets have become a major tourist attraction in their own right (Fig. 5.13). The spectacle notwithstanding, the proximity of the airport to the beach, serves to highlight the issue of coastal development and its exacerbation of both islands' vulnerability to a host of hazards including coastal erosion, storm surge from

Fig. 5.13 A KLM 747, arriving from Amsterdam, approaches Princess Juliana International Airport over Maho Beach for landing. Photograph by D. Fielding

hurricanes, tsunami, and perhaps most insidious—sea level rise due to climate change.

5.5.4 Sargassum

While not a hazard to life or property per se, the recent influx of sargassum seaweed (*Sargassum natans* and *S. fluitans*) has certainly been hazardous to both islands' tourism-based economies. This issue is by no means restricted to St. Martin and St. Barth. Rather, it has affected nearly all the islands and mainland beaches in the Caribbean basin. While some amount of sargassum has always been present in the waters and on the beaches of the Caribbean, 2011 saw an unprecedented increase in its quantity. This influx was repeated in 2014 and 2015, owing to the right combination of sea-surface temperatures, nutrient availability, and ocean currents bringing sargassum from its blooming sites in the Atlantic into the Caribbean (Doyle and Franks 2015). The sargassum problem is one of overabundance. A small amount of the plant is beneficial as habitat for marine fauna while at sea and performs services of beach nourishment and shoreline stabilization onshore (Doyle and Franks 2015). In larger quantities, however, the associated odor, insects, and unsightliness of sargassum on beaches, along with the risk of damage to fishing gear and boat motors, tend to outweigh the plant's natural benefits. While innovative uses for sargassum are being tested—including use as a fertilizer, animal feed, or dune stabilizer—most efforts in the Caribbean, including on St. Martin and St. Barth, focus on techniques for its speedy removal from beaches frequented by tourists. In St. Martin, this effort is primarily the responsibility of beachfront resorts, while in St. Barth the municipality manages the removal of sargassum from popular beaches.

5.6 Conclusion

St. Martin and St. Barth are exemplary forms of Lesser Antillean geography, both human and physical. While both lie within the outer, limestone arc, evidence of past volcanism remains on the surface or just below. The beaches, mountains, bays, and vegetation are typical of the region but perhaps somewhat more concentrated here, owing to the islands' small areas. Each island also reflects the history of European colonialism in the Caribbean—Saint Martin/Sint Maarten has its famous international border and St. Barth, as "history's shuttlecock" (Maher 2013, 29), has its history of European power shifts woven into its very fabric. While the climatic and tectonic processes that shaped the islands are still evident in the form of natural hazards, tourists continue to arrive—along with their attendant infrastructural growth and development—drawn by the densely packed variations in human and physical geography present on these small, lovely islands.

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6 Saba and St. Eustatius (Statia)

Jennifer L. Rahn

Abstract

Saba and St. Eustatius/Sint Eustatius (Statia) represent geologically young (less than a million years) Pleistocene island arc volcanoes that rise at the northernmost part of the Lesser Antilles. Both are small islands less than 21 km^2 in size with populations around 2000, and both have stratovolcanic features and many Pelean domes with adjacent pyroclastic flows. As a single volcano, Saba's steep slopes drop off precipitously into the sea, while St. Eustatius lies at the northern end of a shallow submarine bank that links to St. Kitts and Nevis to the southeast. Similar in geologic history and perhaps co-eruptive (though Statia is slightly older and has more erosional features and some uplift), the islands also have similar climates, winds, waves, and ocean current regimes, but lack often-found-in-the-Caribbean geomorphic features such as dunes, perennial streams, wetlands, karst, aquifers, and inland water bodies. Saba and Statia both have heritage sites, including a few (small) Amerindian archaeological sites, but most historical research centers on post-European history including maritime figures, agriculture, and slavery. Owing to their small sizes, neither has been developed very heavily, though Saba is famous for its scuba diving and Statia is known for its oil terminal. Both islands face similar environmental hazards that include hurricanes, earthquakes and volcanism, and drought.

Keywords

Pelean dome • Coral reef • Scuba • Volcano • Landform

6.1 Introduction

Saba and St. Eustatius/Sint Eustatius (Statia) (Figs. 6.1 and 6.2) are both located near the 17° north latitude and 63° west longitude lines. The smaller of the two, Saba (*say-bah*), hosts about 2000 full-time residents on it 12 km^2, while around 3500 people make the 21 km^2 St. Eustatius—*Statia* (*stay-shuh*) as locals call it—home. Separated by 27 km, Saba and Statia sit 45 km southwest (12 min by plane) and 61 km south (20 min by plane) of St. Martin/St. Maarten, respectively. Both islands are special municipalities of the Kingdom of the Netherlands, and the top of Saba's volcano, Mount Scenery, represents the highest point in the Dutch Kingdom (877 m). Saba has four villages, Zion's Hill or Hells Gate, Windwardside, St. Johns, and The Bottom, which serves the island's administrative capital. Statia does not have towns in the classic sense, only a settlement, Oranjestad, the capital. While most people from Saba call themselves Sabans, in the village of Hells Gate, they use Sabians. On Statia, locals refer to themselves as Statians. As of October 10, 2010 (10/10/10, colloquially know as ten-ten-ten), Saba, St. Eustatius, and Bonaire became special municipalities of the Netherlands and are also referred to as the "BES islands" or "Caribisch Nederland." Day-to-day local affairs are managed by an elected Island Council, presided over by a Lieutenant-Governor. The Dutch have jurisdiction, environmental say (both islands are regarded by the European Union as an overseas territory and subject to

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Fig. 6.1 General physiographic map of Saba and surrounding features, such as Diamond Rock and the Saba National Marine Park run by the Saba Conservation Foundation. The small mountainous island is only 13 km^2 (5 mi^2) but rises from sea level to 877 m at the peak of Mt. Scenery. Cartography by K.M. Groom

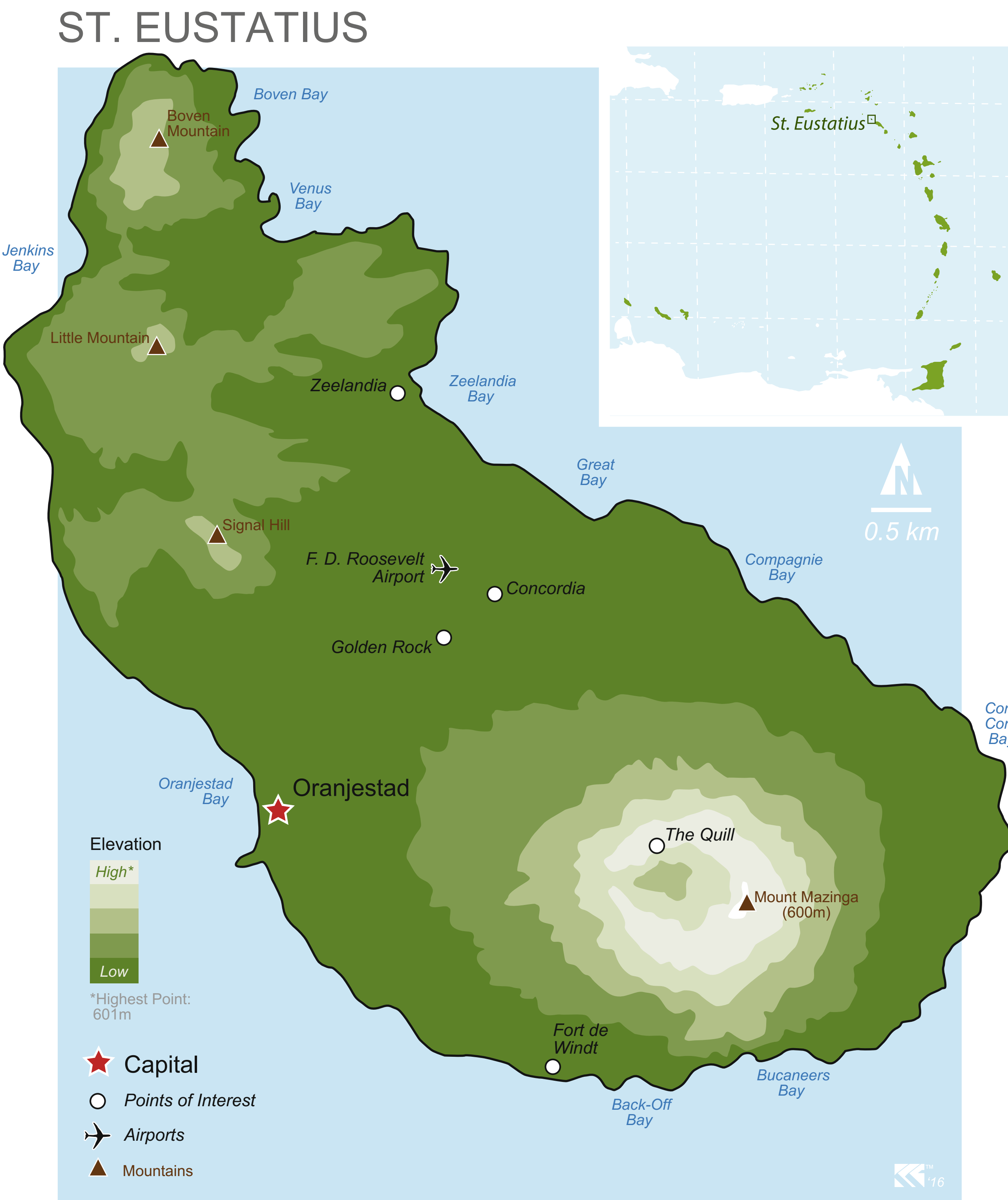

Fig. 6.2 General physiographic map of St. Eustatius. Slightly larger than its neighboring Saba, St. Eustatius is dominated by the large volcanic crater called "The Quill" to the south and a few smaller mountains in the north. Most of the island's population resides within the central lowlands. Cartography by K.M. Groom

EU regulations) and sponsor and subsidize the major projects on the island that affect its landscape and landforms. These islands should not to be confused with the island of Eustatia (30 acres in size) and Saba Rock (approximately an acre and a half in size) in the British Virgin Islands.

6.2 Setting

Saba and Statia represent the northernmost part of the active island arc of the Lesser Antilles. The volcanoes that created Saba and Statia formed from the subduction of the North American plate under the eastern-most section of the Caribbean Plate (see Fig. 2.1). Although the formation of the Lesser Antilles volcanic arc is geologically young (5.3–2.6 Ma), Saba and Statia are the youngest islands of the arc (less than a million years), with the islands' initial underwater activity likely to have happened in the mid-Pleistocene. Statia's subaerial presence occurred about 1 million years ago, while Saba first appeared above sea level around 500,000 BCE.

Roobol and Smith (2004) summarized Saba and Statia's structural evolution and detailed geology, petrology, and petrogenesis specifically, by drawing on previous works of Saba by Molengraff (1886), LaCroix (1890, 1893), Hovey (1905a, b), Sapper (1904), and Perret (1942), and of Statia by Westermann and Kiel (1961), Maclure (1817), Cleve (1871), Molengraff (1886, 1931), Sapper (1903, 1904), and Hardy and Rodrigues (1947). The Quaternary sea-level curve for the Caribbean region shows that sea level fluctuated from +6 to −24 m relative to present sea level, thus affecting the size, shape, and geomorphology of the islands through time (Emiliani 1978; Aubrey et al. 1988). The subsequent volcanic geomorphology was created by both constructive and destructive processes, now visible as landforms on both islands.

Saba is believed to be underlain by a system of parallel dikes emplaced into a fault zone. In contrast, The Quill volcano (Statia) is underlain by a magma chamber in which crystal fractionation occurs to produce a wide range of lava compositions. It has been successfully demonstrated that other volcanoes have similarly contrasted crustal plumbing systems to those of Saba and the Statia (Roobol and Smith 2004). For example, the Soufriere Hills volcano on Montserrat is similar to Saba, whereas Mt. Pelee, Martinique that erupted in 1902 and 1929 is similar to The Quill (Caribbean Volcanoes 2015). Geologists have shown that the island of St. Eustatius is gradually subsiding (DCBIODATA 2015) and there are local reports on Saba of uplift (Eddie Hassell personal communications).

6.2.1 Saba and Statia Climate

Saba and Statia's tropical climate is governed by their latitude, the Northeast Trade Winds, and the North Equatorial Current. Saba and Statia average of 12 h of daylight throughout the year (11 in December and 13 in July), and although temperatures extreems vary throughout the year from 19 to 36 C, they usually range from 25 to 28 C. In general, the islands experience sunny weather, with light constant Northeast Trade Winds that bring constant cool breezes and ample moisture (Statia Tourism 2015). The prevailing winds drive the dominant waves to hit the eastern, windward sides of the islands. Multidirectional wind gusts average 16 km/h (10 mph) and on Saba can reach 40 km/h (25 mph), which often causes all flights to be canceled. On both islands, precipitation varies from 980 to 1110 mm. Both temperatures and precipitation vary on the islands depending on the geographic location (higher precipitation on the windward sides, for example) and local elevation (e.g., cooler temperatures at higher elevations and orographic effect). Several events cause the islands to be relatively cool: The tops of the mountains have frequent cloud cover, winds blow up through the ravines bringing a cool breeze to the higher elevations, and the number of hours of direct sunshine is reduced by the shadow of surrounding mountains. In the case of The Bottom on Saba, this results in only about six hours of direct sunlight each day (DCBIODATA 2015).

While some precipitation falls on Saba and Statia during the hurricane season (June to October) associated with tropical storms, approximately 80% of the annual rainfall is concentrated in the rainy season beginning in October and lasting through December (DCNA 2015). Still, rainfall is inconsistent from year to year, and very dry ones can follow very wet years. Notable droughts happened in 1952/1953, 1982/1983, and 2015 where agricultural production dropped to a minimum, and drinking water had to be imported occasionally (DCBIODATA 2015). The steep hillsides, thin soil layers, and fractured igneous rock prevent the natural catchment of rainfall. Though a few brackish springs exist near the coast, there are no perennial streams, lakes, or aquifers on either island, meaning rainwater must be stored, usually in cisterns below most buildings.

With only rainwater as a freshwater source, Saba and Statia generally remained uninhabited, though it is suspected the islands were being used for fishing and foraging since around 500 BCE. The islands went mostly unused by European Colonialists until the seventeenth century and, though currently Dutch in nationality, the English language remains in strong use, demonstrating the persistence of early British Colonists. While Saba and Statia were a colony of the

Dutch West Indies by 1828, it was not until a couple of decades later that they would become Dutch dependencies (1845), and more than a century after that before they would become part of the Netherlands Antilles (1954). Throughout the twentieth century, Saba and Statia became and remained quiet islands, with tourism (primarily hiking and scuba diving) and archaeological studies beginning in the 1980s.

6.2.2 Saba Geologic History and Evolution

The deceptively simple stratovolcano-like appearance of Saba is misleading because Mt. Scenery, the highest peak on the island, is just one of about twenty Pelean-like domes. These domes, and their associated aprons of pyroclastic material, represent a combination of newer domes sitting eccentrically on top of older Pelean dome complexes (Roobol and Smith 2004). In terms of volcanology, Saba is a single volcanic complex, the subaerial part of which has dimensions that measure 50% of those defined by the 500 m submarine contour. Submarine morphology slopes uniformly away from the island in all directions (Fig. 6.3).

6.2.3 Statia Geologic History and Evolution

St Eustatius lies at the north end of an 80-km-long shallow submarine bank (the edges of which are 180 m below sea level themselves) on which the islands of St. Kitts and Nevis also lie. The geology of St. Eustatius can be divided into three very different landscapes (Fig. 6.4). The oldest geological unit on the island is the northern hills—the Northern Centers as Roobol and Smith (2004) called them—composed of five morphologically distinct older volcanoes, built of lava flows and Pelean domes, and pyroclastic aprons of block and ash deposits, each having varying degrees of erosion. The three youngest centers, although eroded, retain their original volcanic features, and lava flows and lithified pyroclastic deposits from these centers, well exposed in the steep sea cliffs around the northern part of the island, have been dated to an age of less than 1 million years. The southern slopes of the northernmost hill are orange-colored, marking the site of former fumarolic activity. When first formed, the Northern Centers appeared as an independent volcanic island with surrounding shallow water carbonate banks and patch reefs containing volcanic deposits.

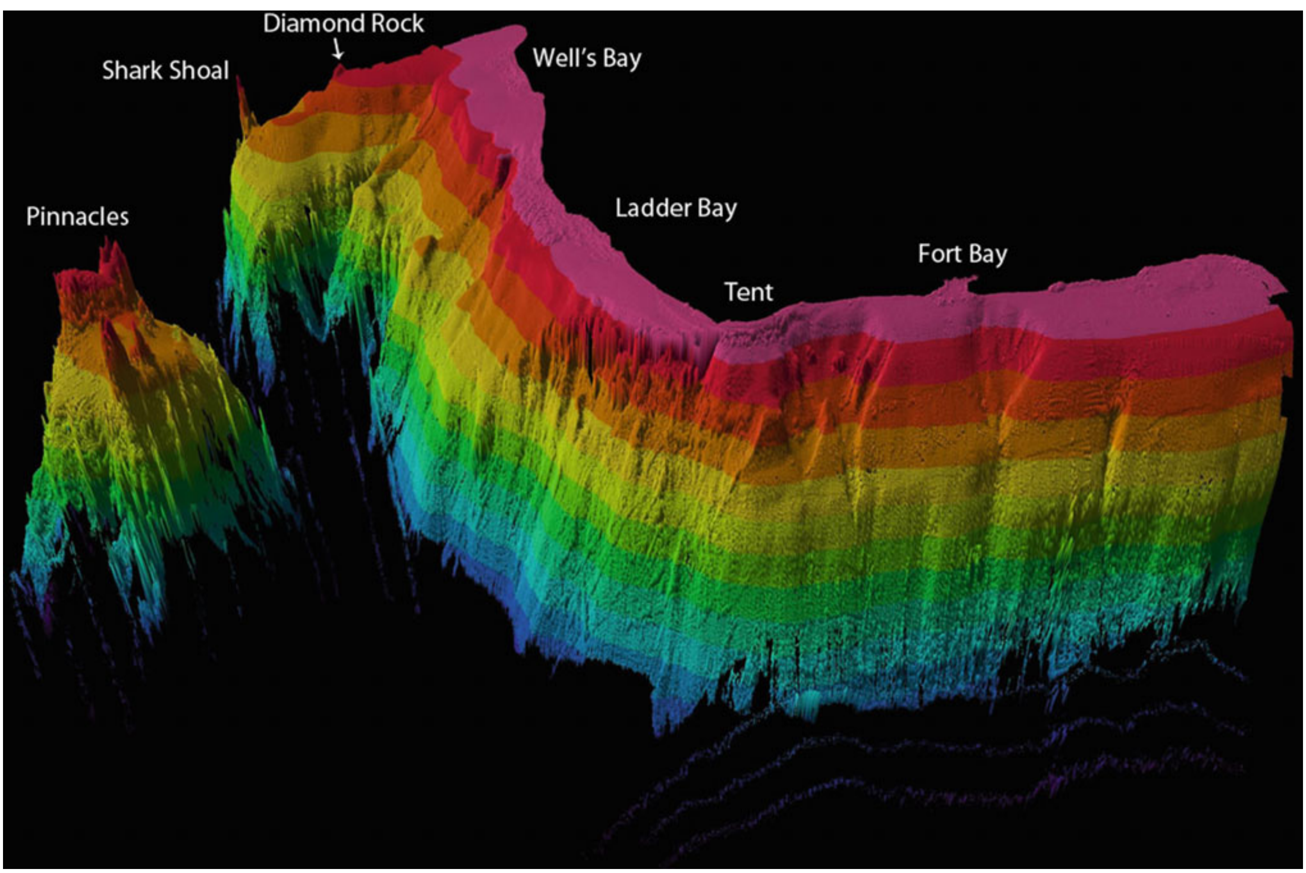

Fig. 6.3 Bathymetric map of Saba. Offshore Saba to the west 1.3 km, a single parasitic submarine Pelean dome (called The Pinnacles) rises from depths of 300 m to only 23 m below sea level. The platform's top, roughly the size of a football field, represents one of the most famous and spectacular dive sites around the island. Image courtesy of http://www.sabapark.org/marine_park/diving/

The Northern Centers may well be broadly contemporaneous ($\sim$500 ka) with the older stratigraphic division of Saba including the Diamond Rock–Torrens Point center. At this time, the islands of Saba and Statia were smaller and had different forms to the present-day islands (Roobol and Smith 2004).

Of intermediate age is Sugar Loaf-White Wall formation, a 1.2 km (0.7 mile) uptilted wall and ridge of shallow marine limestone on the extreme south end of the island embedded in the flanks of The Quill. Most likely, it is part of the limestone cap of the submarine platform uptilted by the emplacement of a dome (Roobol and Smith 2004), and a similar structure exists at Brimstone Hill on St. Kitts. Roobol and Smith (2004) characterize this formation as an unusual and interesting documentation of shallow-water phreatomagmatic activity over a period of several hundred thousand years.

The youngest geological unit is the single volcanic cone, The Quill, at the island's south. This morphologically youthful open-crater stratovolcano has flanks sweeping up to angles of 500 at the crater rim. The crater has a diameter of 800 m, and the eastern rim forms the highest point on the island at 600 m asl, though the crater floor rests at 278 m asl. The distal deposits of The Quill have largely been removed by erosion except where they form the nearly flat-lying central part of the island and terminate against the steep hills of the eroded Northern Centers. The Quill, apart from a few lava dome remnants exposed in the inner walls of the crater, is almost entirely a pyroclastic volcano, and the sea cliffs cut into the flank deposits reveal some of the best pyroclastic sections in the Lesser Antilles (Roobol and Smith 2004).

6.3 Landforms

Because they are both young Pleistocene island arc volcanoes, Saba and Statia have similar stratovolcanic features and many Pelean-type domes with adjacent unstable rock debris. Saba is a single volcano whose steep slopes drop off precipitously into the sea, while St. Eustatius is a more complex and older volcano resting at the northern end of an 80-km-long shallow (<180 m deep) submarine bank. Both islands have similar geologic histories and perhaps even co-eruptive, but Statia is older and has more erosional features, sedimentary structures (carbonate depositional sequences), and experienced some uplift. Common Caribbean island geomorphic features that are absent on Saba and Statia are perennial streams, wetlands, karst, aquifers, dunes, and inland water bodies, although there are a few brackish coastal wells. The islands' prime geomorphic agents include precipitation, rock decay, and gravity, each contributing to steeply eroded gullies ("guts") and coastal erosion, but anthropogenic activities, such as free-roaming goats and poor landuse/farming practices (particularly on Statia), also diminish vegetation growth and increase erosion.

6.3.1 Saba Interior Landforms

Saba's largest and most obvious landform, Mt. Scenery, lies approximately in the center of the island, dominating the geomorphic landscape (Fig. 6.5). Because of its classic volcanic shape, it is often assumed this is the main and only volcano of the island. Roobol and Smith (2004) explain, however, that the stratovolcano-like appearance of Saba results from a series of Pelean dome composites and their surrounding pyroclastic aprons that sit atop even older Pelean dome complexes. Because of its archetypal volcanic silhouette and steep coastal cliffs, the producers of the original 1933 King Kong movie used it as the backdrop of Skull Island (National Geographic Society 2007).

Another youthful volcanic feature, the only visible basaltic andesitic lava flow at the northeast corner of Saba, runs across the landscape, cradling the zigzag road (with 18 hairpin curves) up from the airport to Hell's Gate (aka Zion's Hill). The lava's high viscosity resulted in well-preserved lava levees that can clearly be seen as small, narrow, long hills on either side of the main flow (Roobol and Smith 2004). The airport lies at the terminal end of this flow, and the flat area of the airport is the flow covering a pre-existing wave cut platform. This is the largest area of flat elevation on the island, and the Juancho E. Yrausquin Airport (built in 1963) located here claims to have the shortest commercial runway in the world—a mere 400 m. It has also earned the superlative of being on the list of "scariest landings," as the approach is initially into a cliff face, coupled with a sharp bank-left to align with the runway.

6.3.2 Statia Interior Landforms

Statia's main geomorphic features are divided into three distinct landscapes composed of two volcanic areas (in the northwest and southeast) separated by a central, northward sloping plain (Fig. 6.6). In the northwest, The Quill, a symmetrical stratovolcano, also represents the second highest mountain in the Netherlands (600 m, see Fig. 6.7). Formed contemporaneously with Saba around 50 ka, The Quill contains a 2-km-wide crater. Its tropical rainforest vegetation-covered walls drop steeply, 322 m to the crater floor (at 273 m asl). The southeast, dominated by Mt. Mazinga, supports a small cloud forest on part of its crater rim, and the southern flank drops steeply to the sea where a wall and ridge of shallow marine limestone, known as the Sugar Loaf-White Wall (Fig. 6.8), runs east to west for

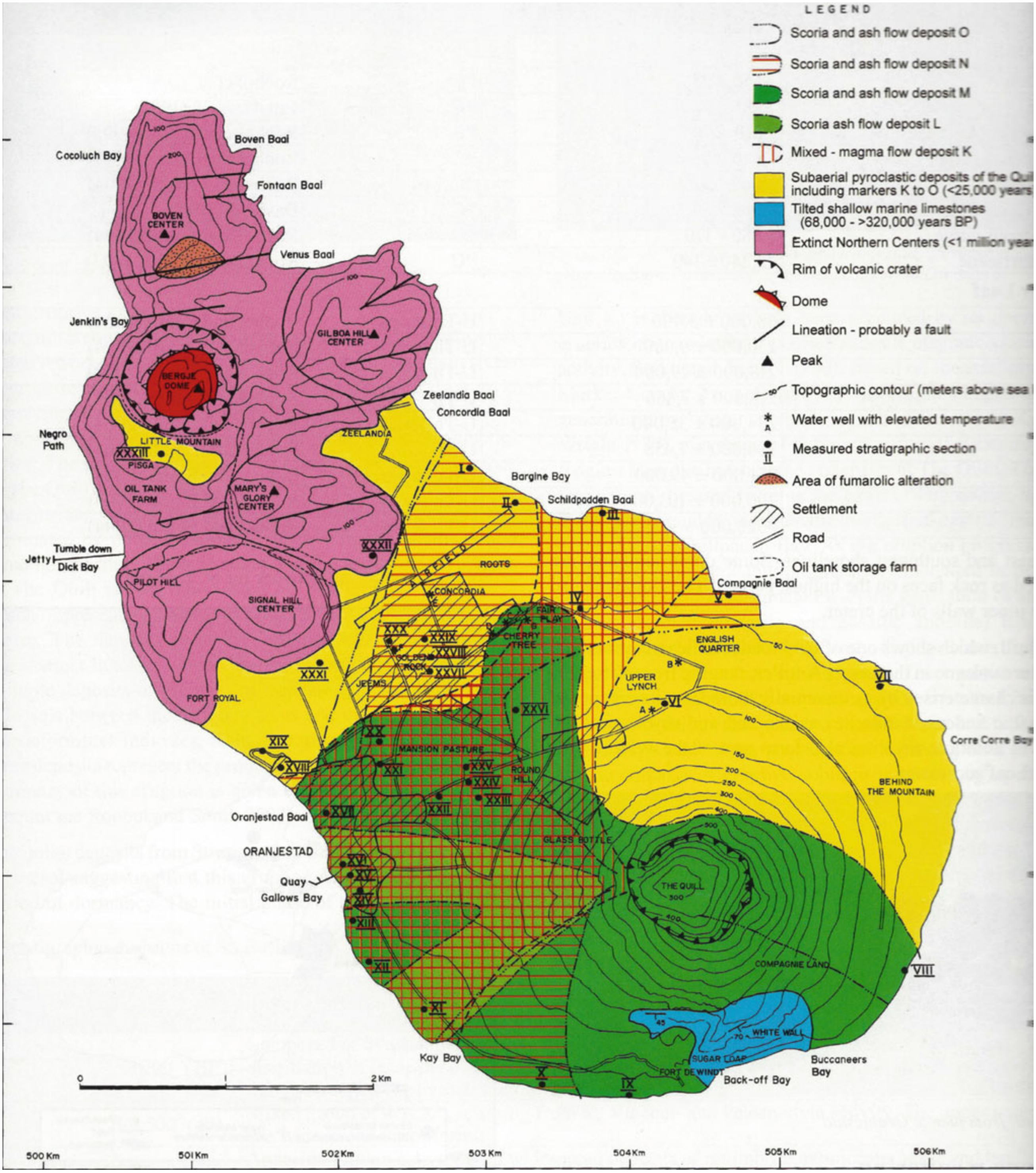

Fig. 6.4 Geologic map of Statia. The southeast end of the island is dominated by a 600 m high dormant volcano, The Quill. In the north end of the island, lower elevation hills have formed from an eroded, extinct volcanic complex (DCNA 2015). Between these two formations, in the central part of the island, is a low sloping 6 km^2 plain at 30–80 m above sea level composed of relatively fertile volcanic soils (DCBIODATA 2015). Map courtesy of http://caribbeanvolcanoes.com/st-eustatius-map/

about 1 km (Roobol and Smith 2004). Perhaps formed as part of the limestone cap of the submarine platform that was uptilted by dome growth, these marine sediments mixed with ash and pumice over time, eventually lithifying into strata visible from the "Around the Mountain" trail and Fort de Windt (Roobol and Smith 2004). On the western side of the

Fig. 6.5 Aerial photograph of Saba' south side with Mt. Scenery dome in the middle of the island. *Center left* in the *shade* is The Bottom. Surrounding The Bottom is the *horseshoe-shaped*, collapse scar of a volcanic lateral blast. Below The Bottom on the coast is Fort Bay, where the piers at the harbor are the only place boats can land on Saba. Photograph by L. Avery

crater, a pyroclastic flow fans out to the coast, and hosts the island's capital, Oranjestad (Roobol and Smith 2004). The northern slope of The Quill gradually drops down to the flat central plain, the Kultuurvlakte ("Culture Plain"), a 6 km^2 fertile plain containing volcanic soil, and where most of the roads, houses, and agriculture occur.

Statia's northern landscape—called the Boven Hills by locals and the Northern Centers by Roobol and Smith (2004)—consists of an extinct Quaternary (500 ka) volcanic complex of unevenly eroded hills. These hills initially comprised the entire island, and outcrops of the lava flows and pyroclastic deposits can be seen in adjacent sea cliffs. In the northern part, the Boven mountain's southern slopes are orange-colored, marking the site of former fumarolic activity (Roobol and Smith 2004). In 1979, on the westernmost hill of the Northern Centers, the Pisgah hilltop was flattened, and excavation began for the construction of an 11.3-million-barrel oil storage and transshipment facility/port. The rest of the Northern Center area is an uninhabited wilderness area with a drier weather pattern than The Quill producing savannah-like vegetation and fauna (DCNA 2015).

6.3.3 Coastal Processes and Landforms

Coastal features on both islands include a few black/brown volcanic sand beaches, more common cobble beaches, and coastlines made up of large rock, coral rubble, and cliffs. The length of coastline of Saba and Statia are 15 and 21 km, respectively. Water temperatures range from 25 to 29 C (77–85 °F), which support nearshore coral reefs. Prevailing Northeasterly Trade Winds drive waves to hit the Atlantic (Windward) sides of the islands, while the North Equatorial Current arrives from the southeast. Average wave heights range between 1 and 2 m, with strong North Atlantic winter storms generating swells up to 12 m along the north coasts. As with other small islands, waves tend to wrap around the islands, creating complex interference wave patterns on the southwest coasts.

6.3.4 Saba Coastal Landforms

Saba's outline shows a series of headlands separated by arcuate embayments (Fig. 6.9). These promontories consist of lava flows and domes, with bays (being) formed in the volcanoclastic host rocks themselves (Roobol and Smith 2004). The steep slopes on Saba continue underwater to approximately 500 m below sea level (Fig. 6.10). Saba's coast is roughly divided into thirds amongst sand and/or cobble beaches, rocky coast, and cliffs—especially steep cliffs because Saba has no shallow platform to prevent being constantly battered by wave action. There is only one permanent sandy beach at Cave of Rum Bay (Fig. 6.11), best accessible by boat.

Fig. 6.6 Aerial view of Statia's Culture Plain (Kultuurvlakte) and surrounding features. Below The Quill and its crater in the foreground, the Culture Plain (Kultuurvlakte) is visible *mid-photo*graph with Oranjestad along the left coast. The Northern Centers, seen in the background, are the remains of an extinct quaternary (500,000 BP) volcanic complex of unevenly eroded hills. Photograph by J. Haviser

This beach is maintained by sediment from hillslope failure of the rapidly eroding guts below Mary's Point.

Wells Bay hosts a seasonal sandy beach that usually appears March through October and disappears in the winter months, exposing well-rounded cobbles. The Wells Bay sandy beach can also disappear for years at a time, when sand sediments are washed offshore below wave base (Rahn et al. 2015). The northern end of the Well's Bay beach transitions into the Torren's Point formation with sea stacks, arches, swim-through tunnels, and caves (Fig. 6.12), and an overhanging >90° cliff of pyroclastic material serves as a backdrop to the beach, the bottom of which illustrates a classic wave cut notch (Fig. 6.13).

Meanwhile, Cove Bay beach—nourished (2010–2016) by white sand dredged from St. Martin and backed by large boulders as revetment—provides an accessible, public sandy beach. Sea Turtles have recently (2013–2015) nested on Cave of Rum Bay and Cove Bay beaches. The cobble beaches on Saba have rounded volcanic clasts and large coral rubble fragments broken from the reef and deposited by hurricane waves and subsequently modified by less energetic waves. In total, nine cobble/pebble beaches surround Saba, with Tent Reef beach being the most accessible and most widely used recreationally by residents. Some recreational swimming occurs at Fort Bay, but this bay is the harbor on the island, is a busy working port, and is primarily used for fishing, cargo, and dive boats. On the northeast coast, below the airport, a hiking/bouldering trail winds between jagged rust-red lava rocks. This area, called the Tide Pools, technically contains wave splash-pools since the tides are so small (Kjerfve 1981). The Tide Pools showcase resplendent tafoni, as well as a few fulgurites (Fig. 6.14).

6.3.5 Statia Coastal Landforms

The majority of St. Eustatius is steep cliff coast, but because a shallow water platform ($\sim$10 m) surrounds the island,

Fig. 6.7 The Quill Crater as seen from above. Tropical rain forest covers the walls and the crater floor. A small cloud forest exists on part of the crater rim near Mount Mazinga. Photograph by J. Haviser

waves are milder than on Saba. The Atlantic coast has average wave heights 1–2 m while the Caribbean, leeward coast, waves average less than 30 cm (St Eustatius Management Plan 2007). Monitoring of cliff erosion between 2004 and 2006 showed erosion up to 2.0 m in one year, resulting in major landslides with chunks of rock over 1 m falling regularly (STENAPA 2007). Six sandy beaches occur around the island adjacent to the Culture Plain, though "sandy" can be a loose term, as most beaches remain a mix of sand, gravel, cobble, and coral rubble. The north coast of Statia contains an escarpment with a series of five, 300-m, closely spaced, undulating, cliffed-coast headlands (Fig. 6.15).

6.3.6 Nearshore and offshore Landforms of Saba

Saba hosts five distinct geomorphic forms of coral reef: coral-encrusted colluvial debris, spur and groove, antecedent bar-beach ridge veneer, sea stacks surrounded by reef, and offshore seamounts/pinnacles. Coral-encrusted colluvial debris from the adjacent steep slopes are the most common reef structures surrounding Saba and consist of hard and soft coral and sponges built on top of cobble- to boulder-sized rocks (van't Hof 1991). Spur and groove reef formations occur on the island's leeward side between the Hot Springs and Babylon dive sites. In the Tent Bay area, a shore-parallel reef and wall called Tent Reef was exposed as an offshore bar and beach ridge system at sea level around 8000 years ago. As this system submerged with sea-level rise, corals kept up with water levels and formed a shallow one to two-meter-thick veneer on top of the rocks and beach sediments. While diving this site, you can often see the well-rounded former volcanic beach cobbles beneath the coral layer. At the west end, this reef becomes a series of coral outcrops topping a vertical wall that drops 30–65 m (van't Hof 1991).

A 900 m^3 sea stack, Diamond Rock rises from Saba's northwestern sea floor. It is a favorite bird roost site and so-called because its silhouette is diamond shaped, and shines from a distance because of the white bird gvano's high reflectivity. The entire subaqueous diameter of Diamond Rock is covered with corals and other coral reef ecosystem inhabitants. Between Diamond Rock and Torrens Point, there are a series of smaller, drowned sea stacks also covered with

Fig. 6.8 Sugar loaf ridge viewed from Fort de Windt, southern St. Eustatius. It is an uptilted wall and ridge of shallow marine limestone on the extreme south end of the island imbedded in the flanks of The Quill. This feature formed from the shallow-water carbonate banks and patch reefs around 500,000 BP. Photograph by J. Haviser

corals. The most spectacular reef formations of Saba are the offshore "seamounts" about one-half km to the west. These "seamount" formations are probably parasitic domes formed by magma chambers connected to the main one below Saba (see Fig. 6.3).

6.3.7 Saba Bank

About 5 km southwest of Saba, separated from the island by a 700-m deep trough, lies a large (2200 km^2 or 849 mi^2) submarine carbonate bank, or atoll, called the Saba Bank. It is the third largest of its kind in the world, and spectacularly rich in marine biodiversity (DCNA 2015). The flat top of this atoll ranges in depth from 20 to 50 m, elevated about 1800 m above the surrounding sea floor. Various oil companies, government agencies, and academic institutions researched Saba Bank geology between 1970 and 1999, with approximately 4300 km of seismic data acquired over the Saba Bank area (Church and Allison 2004). Church and Allison (2004) summarize the Saba Bank geochronology as remnants of volcanic islands from the Cretaceous volcanic island arc with a thin Tertiary section overlying a thick pre-Eocene sequence and an eastern area with a thick Tertiary sedimentary section overlying Eocene volcanics and an even older (perhaps Cretaceous?) sequence. The upper layers indicate early Miocene fluvial-deltaic volcaniclastics and late Miocene–Pliocene carbonate deposition, capped with Quaternary coral reefs. The coral reefs are found primarily along the east and southeast edges of the Bank and contain a rich cover and diversity of reef-building corals. The Saba Bank hosts various reef types, from patch reefs to spur and groove type reefs with sandy channels. Each of these provides a hard substrate for coral and other animals to settle on, which in turn attracts fish and an abundance of other invertebrates (Saba Bank National Park 2012). The extensive reef development of the Saba Bank (estimates put it

Fig. 6.9 Northeast coast of Saba. The peaks of Mt. Scenery (*right*) and Booby Hill (*left*) rise above the rugged northeast coast of Saba. The airport on Flat Point (the only large flat area on Saba) and the hairpin road going up from there to Hells Gate are on Saba's only visible basaltic andesitic lava flow (*right foreground*). Well-preserved lava levees can be seen cradling the zigzag road. On the coast in the *central part* of the photograph are Spring Bay (*left center*) and Cove Bay (*right center*, adjacent to airport Flat Point area). On the coast below Flat Point are the Tide Pools. Photograph by J. Haviser

around 150 km^2) provides a rich fishing ground for Saban fishermen and hosts large populations of reef fish and associated spawning grounds.

6.3.8 Nearshore and offshore Landforms of Statia

The nearshore landforms on Statia's surrounding shallow platform also include coral reefs. The platform is the narrowest in the north and southeast. In the south, the steep slope of The Quill volcano continues into the sea. Here, corals enhance a vertical wall of the Drop Off, Grand Canyon, and The Cliffs dive sites. Statia dive shops lay claim to areas of coral-encrusted lava flows, boulders, and patch reefs, as well as more than 100 sunken trading ships, submerged anchors, and cannons. A number of artificial reefs have been created by the Marine Park since active management commenced in 1997. Some of these artificial reefs have been created for fishing purposes, and others for divers (Statia Park 2015).

6.3.9 Landscape

Little is known of Saba and Statia's Amerindian occupance, though archaeological excavations continue and most evidence points to basic hunting and gathering (and fishing) occurring around and on the islands as early as 500 BCE (SABARC 2015). Mostly uninhabited until the seventeenth century, Saba and Statia remained untouched until Colonial powers began expanding. Saba's rugged landscape and treacherous coastline that makes boat landings difficult, kept its historic population small (no greater than 3000). Saba had

Fig. 6.10 Image of the west coast of Saba showcasing Mt Scenery (the *highest point* in the photograph), Great, Paris and, Bunker hills to the *right*, and Diamond Rock about 425 m (1400 ft) offshore in the foreground. The seabed between Torrens Point and Diamond Rock is very rugged with irregular outcrops of dome remnants that house abundant coral reef communities, making the area a favored dive site. To the *right* and *left* of Torrens Point are the deeply incised and eroded ridges and guts that are successions of massive lithified, coarse block, and ash flow deposits. Photograph by C. Meijvogel

a small agricultural economy mainly for local consumption, but the people themselves were in demand, even today, for their navigation skills and seamanship (Haviser 2001).

Although Mt. Scenery dominates the island, Saba also hosts numerous hills giving the island an irregular topography, and the island's four villages sit on the gentler slopes between the peaks of hills. The village of The Bottom, for example, sits in the horseshoe-shaped, collapse scar of a volcanic lateral blast. As you descend into The Bottom, from the road there is an excellent (and much photographed) view of some of the newer volcanic dome hills that looks like, and is called, the whale (Fig. 6.16). The Whale's Tail represents an outstanding example of a well-preserved volcanic spine (or spike), usually created by dome growth and collapse. The Whale's Tail is also the teepee tent-like feature after which Tent Bay is named.

To transport goods, for many years, locals trekked through grueling elevation changes on twisting trails with perhaps a lone donkey to help. In the 1930s, Sabans asked the Dutch government to build a road on the island. Primarily experienced with engineering roads on flat ground the Dutch government considered it a foolhardy task due to the island's extreme topography. Eschewing the opinion of the Dutch engineers, Sabans decided it *was* possible to build a road on Saba. Today, the 14 km road that half-circumnavigates the island stands as a testament to the impressive local terrain knowledge and clever application of design and construction that allowed for slope stabilization on tropical mountain roads where heavy rain, steep grades, and weak soils and rocks combine to create slope instability. The outer side of the road usually has a steep drop off, and the inside has a steep cliff rising above it. The sole main road on Saba, winding-up from the airport on the northeast side, through the four villages, and terminating at the southwest coast in Fort Bay, traverses four ecological zones from dry scrub to dense tropical vegetation. The other half of the island is actually too steep for road construction and consists primarily of spectacular successions of block and ash flow deposits forming steep and precipitous slopes (Roobol and Smith 2004). These western slopes are so steep that there are no settlements in the area and, although there is a hiking trail there called the North Coast Trail, it is dangerous and requires a local guide.

Today, Saba and Statia rely on tourism in the form of world-class scuba diving and oil transshipment. In fact, because the rugged topography of Saba permits only small-area development, and most of that occurs above 240 m, few terrestrial human impacts have affected the reefs. On the other hand, potentially the most conspicuous coastal

Fig. 6.11 Cave of Rum Bay on the northeast side of Saba taken from the air with a drone. Cave of Rum Bay beach is about 150 m long 15 m wide, nestled between the headlands of Torrens Point to the south (*right* of photo) and Great Point to the north (not in photo). Photograph b C. Meijvogel

feature on Statia is its oil terminal, located in the northeast corner of the island on Little Mountain. Here, oil is offloaded from large tankers from other countries, modified, and then reloaded back on tankers that can distribute it to other places. Typically, tens of tankers are lined up offshore waiting for their turn for this exchange.

Even though they are part of the Netherlands, English is the primary language on both Saba and Statia—a holdover from Colonial times. But more than this, Saba and Statia remain quite different from other Caribbean islands (including the other Dutch Caribbean islands) in terms of heritage and culture. For example, Saba's architecture has evolved differently from the majority of other Caribbean islands, displaying mostly white buildings, with red roofs and green shutters that give the island a fairy tale-like ambience. Though small in size, the islands retain distinct physical and cultural characteristics, often enhanced by their heritage and tourism-focused economies centered on geotourism (see Dowling and Newsome 2006a, b for overview).

6.4 Heritage and Tourism

6.4.1 Heritage on Saba and Statia

The human history of both islands began with Amerindian peoples utilizing the land and sea for fishing, hunting, and foraging around 500 BCE. Columbus sailed by the islands on his second voyage in 1493, but both islands were deserted when Europeans visited in the early seventeenth century, perhaps due to an extended drought (Statia History 2015). European settlement on Saba and Statia occurred in 1640 and 1636, respectively. The British were the majority of the early settlers on both islands, and English is still the primary language spoken on Saba and Statia. During colonial times, the islands' populations and ownership varied. Statia's geographic location and its landscape with an accessible harbor and flat central plain allowed for a robust commercial and maritime economy, and up to 100 plantations. Statia's plantation economy consisted of various crops

Fig. 6.12 Oldest exposed rocks on Saba at Torrens Point on the northwest shore. These rocks include sea stacks, arches, caves, and swim-troughs that are remnants of a Pelean dome heavily hydraulically eroded. Photograph by J. Rahn

including tobacco, cotton, coffee, indigo, and its most important crop, sugar (Haviser 2001). Numbers for Statia's largest population range from perhaps 10,000 to 20,000, though this was a largely transient population in the mid-1700s (Statia Tourism 2015). Other commercially exploited natural resources over the centuries included sulfur deposits on Saba and sisal and pumice on Statia (Haviser 2001).

Throughout the seventeenth and eighteenth centuries, both islands were claimed successively by the Dutch, French, English (and Saba by the Spanish), with Statia changing hands 22 times. The islands first became a Dutch West Indies Colony in 1828, before being included as a Dutch dependency in 1845 along with other Caribbean Islands. It was not until the mid-1950s that the islands became part of the Netherlands Antilles (Britannica 2015). Since then, and up to present, Saba and Statia remain quiet islands that rely heavily on tourism (primarily hiking and scuba diving) for disposable income. archaeological studies on the islands are recent, beginning just a few decades ago in the 1980s. The Saba Archaeological Center (SABARC) seeks to integrate archaeological work with community-oriented projects and have succeeded in attracting and training youth in their preservation activities while promoting pride in local heritage. In February 2016, SABARC opened the Saba Heritage Center in the villages of Windwardside. The center endeavors include “living history” demonstrations, artifact exhibitions, technical laboratory facilities for scientific research, and a public facility for lectures on heritage (SABARC 2015). SABARC also has ongoing excavations at several Amerindian and colonial sites and often conducts weekend digs with local youths.

6.4.2 Coastal and Marine Conservation and Tourism on Saba and Statia

The national parks of Saba have been under the domain of the nonprofit Saba Conservation Foundation (SCF).

Fig. 6.13 Wells Bay beach: a seasonal sandy pocket-beach that usually disappears in wither months, replaces by small ($\sim$20 cm) volcanic cobbles. Locally called "wandering beach "or "disappearing beach," it is the only road-accessible, natural sandy beach on the island. At the bottom of the dramatic cliff is a wave cut notch (*center* of photograph) and the northern end of Well's Bay (*left* side of photograph) transitions into Torren's Point. The cliff face is unstable and beachgoers need to be aware of the danger of falling rock. Photograph by J. Rahn

Institutionalized forms of nature conservation on Saba date back to 1987, when the first protected area, the Saba Marine Park (SMP), was established, coinciding with formal incorporation of the SCF. The SMP circles the entire island from the high watermark to a depth of 60 m, including the seabed and overlying waters, and comprising a total area of approximately 1300 ha (see Fig. 6.1). A zoning plan divides the park for various recreational and commercial uses, including a system of permanent mooring buoys to facilitate diving and prevent damage to corals across 30 different dive sites. One of the few self-sustaining marine parks anywhere in the world, the SMP raises revenue through visitor fees (visitors pay US $3 per dive and $1 per night in hotels), souvenir sales, and donations (Saba Park 2015). In 2010, the Saba Bank National Park (SBNP) became an additional underwater-protected area run by The Saba Bank Management Unit (SBMU). An independently operating organization under the SCF umbrella, the SBMU is designed to safeguard the wealth of biodiversity of the entire 2680 km^2 (268,000 ha), flat-topped seamount of the Saba Bank. In particular, it regulates the prime fisheries to ensure their sustainability since Saba Bank remains an important economic resource for Saba, with the fisheries on the Bank contributing about 8% to the island's economy and providing full-time employment to 20 people and part-time employment for an additional 30 people (Dilrosun 2002). In 2012, Saba Bank became the world's thirteenth Particularly Sensitive Sea Area (PSSA), with designation from the International Maritime Organization (IMO). In the past, many freighters, tankers, and cruise ships passed over the Saba Bank and frequently anchored in the shallows, causing significant damage to the coral reefs and other bottom-dwelling ecosystems such as conch feeding grounds. After the IMO declared it an area to be avoided, oil tankers (and other large ships) were no longer allowed to pass over it, which reduced anchor damage on the fragile reef ecosystems (Saba Bank National Park 2012). Scuba diving-related tourism, which includes hotels and restaurants, comprises nearly one-third of Saba's economy. There are three dive shops on the island, and dive tourist numbers

Fig. 6.14 Distal end of Saba's only visible basaltic andesitic lava flow in the Flat Point area is known as the Tide Pools. These sharp, red volcanic rocks are a great place to climb and watch the northern-swell waves crash against Saba's shore. Hikers and climbers should be very aware of rouge waves in this environment, as several Sabans have been swept away. Old Booby Hill is visible in the background. Photograph by J. Rahn

hover around 8000 divers completing as many as 20,000 dives annually.

The national parks of St. Eustatius, which comprise The Quill/Boven Park, the Botanical Garden, and the Marine Park, remain under the control of the nonprofit NGO, St. Eustatius National Parks (STENAPA). The St. Eustatius National Marine Park was created in 1996 and extends around the entire island from the high waterline to 30-m depth contour. The park covers an area of more than 27 km^2 and protects a variety of habitats, including pristine coral, eighteenth century shipwrecks, and modern-day artificial reefs to promote fishing and dive tourism (Statia Park 2015). Within the park are two actively managed reserves in which no fishing or anchoring is permitted in hopes of conserving marine biodiversity, protect fish stocks, and promote sustainable tourism. Annually, around 11,000 visitors visit St. Eustatius, staying an average of eight nights. Figures from Statia Park (2010) determined that approximately 80% of those visitors engage in coral reef related activities.

Both the Saba and St. Eustatius Marine Parks work closely with the three local dive centers on each island to ensure that diving practices minimize impact on the reefs. Saba and Statia's marine environments are also a home, migratory stop over, or breeding site for four IUCN Red List Species, 10 CITES Appendix I species, and 98 Appendix II species (St. Eustatius Marine Park Management Plan 2007). The Yarari Marine Mammal Sanctuary is the fourth Caribbean marine mammal sanctuary and includes the Caribbean Netherlands' territorial waters of Saba, St. Eustatius, and Bonaire. The waters surrounding Saba and Bonaire became

Fig. 6.15 Aerial photograph of Statias' windward coast with The Quill volcano surrounded by clouds. Oranjestad, the island's single town and capitol, is visible to the *right* of the image. The *center* of the photograph is dominated by the Culture Plain, Kultuurvlakte, where most of the agriculture occurs. Historically, cultivation went high up the slopes of The Quill. Photograph by J. Haviser

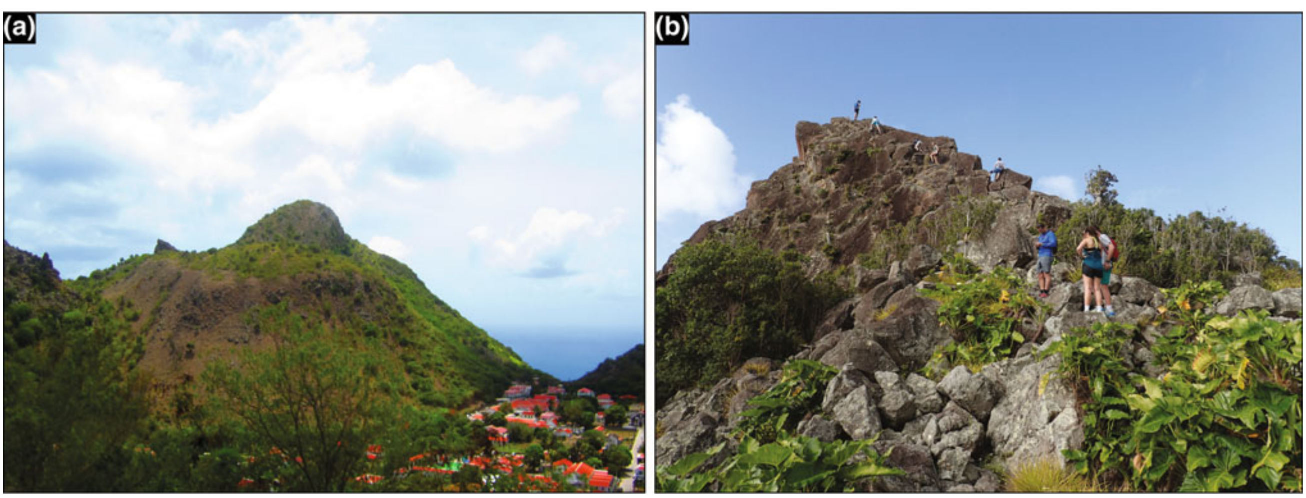

Fig. 6.16 Landform known as "The Whale" on Saba. **a** View of The Whale (*center left*) from the road descending from St. John's to The Bottom. The much-photographed anthropomorphized volcanic domes of Paris Hill and Great Hill create the whale's body and the well-preserved volcanic spine serves as the Whale's Tail. **b** Close-up view of climbers on the Whale's Tail displaying the ridge's rough volcanic geology and lush vegetation. Photographs by J. Rahn

shark sanctuaries in 2015 that cover the islands' full exclusive economic zones. All commercial shark fishing is prohibited up to 200 nautical miles from each island.

From a landform perspective, Saba offers underwater explorers a unique treat, with several dive sites encompassing underwater pinnacles covered completely by coral that begin at 150 m below sea level and rise to 30 m below sea level. Deep sea pelagics frequently swim by and rare corals, such as black coral (*Antipatharia*), grow at deeper depths. This combination of marine ecosystems and (semi-stable) subaerial geology make Saba and Statia one of the more unique Caribbean locations in terms of underwater attractions.

6.4.3 Terrestrial Conservation and Tourism on Saba and Statia

In 2012, the Saba Conservation Foundation created a terrestrial park, the Saba National Land Park, a pie-shaped, 43-ha tract of land on the north coast of Saba, formerly owned by the Sulfur Mining Company. The area has important biological, geological, and historical values, as well as encompassing all vegetation zones present on Saba, an abandoned sulfur mine, hot springs, and serving as an important nesting area for Red-billed tropicbirds (*Phaethon aethereus*) and several other species of seabirds (Saba Park 2015). At the top of Mt. Scenery (877 m), an 8.6-ha plot is being considered for acquisition as an Elfin Forest Reserve. Reached by climbing 1064 Saban-built, rock-hewn steps from the village of Windwardside (Fig. 6.17), this area hosts montane cloud forest, also known as elfin forest, and consists of two primary tropical rainforest areas that represent climax vegetation. Saba's cloud forest is unusual because the Mountain Mahogany (*Freziera undulata*) is the "signature tree" and because the canopy is significantly higher than in other cloud forests (van't Hof 2010). Van't Hof also believes that this was a climax forest of approximately 500 years until four hurricanes from 1989 to 1999 devastated the area and only a few survived.

The SCF is also responsible for hiking trails (the Saba Trail Network), and they staff the Saba Trail and Information Centre in the village of Windwardside. Mapping and maintenance of the more than one-dozen hiking trails is done by park rangers and a significant amount of volunteer help. The SCF fulfills an important role as advisory body for the government and as management agency for protected areas. They are also committed to the belief that a stronger island economy will result from the sustainable use of Saba's rich and virtually unspoiled resources (Saba Park 2015).

Other nonprofits on Saba include Sea and Learn, which sponsors a month-long event each October. Sea and Learn on Saba is a nonprofit foundation that "brings together the local community, diverse nature experts, and visitors to understand the value of preserving, protecting, and sustaining the local natural and cultural resources and heritage on Saba, and worldwide; and to educate the potential safe-keepers in order to sustain viability and infinitum as an ecotourism destination" (Sea and Learn 2015). There are also two other heritage museums on Saba in Windwardside: the Harry L. Johnson Museum and the Dutch Museum. The former includes an original Saban cottage in the middle of a garden highlighting Saba's marine heritage (and located in a public park), while the latter houses collections of Dutch antiques from the 1500s to 1900s.

On St. Eustatius, STENAPA protects The Quill/Boven Park and the Botanical Garden. The Quill/Boven National Park was pronounced the first national park of the Netherlands Antilles in 1998. The park was created "to protect Statia's unique biodiversity and to ensure sustainable use by all stakeholders." This 5.4 km^2 park consists of two subsectors, The Quill and White Wall, and the Boven area covering five hills in the north of St Eustatius. Varying types of habitat are protected, ranging from elfin forest at the top of The Quill volcano to thorny woodland on the lower slopes. The park gives guided tours to visitors and maintains a network of 10 trails in The Quill sector (Statia Park 2015). The Miriam Schmidt Botanical Garden was also established in 1998 to display the island's flora (and fauna). This garden is adjacent to The Quill National Park boundary and extends for over 5-ha across the southern slopes of The Quill.

Established in 2004, the St. Eustatius Center for Archaeological Research (SECAR) provides a permanent archaeological presence on Statia focusing on basic heritage resource management issues working with the locals. SECAR is an active and vibrant research group involved in education, pioneering research techniques, and protecting underwater and terrestrial cultural heritage resources, including more than 100 sunken trading ships, submerged anchors, and cannons off the shores of Statia and terrestrial Amerindian and colonial excavations (SECAR 2015).

6.5 Hazards

6.5.1 Meteorological Hazards

Meteorological events (as well as their secondary and tertiary effects) represent the greatest hazard each island faces, and as world and local climates continue to change, smaller islands such as Saba and Statia feel the alterations first. The most frequent and costly natural hazard to Saba and Statia are the effects of tropical storms, hurricanes, and increasingly, drought. Thought there is little to no meteorological data on either island, because of their small populations, preparedness, and community spirt, there has been little loss

Fig. 6.17 Sign at the bottom of the Mt Scenery trail in Windwardside. At the top of the trail, there is a plaque stating, in Dutch, that Mt Scenery is the highest point in the Netherlands. Photograph by J. Rahn

of life due to tropical storms on Saba or Statia. Historical damage has included the removal of roofs, flooding, tree and other airborne debris, soil erosion, and small landslides. Power, telecommunications services, and food deliveries can be disrupted for a few days to weeks, depending on the extent of the storm. Flash flooding can occur on steep slopes, and roads in these areas can become ephemeral streams directing fast-flowing water to lower elevations. On Saba, this becomes a travel hazard since there is only one road, while the only low-lying flood-prone areas on Statia occur in the Culture Plain.

Wet and dry periods on Saba and Statia can be pronounced. In the last decade, drought has become a problem, with climate change seeming to affect the frequency and magnitude of these events. This is especially a problem since most water on Saba and Statia is provided by roof catchment collection and subsequently stored in cisterns. Local islanders are very water-conscious and aware of the amount of water they have for daily use. Measures like 2 minute showers, dish-washing by hand, small-capacity washing machines (or hand-washing clothes), and flushing toilets only when necessary are common island-wide. However, groups of foreigners (including the approximately 400 people associated with the Saba Medical School, the hundreds of people connected with the Statia oil terminal, and tourists) have little care for their water consumption, and this exacerbates the problem. In severe droughts, water has to be shipped to the islands. Additional problems occur because of the lack of a distribution system for water, where the current distribution system relies on privately owned trucks with 1000-gallon tanks to move water across the islands. Both islands have desalinization plants, but they have limited production volumes, and Statia's has not been operational for three years (Ryan Espersen personal communication).

High winds can also be a problem, preventing flights from landing on the small airstrips for days at a time. Usually occurring in winter and accompanied by large ocean swells, the winds can often preclude boats from running as well, exacerbating the problem further, as most food is shipped to the islands once per week.

Mass wasting can occur from high precipitation, ground shaking (earthquake or human- induced), and when gravity and time take their toll on the steep, thinly soiled, lightly vegetated slopes on both islands. On Saba, mass wasting occurs on both terrestrial and on steep submarine slopes. Most commonly, on both islands, it will occur along the coast where waves erode cliff bases.

6.5.2 Seismic and Volcanic Hazards

Historically, both islands have low-seismic dangers, and no damaging earthquakes or tsunamis have been recorded on Saba or Statia. The main risks would come from earthquakes in the Caribbean region possibly producing a tsunami (very rare: only two have been documented historically in the 1700's) or from local earthquake swarm precursor to a volcanic eruption. A seismic swarm occurred near Saba in 1992 (Ambeh and Lynch 1995), but the magnitudes were not large enough to cause any damage. In June of 2015, seismologists from the Dutch Meteorological Institute (KNMI) installed four seismometers each on Saba and Statia. The real-time feed can sometimes be viewed (http://www.knmidc.org/seismology/?NA_SEUT_—although some seismometers intermittently cease functioning and occasionally the Web site is down). Large earthquake induced mass movement events would hit Saba especially hard because it has only one road, and landslides could block access to the only two evacuation points at Fort Bay and the airport. All of Saba's infrastructure, except the Fort Bay port and the airport—both of which lie near sea level—would not be at risk to tsunami waves. For example, the power plant used to be at 3 m above sea level in Fort Bay, but was moved to a 100 m elevation (along the road above Fort Bay) in February 2016. Statia would receive more damage from a tsunami, and possible effects there would include oil spills from the terminal, as well as some infrastructure located at low elevations near the west coast.

For both Saba and St. Eustatius, there are no historical records of eruptive activity. The most recent eruption on Saba and Statia were 1600 AD and 400 AD, respectively, as determined geologically (Hartog 1975, 1976). Volcanic hazard and risk assessments were made for Saba and Statia in 1977 (Fournier and Tomblin) and again in 1997 (Roobol, Smith, and Tomblin). In 2005, the Volcanic Hazard Atlas of the Lesser Antilles was published by the University of the West Indies, where Roobol, Smith, and Tomblin wrote the Saba and Statia chapters that contained a summary of the work the authors carried out on these islands over the past 25 years. Saba is clearly an active volcano as indicated by the presence of hot springs with temperatures around 72 and 55 °C and The Quill, even though it has no external manifestations, is still regarded as an active volcano (Roobol et al. 1997). Using geohazard interpretations reconstructed from the stratigraphic records of the entire pyroclastic history, Roobol and Smith (1989) note that the present period of volcanic inactivity on Saba and Statia does not indicate the extinction of these volcanoes, but rather periods of dormancy. It should be stated, however, that the overall volcanic hazard for these two are similar to other Lesser Antilles Caribbean volcanoes, and Roobol et al. (1997) recommended that the governments should have plans and designated funds to evacuate each island in 1–2 days. As of December 2016, the local governments have been working with the Dutch on these plans, but they have not been released to the public. Additionally, continuous seismic and monthly hot springs monitoring should be taking place. Ash fall from other nearby Caribbean islands might also be a hazard on Saba and Statia as, for example, Montserrat's 1995 eruption column that spread an ash across Saba and Statia.

6.5.3 Other Hazards

Though small islands in size, Saba and Statia still face hazard challenges beyond storms and drought. Neither Saba nor Statia are self-sufficient as far as water, food, or energy are concerned, and the delicate balance of subsistence could easily be affected by a variety of environmental problems and hazards including coral reef bleaching, alien species invasion, land removal, solid waste, and oil refinery-related hazards. The coral reefs ecosystems of Saba and Statia have had little subaerial human effects since populations are so small and many of the reefs are not near human habitations. The largest aquatic impact has been various Caribbean coral reef diseases, large scale herbivore removal with the demise of the spiny sea urchin (*Diadema antillarum)* in the 1980s, and higher than normal sea surface temperatures. Coral bleaching has occurred on these reefs. The worst event happened in 2005, but there have been several minor cases. Beach erosion on Statia (especially Zeelandia Beach) could affect sea turtle nesting.

Additionally, free-roaming goats on both islands are a large problem, causing soil degradation, loss of organic matter, reduced water retention, and overall erosion in semiarid rangelands (Rojer 1997). Although goats occur mostly below the 300-m contour level, in arid times they often graze above 600 meters. According to Romeijn (1987) and Rojet (1997), areas where goats have influenced the vegetation on the major part of the island and large parts of Saba and Statia remain permanently deforested, and in some areas, a complete absence of herbaceous and shrub layers in the forest is due to excessive goat grazing (Debrot 2010).

There have been unsuccessful efforts on both islands to cull, restrict, and better manage the roaming goats.

Removal and movement of large amounts of land for private commercial purposes continues to have effects on the ecological integrity of both islands. On Saba, 1.6 ha (19,000 yds^3) of Fort Hill was removed as part of a rock crushing operation, resulting in approximately 100,000 tons of rock (by estimate of a Saban to the author). Continuing expansion of the stone crushing facility has consequences for the geological formations, scenery, biodiversity in the sea, and dive tourism (Sybesma and Visser 1996; Rojer 1997). On Statia, the top of Signal Hill was leveled about 0.23 km to situate the oil terminal tanks. Signal Hill and Fort Hill were prime sea bird nesting sites. On Saba construction debris dumping (of up to 500 dump truck loads) has occurred on the coastline adjacent to Tent Reef dive sites, and that much sediment, were it to wash onto the nearby reefs, could decimate the fragile ecosystem. Efforts by this author and the SCF resulted in a $100,000 federal grant to remove the fill, but the project has still not occurred. To this author's knowledge, although required by The Netherlands (and the EU), environmental impact assessments do not occur prior to large projects on either island.

A large oil spill potentially affecting both islands could be a hazard, considering the 11-million-gallon Nustar Energy oil storage and distribution facility on Statia. On a busy day, ten large tankers come and go off-loading and on-loading fuel. Based on prevailing winds and waves, the most likely oil spill scenario has the oil heading directly to Saba, with limited localized effect on Statia. Though no major damage resulted from them, there have been several small oil spills between 2009 and 2015, and in response, the Dutch government has provided Saba and Statia with oil spill cleanup, training, and equipment. In 2010, the Saba government and SCF, in consultation with Dutch and EU scientists, decided to not use dispersant if there is a large oil spill because Saba's coastal resources are primary subaqueous (the coral reefs) and dispersant would submerge the oil and harm the reefs. Instead, the plan centers on allowing oil to hit their shores and float past the island, where perhaps dispersant would then be used at sea. On Statia, the oil terminal has affected ecotourism on the island, at least from a visual standpoint, since the main inhabited area hosts many oil storage tanks.

6.6 Conclusion

The landforms of Saba and St. Eustatius originate from subduction in the Lesser Antilles, resulting in Pleistocene island arc volcanics. Both islands have stratovolcanic landscapes and many Pelean-type domes with adjacent pyroclastic flows. Saba is a single volcano whose steep slopes drop off precipitously into the sea, while St Eustatius lies on a shallow submarine bank. They both have similar geologic histories and landforms and are perhaps co-eruptive, but Statia is slightly older, has more erosional features, a flat central plain, and experienced some uplift. Both islands have young, visually predominant volcanos that represent the highest (Saba) and second-highest (Statia) elevations in the Kingdom of the Netherlands. Their steep slopes are embedded with ephemeral, waterworn ravines locally called guts—some of their volcanic landforms being obscured by dense tropical vegetation—and most of their coastlines are rocky (abrasional) cliffs. While other Caribbean Islands contain karst, lakes, continually flowing rivers, and even abundant aeolian features, Saba and Statia lack these. Climatological events of tropical storms, hurricanes, heavy precipitation, and drought have been the most impactful hazards. Changing regional climate regimes will likely be the biggest environmental hazard and geomorphic agent in the future. Like other Lesser Antilles islands, seismic and volcanic activity also poses possible risks, including landslides, but these are rare events on Saba and Statia. Some of the best coral reefs in the Caribbean surround both islands and are important for tourism, especially on Saba where scuba-related tourism accounts for about a third of the economy. Saba and Statia both have influential NGOs that work with the government to protect their natural environments and cultural history, with each island hosting active Amerindian and colonial archaeological sites and nonprofit archaeological organizations.

Saba and Statia are atypical of other Caribbean islands because of their small sizes, rugged topographies, and lack of large resorts, development, and industry. They have maintained their relatively pristine environments because of low human impact. A healthy natural environment is important to the priorities and pride of the local peoples. Indeed, Saba is known as "The Unspoiled Queen" in the Caribbean, and inhabitants of Saba and Statia form close knit, small-town like societies allowing them to interconnect with their environment and with each other. While Sabans and Statians are community-oriented, environmentally aware, inquisitive, and work together to be resilient in the face of adversity, finding solutions to current and future problems will require continued solidarity and good relations between communities, governments, and the rest of the Caribbean.

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7 St. Kitts and Nevis

Richard Edward Arnold Robertson

Abstract

The islands of St. Kitts and Nevis are part of a binary federation located within the northern Leeward Islands. Their landscapes are as much a result of their geological history as they are the manifestation of interactions of man and nature over time. From the central volcanic mountains draped with tropical rainforests, to the gently sloping pyroclastic fans that have provided rich soils for agriculture and land for settlement, to the coastline dominated by cliffs, to its variety of inshore and marine natural resources, the islands morphology is a key facet of its existence. The islands economy has always depended on the bounty of the land, first for agriculture and increasingly for a tourism product that is based largely on its natural environment.

Keywords

St. Kitts • Nevis • Volcanic • Environment

7.1 Introduction

The Federation of Saint Christopher (St. Kitts) and Nevis consists of three small islands: the inhabited islands of Saint Christopher (St. Kitts) and Nevis and the uninhabited Booby Island (Fig. 7.1). This Small Island Developing State is located in the northern section of the Leeward Islands and is part of the geo-political grouping called the Organization of Eastern Caribbean States.[1] Although there is only a small ocean channel (knows as the "Narrows") that physically separates the two islands, their separation is significant in terms of geo-political setting. Although provision is made under the binary "Federation" for the two islands to officially operate as one, a special relationship exists between them, which means that they function together and separately at the same time.

The most dominant influence on the landscape of both islands has been their volcanic history, which has resulted in a combination of volcanic mountains, rain forests, and unspoiled beaches. The fact that both islands have an adequate supply of groundwater and an abundance of well-drained fields on gently sloping land ($<10^o$) suitable for agriculture is to a large extent also due to the underlying geology. Single, young volcanic centers dominate each island, comprising the core of central volcanic mountains, which are densely vegetated by rainforest. These central mountains remain surrounded by gently sloping land that falls away uniformly toward the coastline in all directions (Fig. 7.2a).

St. Kitts is 176 km^2 (68 mi^2) in area and roughly oval in shape with a narrow neck of land extending like a handle toward the southeast. It consists of a central mountain range dominated by Mt Liamuiga and surrounded by cultivated slopes, dissected by dry river valleys (ghauts) that drain into the sea. The southern sections of the central range enclose a

[1]This is an inter-governmental organization dedicated to economic harmonization and integration, protection of human and legal rights, and the encouragement of good governance between countries and dependencies in the Eastern Caribbean. It also performs the role of spreading responsibility and liability in the event of natural disaster, such as a hurricane.

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Fig. 7.1 General physiographic map of St. Kitts and Nevis highlighting the islands' mountainous topographies and political parish boundaries. The waterway separating the two main islands, the Narrows, contains the small island of Booby Island. Cartography by K.M. Groom

spacious fertile valley that opens into the capital city of Basseterre. Although golden sandy beaches are common in the Southeast Peninsula, most of the beaches on the island are of gray and brown volcanic sand. Manifestations of recent volcanic activity include active fumaroles in the crater of Mt Liamuiga (1156 m, where an ephemeral lake exists—see Fig. 7.2b) and past periods of intense earthquake activity associated with the volcano.

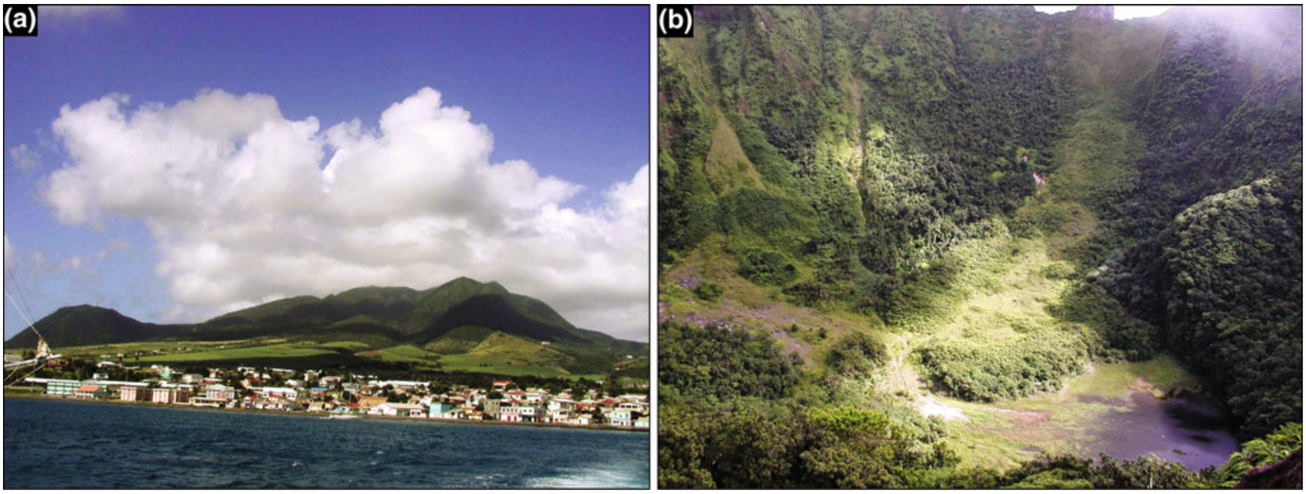

Fig. 7.2 Mountainous features of St. Kitts and Nevis. **a** Offshore view of St. Kitts showing its core of densely vegetated, central volcanic mountains (*left* to *right* are Brimstone Hill, Mt. Liamuiga, Middle Range, Southeast Range), surrounded by gentle cultivated slopes that drain to the sea. Basseterre, the capital of St. Kitts with its reclaimed waterfront area, is in the foreground. **b** The steep-walled summit crater of Mt. Liamuiga volcano is a 900 m (width) × 244 m (depth) feature that contains low temperature fumaroles, a small ephemeral lake visible at the bottom of the image and a dense cover of mainly cloud forest. Photographs courtesy of R. Robertson, The UWI Seismic Research Centre

At 93 km^2, Nevis is also dominated by a central peak (Nevis Peak, 985 m) and dissected by deep ghauts that run from the peak to the sea. No regular stream flow occurs in the ghauts except during heavy rains, and the island has no significant bays, inlets, or cays, but has long stretches of golden, sandy beaches around most of the island. Vegetation cover is extensive but not dense, and many wetlands occur along the leeward coast.

Understanding and appreciation of the value of the landscape on both islands have spawned the creation of various organizations, policies, and practices in an attempt to manage the island's heritage resources. Institutionalized concern is reflected in extensive government policies and legislation as well as in such organizations as the National Conservations Commission, the St. Christopher Heritage Society, and the Nevis Historical and Conservation Society. The creation of national parks as well as the organization of various beautification and environmental management projects represents specific actions that focus on preservation of heritage resources.

7.2 Setting

Volcanic in origin, St. Kitts (17° 15′ N, 62° 45′ W) and Nevis (3 km to the southeast, at 17° 10′ N, 62° 35′ W), is located in the northern part of the Lesser Antilles chain of islands in the Eastern Caribbean, upon a submarine ridge that extends from St. Eustatius to just south of Nevis, covering an area of 80 km × 16 km. The coastal shelf widens slightly between both islands, and a total area of 595 km^2 lies within the territorial waters of St. Kitts and Nevis (Island Resources Foundation 1991). The islands have a combined area of 269 km^2 and a population of approximately 46,000 persons (2010 census). With a Tropical Marine Climate that is strongly influenced by steady northeast trade winds and tropical oceanic cyclonic movements, the Federation experiences warm temperatures averaging about 28 °C, with small seasonal and diurnal variations. At high altitudes, temperatures can drop below 17 °C. Rainfall is mainly orographic, affected by a central mountain range that extends from Mt. Liamuiga (1156 m) to the Southeast Range (901 m). Precipitation increases in amount and frequency with altitude. The yearly average rainfall is 1620 mm, but it can range from ~1000 mm in coastal areas to ~3800 mm in the central mountains. Except for the Southeast Peninsula, which is very dry, rainfall is fairly well distributed throughout the island with a seasonal variation between the "wet" and "dry" season. The wet season extends from August to November, while the driest months are from January to April. Relative humidity is low in the dry season and high in the wet season with a mean value of 76%. The prevailing winds blow from the northeast (NE trade winds) with speeds ranging from 15 to 30 kph.

The volcanic landscape has resulted in beaches that consist of a variety of mostly volcanic materials ranging from black sand to cobbles, rocks, and boulders. In the Southeast Peninsula, south of Friar's Bay, beaches are comprised of marine sands consisting of coral and shell materials, and at Sandy Point, Dieppe Bay, and Conaree there is a mixture of land-based and marine sand (Island Resources Foundation 1991). In addition to the coral and volcanic beaches, the coastal areas of St. Kitts and Nevis abound in shore and marine natural resources including coral reefs, mangroves, saltwater lagoons, and sea grass beds.

The increasing importance of tourism to the economy of both islands makes these coastal areas a vital asset that needs to be protected from the effects of human activities and the ravages of storms. The coastal zone has been affected by developments along the shore, including farming, quarrying (sand mining for construction), sewage disposal, and land reclamation. Human activities have placed tremendous stress on the ecological balance of coral reefs, sea grass beds, and mangroves leading to a rapid decline of marine ecosystems. Elevated nutrient levels in the coastal zone due to runoff from urban and agricultural areas along ghauts and storm drains has led to imbalances to the marine ecosystems (Williams 2013). Wetland infilling for residential homes and hotels due to development pressure and natural hazards is causing the islands to lose its coastal mangrove habitats.

7.3 Landforms

7.3.1 St. Kitts Landforms

7.3.1.1 Major Features

St. Kitts is an elongated island oriented NW–SE, 36.8 km (23 mi) long and roughly oval shaped with a narrow neck of land extending from the southeastern end (Fig. 7.3). It generally rises from the coastline toward its mountainous interior. The island is suspended on an underwater ridge which has a northwest to southeast axis from which Nevis also arises. The physical landscape of St. Kitts has a rugged backbone characterized by three volcanic centers dominated by Mt. Liamuiga, which rises with a pronounced crater to 1156 m.

Southeast of Mt. Liamuiga the Central Range and Southeast Range continue the trend after which the land descends into the Basseterre Valley. The Central and

Fig. 7.3 Elongated shape of St. Kitts with its rugged backbone of volcanic centers that trend NW–SE is clearly seen on a largely cloudless day from Nevis Peak, Nevis. The contrasting morphology of the youthful Mt Liamuiga volcano (*upper left*) to the older dissected domes of the Salt Pond Peninsula (*mid-center*) is well illustrated in the photograph. The lush slopes of Nevis Peak occupy the foreground of the image. Photograph courtesy of R. Robertson, The UWI Seismic Research Centre

Southeast Range consist of a number of irregular peaks; the highest of which is Verchild's mountain at 975 m (3200 ft). The slopes in these ranges are generally steeper and shorter toward the leeward coast. The main mountainous interior blends downslope into a gradually sloping coastal plain that is interrupted by minor domes at Brimstone Hill, Ottley's Mountain, Sandy Point Hill, and Monkey Hill. Most of the flat and moderately sloping land occurs in these areas near the coast, which as a result, has been the areas used for urban and agricultural development.

7.3.1.2 Volcanic Centers

Although the core of St. Kitts is comprised of older (possibly Eocene) volcanic material, three younger volcanic centers encompass most of the island: the Southeast Range, the Middle Range, and Central Range dominated by Mt. Liamuiga (Martin-Kaye 1959). These are Pliocene to Pleistocene in age and become progressively younger toward the northwest (Hovey 1903, 1905; Sapper 1904; Davis 1924; Martin-Kaye 1959; Fels 1903; Earle 1925). The Salt Pond Peninsula is an old dissected landscape that consists of many low, rounded hills that comprise the topographic highs and reach a maximum height of 319 m, with flat, low-lying areas, and salt ponds comprising the topographic lows. Geologically, this area consists of lava domes and volcaniclastic deposits, which may have originally been pyroclastic flows and lahars from past eruptions. The oldest rocks exposed on the island (2.77 ± 0.3 Ma, Baker 1969) are found in this region (Fig. 7.4). Lang and Carroll (1966) suggested that the St. Anthony's Peak, the highest point on the Peninsula, might have been the site of a volcanic crater.

Younger Pleistocene volcanic centers (Southeast Range, Middle Range, and Mt. Liamuiga) that consist mainly of andesitic pyroclastic deposits are found along the island's central spine. They occur as ash, reworked sands and gravels, cobbles, and boulders. The Southeast Range rises up to 900 m and is a younger volcanic center made up of lava flows and volcaniclastic deposits. Due to poor exposures, little is known about its past eruptive history, but Baker (1985) obtained an age of 1 million years for a lava flow on its southern slopes. The Middle Range is heavily forested with few outcrops of hard rock and with difficult access to exposures of its geology. It has a summit lake and youthful appearance, but no age dates have been obtained and so it is difficult to make any conclusions about its eruptive history.

Located on the northwestern most mountain and being the youngest volcanic center on the island, Mt. Liamuiga represents a typical stratovolcano, composed of alternating layers of andesitic and basaltic lava flows, agglomerates, and pyroclastics (Fig. 7.5a). The last eruption is estimated to have been about 1620 years before present (Baker 1985). Its young age, associated geothermal and seismic activity, suggests that it is a potentially active volcano that is likely to erupt again in the future (Robertson 2005). There is a steep, summit crater ∼900 m wide, and 244 m deep which contains a small ephemeral lake and has active low temperature (up to 100 °C) fumaroles along the crater walls (Robertson 2005). An old Carib legend suggests that Brimstone Hill, an andesite lava dome located on its lower flanks, grew out of the Mt. Liamuiga (Baker 1985), hinting that pre-Columbian peoples may have witnessed the growth of this dome.

7.3.1.3 Southeast Peninsula

The Southeast Peninsula is a cluster of seven older islands that have become linked by recent beach and saline marsh deposits. These were originally tombolos, which have widened into flat sedimentary plains and marshland linking the seven preexisting small islands/islets. The hills on the Peninsula are smoothly rounded with slightly convex peaks. The largest is St. Anthony's Peak at 319 m. Eight saline ponds that vary in size from 160 to 1.6 ha occur in the area.

The Peninsula consists of two distinct features (1) a narrow spit or bar that is slightly more than 0.5 km wide and about 4.5 km in length that extends in a southeasterly directly from Timothy Hill at Frigate Bay to Salt Pond Hill and (2) a larger, roughly triangular tombolo cluster surrounding the largest saline pond, 440 acre Great Salt Pond (Island Resources Foundation 1991).

7.3.1.4 Coastal Features

The coastline of St. Kitts consists largely of cliffs that range in height from 15 to 30 m. At Black Rocks, a basalt lava flow forms prominent distinctly black coastal cliffs (Fig. 7.5b). Narrow black sand beaches comprised of the eroded products from the volcanic hinterland occur at the base of most cliffs. In the northwest, the cliffs are lower, and some of the beaches are wider and comprised of yellow sand (Island Resources Foundation 1991). There are long stretches of fine yellow sand beaches extending from Conaree Beach on to the southeast of the island. Unfortunately, excessive sediment loads, biocide runoff, and other land-based sources of pollution continue to be the main causes of reef damage leading to coastal erosion across the islands (Island Resources Foundation 1991; Williams 2013).

7.3.2 Nevis Landforms

7.3.2.1 Major Features

Nevis is an oval-shaped island, 12.3 km long (7.64 mi) and 9.6 km (5.96 mi) wide at its widest part with its topography dominated by the central Nevis Peak. Although it is comprised of seven volcanic centers strung out SE–NW, the dominance of Nevis Peak on its topography is such that the peak overshadows all other topographic features, giving the island the appearance of a classic volcano-island. Windy Hill

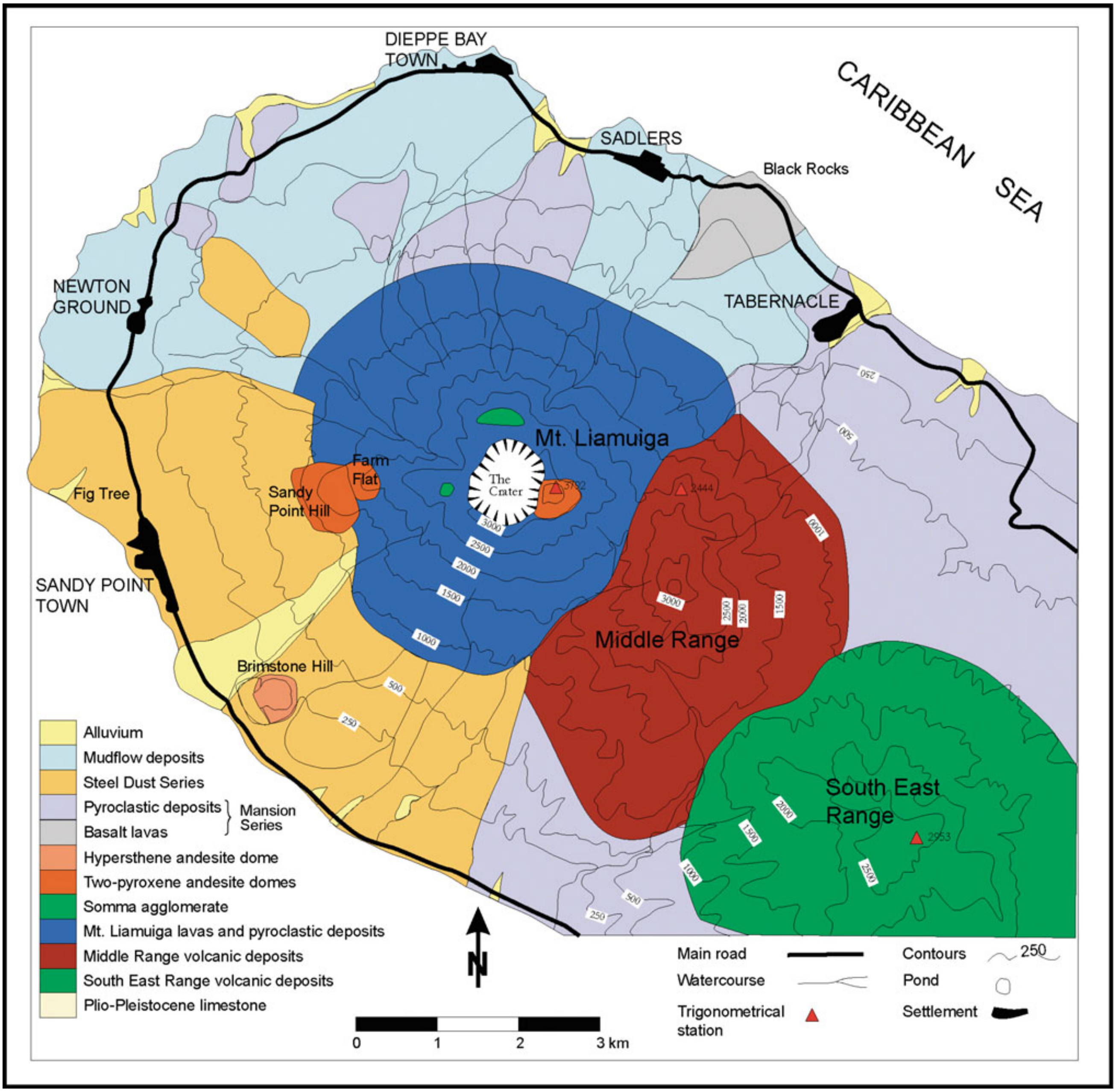

Fig. 7.4 Geological sketch map of the northwestern part of St. Kitts (adapted from Baker 1969) showing the main geological formations that make up the island. Note the different lava and pyroclastic flow events that cover much of the island's landscape. Cartography by Shahiba Ali from the Volcanic Hazard Atlas of the Lesser Antilles (see Robertson 2005)

(309 m) also called Round Hill in the northwest and Saddle Hill (381 m) in the southeast end of the island line up with Nevis Peak in the center to form a similar north-northwest to south-southeast trending trend as the more pronounced orientation of the mountains in St. Kitts.

7.3.2.2 Volcanic Centers

Seven volcanic centers have been identified on the island of Nevis: Hurricane Hill, Round Hill, Cades Bay, Saddles Hill, Red Cliff, Butlers Mountain, and Nevis Peak, all considered to be the remains of lava domes that were created by quiet, effusive eruptions (Hutton 1965; Hutton and Nockolds 1978; Fig. 7.6). The oldest rocks are found in the northwest of the island at Round Hill (3.43 Ma) and the youngest are associated with Nevis Peak (0.10–0.98 Ma; Hutton and Nockolds 1978).

Nevis Peak, rising to 985 m and representing the island's highest point, is comprised of a central cone with flank

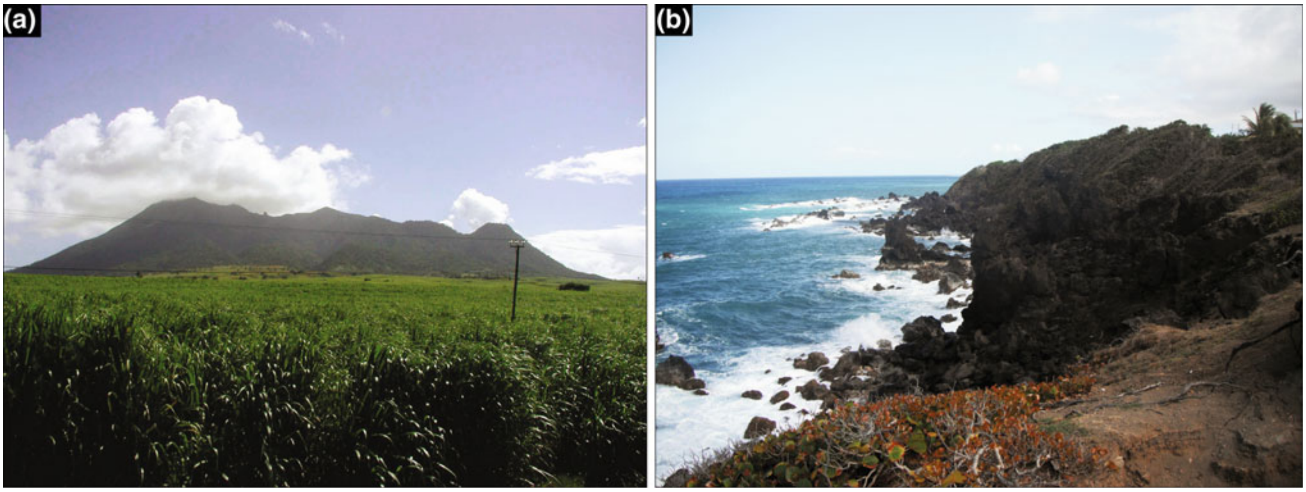

Fig. 7.5 Examples of volcanic landforms on St. Kitts. **a** Mt. Liamuiga volcano, which rises up to 3792 ft. (1156 m), the youngest volcanic center on the island of St. Kitts and its highest mountain. Its lower flanks are occupied by farmland and small villages but at higher elevations tropical rainforest and cloud forest takes over. **b** Black Rocks (also called Black Stone), a notable rock formation that is an old lava flow from Mt. Liamuiga volcano, located on the northeastern coast of St. Kitts. This black basaltic rock was formed during the early evolution of Mt. Liamuiga volcano. Photographs courtesy of R. Robertson, The UWI Seismic Research Centre

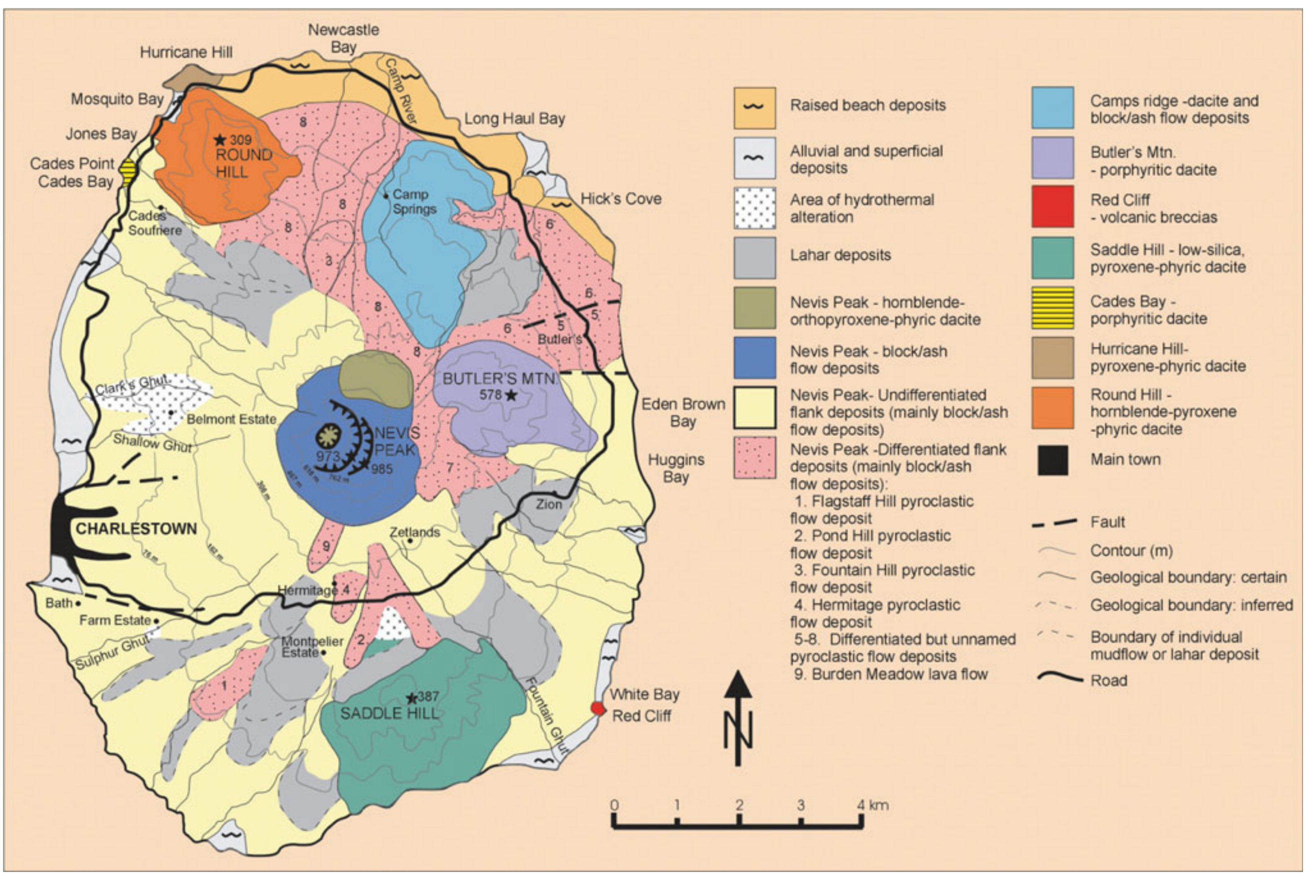

Fig. 7.6 Generalized geological map of Nevis Island (modified from Hutton and Nockolds 1978) showing all the major geologic features on the island. Cartography by Shahiba Ali from the Volcanic Hazard Atlas of the Lesser Antilles (see Simpson 2005)

deposits radiating outward toward the sea and two younger lava domes. Past eruptions have produced lava domes and associated volcaniclastic deposits that range in compositions from andesite to dacite (58–65% SiO_2; Hutton and Nockolds 1978).

Although there are large areas of hydrothermally altered rocks found throughout the island, only two localities exist with focused fumarolic activity: Cades Bay and Farm Estate. These are relatively low-temperature (53–100 °C) fumaroles characterized by warm, hydrothermally altered ground, small boiling pools, and weakly steaming vents (Robertson 2005). Geothermal activity on Nevis is also exhibited at a number of hot springs—the hottest being Bath Estate and Cades Bay beach. At these locations, the emission of hot gases under water provides a "champagne" effect.

7.3.2.3 Microclimates and Drainage

The presence of several peaks on Nevis results in a range of microclimates that vary greatly with height, location, and orientation. Possibly due to the lower elevation of its central mountain, the average rainfall is lower than on St. Kitts with considerable variation from year to year and month to month. Rain falling on the elevated mountain core of St. Kitts drains toward the sea by way of river valleys (called ghauts) that are mostly dry. Many of the streams are fed from springs and their overland flow disappears underground at about the 250 m contour. The only two rivers that flow consistently to the sea for most of the wet season are the relatively large Wingfield and Canyon Rivers.

On Nevis, the dominance of Nevis Peak as the major topographic feature on the island results in a radial drainage pattern, which is only disrupted by the smaller volcanic cones of Hurricane, Saddle, and Round Hills. Like St. Kitts drainage is via dry ghauts, which develop as deep, steep sided ravines on the flanks of Nevis Peak. There are no lakes or ponds on the island and only intermittent streams. Most of the ghauts are ephemeral and only Bath and Camps Rivers, which are fed from springs located close to the shoreline (<1.6 km), actually flow into the sea.

7.4 Landscape and History

7.4.1 Biogeography and Landscape

The biogeographical face of the country is as much a result of nature as it is interaction with people over time. Centuries of successful sugar cultivation have left an aesthetically pleasing, orderly, well-proportioned rural landscape on St. Kitts. In contrast, the long, less successful experience with sugar (until the 1950s) in Nevis and later free-grazing goats, sheep, cattle, and pigs has scarred and ravaged the landscape. Lack of this protective vegetation cover has resulted in greater erosive impact of wind and water erosion and sediment flow downslope that impact coastal areas and reefs (Island Resources Foundation 1991). The human-environment impact on Nevis differs significantly from that on St. Kitts.

Vegetation coverage on both islands comprises a variation of Rainforest, Dry Evergreen Forest, Dry Scrub Land, Palm Break, Elfin Woodland, and Disturbed lowlands that resulted from farming (Ministry of Sustainable Development 2014). The dominant influence on vegetation distribution on both islands is the effect of moisture-laden trade winds forced upwards by their prominent central peaks. Cooling of the moisture-laden air results in rain that falls more consistently on the upper slopes and leads to differential distribution between the windward and leeward side of the island. This has led to the development of classic island vegetation: Elfin Woodland and Palm Brake in the highest areas, giving way to rain forest on lower slopes, then seasonal and dry evergreen forests, and finally transitioning to littoral and mangrove along the coast. An upland forest belt occupies the steeper part of the central mountainous interior that comprises the northwest, central, and southeast ranges. This forest blends downslope into a gradually sloping coastal plain that flows gracefully toward the sea. It is an area that was traditionally occupied by sugarcane plantation but has increasingly become occupied by diversified agricultural crops and pastureland.

7.4.2 Anthropogenic Impacts

The vegetation on St. Kitts and Nevis has been greatly disturbed by human activity. Intensive land use in the lowland areas has removed all semblance of the natural vegetation, and agricultural crops dominate most areas not currently urbanized (Island Resources Foundation 1991). Although the mountains are still largely covered by forest, it is unlikely that any of this is still virgin forest. The lower reaches of forested areas (244–457 m), where the land has been under cultivation (with sugar, cotton, ground provisions) for a long period of time, are now occupied by secondary growth of dry evergreen forest of small trees (15–18 m in height) on abandoned farms. The resident vegetation consists of about 243 species of trees (Beard 1949).

The range and abundance of flora and fauna on St. Kitts and Nevis have also been adversely affected by human settlement particularly with the coming of the Europeans who replaced the indigenous Caribs and Arawaks. Modification, and in some cases elimination, of habitats and their associated wildlife followed the wholesale clearing of vegetation and changes to the landscape for estate development (sugarcane cultivation) and infrastructure development. Europeans civilization also introduced exotic animal species such as cats, dogs, rats, pigs, and mongoose that significantly affected native habitats and local populations of wildlife species such as ground-dwelling birds, beach-nesting sea turtles, agouti, and iguanas. The relatively inaccessible central mountainous backbone of St. Kitts (extending from Mt. Liamuiga to Olivees) and the island's largely remote Southeast Peninsula are areas where wildlife has been largely untouched and preserved. On Nevis, the combination of Nevis Peak and lower population densities has served to moderate the loss of wildlife.

Located along the island's coastal belt, the wetlands represent St. Kitts' most important habitat for migratory and marine avian species. The best example of a mangrove swamp on the island, Greatheeds Pond, resides on the Windward coast at Conaree, just below the Canada Hills. Other wetland habitats are found at Friar's Bay, Frigate Bay, and the pond system of the Southeast Peninsula. The island is among the few in the Eastern Caribbean to have large pond systems, and certainly unique in having one large pond (Salt Pond) that attracts a large number of shorebirds.

7.4.3 Historical Impacts

When St. Kitts and Nevis was first sighted and named by Columbus in 1493, Carib Indians inhabited the island. They called the island "Liamuiga" (fertile land) and were the last of several Amerindian migrations from South America during the prehistoric period. These included the hunter-gathering people called the Siboney who arrived around 4500 BP, followed by the agriculturally based Arawaks who arrived around 2000 BP. Archaeological investigations by Goodwin (1979, 1980) indicate that Amerindian land use at this time was often high. Centuries of slash and burn agriculture destroyed much of the primary forest on both islands well before European arrival.

On Nevis, preceramic people occupied the island as far back as 4000 BP. The island was affected by similar migrations of indigenous peoples from South America, but its written history did not begin until the arrival of Columbus in 1493. The Caribs called the island "Oualie" (land of beautiful water), but the island's current name was derived from the Spanish "Nuestra Senora de las Nieves" (Our Lady of the Snows), so called due to the ubiquitous and continual cloud cover that encircles Nevis Peak (Fig. 7.7).

Columbus claimed both islands in the name of Spain, but since the Spanish focused more on the large islands in the region, they made little effort to colonize the two islands. This enabled the Caribs to remain unchallenged on the island until the early seventeenth century when land-hungry northern Europeans descended on the Eastern Caribbean. The first permanent European settlement on the island occurred in 1624 when Thomas Warner landed with a small party of British men (Island Resources Foundation 1991). The Caribs allowed him to establish a settlement near their village at Old Road. The French, led by Pierre Belain, arrived a few months after and were also welcomed by the Caribs. As was the practice at the time, French and British settlers began to enslave (and in some cases massacre) their indigenous hosts by 1626. Thereafter the island was divided between the two nations who maintained a peaceful co-existence since they had to guard against attacks by the Spanish. In 1628, the British expanded to Nevis when a group led by Anthony Hilton moved there and established a settlement named Jamestown.

In the early parts of the seventeenth century, St. Kitts was used as a base by the two colonial powers to expand their influence in the region with the French occupying Guadeloupe and Martinique, and the British expanding to Antigua and Montserrat. St. Kitts soon developed a reputation as one of the most fertile sugar colonies although intermittent colonial warfare between 1666 and 1708 prevented its emergence as a full-fledged sugar monoculture. During this period, the French and British attacked and seized each other's territory on St. Kitts and twice the French overran Nevis. The British eventually gained control, and in 1713, France ceded its portion of St. Kitts. The sugar industry expanded rapidly thereafter, and between 1715 and 1735, sugar monoculture supported by African slave labor replaced the preexisting diversified economy of the island. The island's population expanded significantly after this period as well, giving St. Kitts one of the highest population densities in the Caribbean by the middle of the eighteenth century (Island Resources Foundation 1991).

The main reason for colonization of the islands by the British was for sugar and Sea Island cotton export. Sugar has dominated the economic life of the two islands from colonial times until recently, when the focus has turned to tourism. All of this activity depends heavily on, and is affected by, the environment—all of which remains dominated by the volcanic landscape. Prior to the 1970s, most of St. Kitts' water needs were satisfied by surface springs and streams. Since then, there has been increasing focus on the island's groundwater resources as a source of supply to meet growing demand and ensure greater reliability. Still, on St. Kitts, springs, rather than groundwater, continue to provide the largest proportion of the total water supply. On Nevis, all water needs (domestic, agricultural, and industrial) are met by a combination of surface, rain, and groundwater sources, with groundwater providing the largest proportion of their public piped water supply.

Despite over 300 hundred years of continuous and intensive use for agriculture, St. Kitts' and Nevis' soils have generally stood up well. This is largely a result of the beneficial properties (chemical and physical qualities) resulting

Fig. 7.7 View of Nevis Peak from the ferry between St. Kitts and Nevis. A 3232 ft. (985 m) high stratovolcano, Nevis Peak is the highest point on the island of Nevis. Its central cone rises up behind the capital Charlestown and flank deposits radiate outward toward the sea in all directions. On days when the peak is completely free of clouds, there are remarkable views from its summit of the surrounding islands. Photograph courtesy of R. Robertson, The UWI Seismic Research Centre

from recent volcanism on the islands, since fresh volcanic materials can give rise to fertile soils up to 20 years after deposition (Hardy 1939). Rapid soil formation resulting from the abundance of fragmentary volcanic ejecta has also reduced the impact of soil erosion on cultivated slopes on both islands.

7.4.4 Geothermal Resources

The relatively young volcanic geology of St. Kitts and Nevis has provided it with significant untapped high-temperature geothermal resources with the potential for the development of geothermal power. Given that renewable energy resources (wind and solar) provide only 5.7% to their total installed power capacity of 56.4 MW, development of these resources has the potential to dramatically alter the energy balance of these islands (Alexander et al. 2015). Investigations undertaken by Energy and Climate Partnership for the Americas on a potential interconnection between St. Kitts and Nevis and Puerto Rico concluded that such an interconnection could simultaneously reduce oil and natural gas use on the islands and promote geothermal development (Alexander et al. 2015).

Investment and development plans have increased in recent years with exploratory drilling already completed in Nevis, and geothermal exploration exercises started in St. Kitts where consideration is being given to the generation of up to 20 MW for the initial phase. In both instances, however, plans for development have been challenged by political opponents and by lack of incentives for private sector participation (Alexander et al. 2015). On Nevis, the US Department of State and other partners in the USA are providing assistance.

St. Kitts and Nevis have separate utilities with exclusive rights to operate power systems on each island, and current developments demonstrate each island is utilizing different approaches to explore and develop their geothermal resources. Additionally, the high upfront capital needs, including the exploratory drilling, presents a major barrier to development of operational geothermal power. The relatively small power demand on both islands poses a challenge to profitability and points to the need for regional interconnection, collaboration, and trade in development of these resources.

7.5 Heritage and Tourism

The uniqueness of St. Kitts and Nevis, which has helped to shape the national identity and public image, is derived in part from the country's distinctive, dramatic, and spacious profile—all a direct result of its geologic past (Island Resources Foundation 1991). Each island is dominated by a single, volcanic edifice surrounded by a wide expanse of gently sloping fertile land that uniformly spreads toward the sea in all directions. Unlike other volcanic islands in the Lesser Antilles Island Arc, there is no complex interior landscape rising abruptly from the coastline. The hinterland of both islands is clearly visible from the coastline, often in one continuous parade of microhabitat variation and attitudinally conditioned biodiversity (Island Resources Foundation 1991).

Over the past two decades, the Federation has been transitioning from a way of life that evolved over four centuries of sugarcane cultivation to a political economy influenced by investments in the development of tourism, the challenges of international trade, and an uncertain environmental future (Williams 2013; Fig. 7.8). The sustainable management of land is a critical issue for the economic and social well-being of the country (Williams 2013). Partly in response to this, the Government of St. Kitts and Nevis (GOSKN) has established a number of laws, regulations, guidelines, and standards designed to govern the Federation's sustainable use and exploitation of the terrestrial and coastal resources. Each of these provides policies and guidelines for dealing with environmental issues with the overall intention of promoting sustainable development of the island.

Over the past few decades, a number of laws have also been passed to provide for the management, development, and protection of the natural environment. The legislation requires the preparation of Environmental Impact Assessments for projects that are likely to impact natural resources. Although there is no specific legislation that deals with soil conservation, there are legislative provisions that cover forestry and land tenancy—issues often related to soil conservation. One of the key issues is the existence of "landless" livestock farmers who graze animals in unrestricted areas.

St. Kitts and Nevis is signatory to five, and Party to 41 international environmental agreements, of which 18 are deemed to be the most important (Williams 2013). The obligations of the twin-island federation under a number of these international agreements have been recognized in national law. Despite the number of policies and laws that exists, Williams (2013) noted that outdated legislation and poor enforcement along with limited exposure of legal personnel to environmental issues and impacts are major weaknesses that minimize the effectiveness of the environmental regulations.

There are several designated national parks or protected areas on the islands. Brimstone Hill National Park Fortress (St. Kitts) and the Bath Hotel (Nevis) were two of the first, but recently the Central Forest Reserve National Park (CFRNP), the Royal Basseterre Valley Park (RBVP), St. Mary's Biosphere Reserve, and Frigate Bay Salt Pond have been declared protected. In addition, all land above the 300 m contour on Nevis is totally protected through administrative means and there are plans to establish a Nevis Peak Park to encompass this area.

Brimstone Hill Fortress National Park is a UNESCO World Heritage Site, and a key component of St. Kitts tourism product. Designed by British military engineers and constructed with skill, strength, and endurance of African slaves, it features great historical, cultural, and architectural significance. Although its primary focus is historical and cultural preservation, it also serves as an unofficial bird and monkey sanctuary. Alongside Brimstone Hill, the other early tourism draw for the Federation was the Bath Hotel, built in 1778 on a site overlooking Charlestown, the capital of Nevis, and adjacent to natural hot springs. Similar in function and style to its namesake in the UK, it first attracted many European travelers who would come for the hot springs.

The Central Forest Reserve National Park (CFRNP) is one of the largest protected areas on both islands encompassing 50 km^2 of cloud forest that provides habitat to a number of threatened birds and represents the last stand of undisturbed tropical rainforest on St. Kitts. The area is most important for its water resources, with an estimated 30% of St. Kitts' potable water supply originating from surface runoff within the Park. Heritage resources include scenic trails, as well as budge wood (*Myrtaceae*) for fish pots; bamboo, coconut, and calabash for traditional arts and crafts; and plants for traditional medicines.

The Basseterre Valley Park, at ~ 2 km^2 and immediately adjacent to the capital city Basseterre, houses an aquifer that provides 40% of the water supply for Basseterre. The water supply, however, is under threat from human-induced impacts such as fertilizer usage, sewage treatment and disposal, and storm water runoff along roadways. While still under development, plans have been put forth to provide a variety of development such as trails, parking lots, train station, and a large rainforest arboretum.

St. Mary's Biosphere Reserve and Frigate Bay Salt Pond are the most recently declared protected areas on the islands. Comprising cloud forests, mangroves, and coral reefs, St. Mary's Biosphere Reserve represents an important site in terms of biological diversity and is, in fact, one of the most

Fig. 7.8 Various tourism resources, both historic and geologic/geomorphologic, found on St. Kitts and Nevis. **a** Brimstone Hill Fortress National Park—a UNESCO World Heritage Site of historical, cultural, and architectural significance that is a prominent feature on the landscape of the island of St. Kitts. Its construction is a testimony to the ingenuity of British military engineers who designed it and to the skill, strength, and endurance of African slaves who built and maintained it. **b** The historic Church of Immaculate Conception located in Basseterre was built in or about 1856 and grew to become a beacon of Catholicism on St. Kitts during the ensuing years. Steeped in the history and traditions of Portuguese and Irish immigrants, the parish is one of two cathedrals in the Diocese of St. John's-Basseterre. **c** St. George's Anglican Church in Basseterre, one of the oldest surviving Anglican churches in the English-speaking Eastern Caribbean; a major tourist attraction and landmark on the island of St. Kitts. Its history, which consists of significant impacts by natural hazards (the 1842 earthquake, 1843 hurricane, and several others since 1989), along with human impact (the Great Fire of 1867), is symbolic of the two key influences on the evolution of the landscape on the island. This Church was originally built by the French as a Catholic Church but was subsequently burnt by English soldiers and rebuilt. **d** A green clock tower and water fountain that is known as Piccadilly Circus, or The Circus marks the main square of Basseterre, the Capital City of St. Kitts. This area was once a slave market for African slaves, who were one of the driving forces in the modification of the landscape on the island. It is a memorial to the former president of the General Legislative Council, Thomas Berkeley courtesy of R. Robertson, The UWI Seismic Research Centre

diverse natural communities on St. Kitts. Frigate Bay Salt Pond is located in an area that supports a number of bird species and is linked to the breeding of three such species. There are plans for its rehabilitation and generation of eco-tourism and educational experiences.

Two key NGOs remain actively involved in projects related to heritage conservation, environmental management, and protection in St. Kitts and Nevis: the *Saint Christopher National Trust* (SCNT) and the *Nevis Historical and Conservation Society* (NHCS). The SCNT evolved from the St. Christopher Heritage Society, which was incorporated as a private company in 1994. The Trust manages the National Museum in the Old Treasury Building in Basseterre and has as its key objective the protection, conservation, interpretation, and enhancement of the natural environment of St. Kitts, including its animals and plant life. The Trust provides a forum for the exchange of ideas, information, and knowledge on a range of issues related to conservation and heritage. The NHCS, established in 1980 to conserve the natural, cultural, and historic resources of Nevis, and its adjacent marine areas have worked to institute projects and policies designed not only to preserve Nevis' unique history and environment, but also to make that heritage accessible and intelligible to locals and visitors to the island.

7.6 Hazards

St. Kitts and Nevis remain exposed to a wide range of hazards, similar to other islands in the Lesser Antilles: hurricanes, floods, droughts, landslides, earthquakes, and volcanic activity. An estimated 39% of the population is considered to be at risk from such hazards (GFDRR 2010). The islands are among the top 60 countries exposed to risk of mortality and within the top 40 who would suffer significant economic risk from two or more hazards (GFDRR 2010). Risk to GDP is estimated to be 65% (GFDRR 2010). Destruction caused by natural disasters has had a negative impact on tourist arrivals and as such affects an important foreign exchange service sector.

The principal hazards affecting both islands are those related to hydro-meteorological events (high winds and rainfall due to tropical storms and hurricanes). The tendency toward urbanization with its resulting increased exposure to wind damage makes the islands increasingly vulnerable to wind storms. In addition, tourism development, the main trust for the island's economic development, is focused in the coastal zone, which is exposed to hurricane and storm surge impacts. The islands' topography limits the areas prone to the flooding which invariably results from prolonged rainfall and storm surge events, resulting in relatively few flood-prone areas. Those places prone to flooding, however, are usually located in low-lying coastal areas (e.g., coastal fishing villages) and along stream passages, and given that the general preference on St. Kitts to live in low-lying areas close to the sea, vulnerability to flooding and related storm surges is high. This is less so in Nevis where the settlement pattern is more dispersed, due to its legacy farming practices. Areas used for tourism and port facilities, however, are particularly exposed to storm surge events since these are also located near the coastline.

Hurricanes have had the most devastating effect on the islands with over 20 named storms passing within 60 nautical miles of the Federation between 1995 and 2004 (Carter 2010). Nine of these (three in particular were Category 3 or higher) made landfall on the territory. Hurricane damage to St. Kitts and Nevis was estimated at 85 and 140% of GDP in 1995 and 1998, respectively—significantly impacting the economy. In 1998, damages of Hurricane George were estimated to be US$445 million, including damage to 80% of the housing (GFDRR 2010). This hurricane significantly impacted not only natural resources closely linked to economic activities, but also funds required for rebuilding infrastructure and provision of social services. In 2008, Hurricane Omar, a Category 4 storm, passed 150 km east of the islands, but still caused significant damage from wind and storm surge.

Perhaps the greatest hazard potential lies in St. Kitts' and Nevis' volcanic origins. Mt. Liamuiga, the active volcanic center on St. Kitts, is considered likely to erupt in the future despite not currently showing any signs of increased activity (Robertson 2005). Based on its history, future events are likely to be explosive magmatic eruptions accompanied by the formation of a lava dome. The most devastating volcanic hazards (pyroclastic density currents and lahars) are gravity controlled, and strongly affected by St. Kitts' topography, relegating these major impacts to river valleys and associated outwash plains. This will most directly affect the northern parts of the island, but thick ash fall deposits could extend as far as the southern parts of the island, posing a threat to aviation especially (Robertson 2005).

Nevis Peak represents the active center on Nevis and the most likely location of future eruptions for that island. Although there have been no recent signs of increased activity, frequent shallow earthquake swarms and hydrothermal activity indicate that this center is still volcanically active, and an increase in activity could occur in the future (Simpson 2005). Based on past eruptions, the most likely future event would be a lava dome-forming eruption from the summit of Nevis Peak. Given the size of the island and the potential impact of hazardous volcanic activity, a major volcanic eruption would require the evacuation of the entire island (Simpson 2005). The Southern Peninsula of St. Kitts could also be affected by ash fall from an eruption of Nevis Peak.

7.7 Conclusion

The Federation of St. Kitts and Nevis is unique in the region in terms of the openness of its landscape and the bifurcated nature of its governance. Its volcanic geology has imprinted itself on all aspects of the landscape with densely vegetated central volcanic mountains that help seed the islands water supply, surrounded by gently sloping pyroclastic fans that have provided rich soils for agriculture and land for settlement. This picturesque landscape has been able to withstand decades of mono-crop agriculture and remains supportive of continued farming, settlement, and infrastructure.

The island has a rich history beginning with settlement by migratory Amerindian peoples originating in South America to eventual and subsequent conquests by the Spanish, French, and British colonial powers. After several decades of relative neglect, the islands rose in importance to at one time being the base for French and British colonial expansion in the region. With the onset of plantation agriculture built on African slave labor, the island was for many decades dominated by sugarcane cultivation, which left a lasting legacy on the landscape.

The interaction of people and the environment has also left its imprint on flora and fauna, to the point that very few untouched areas remain. With increasing realization of the importance of careful environmental management to help ensure sustainable development, there has been greater emphasis placed on implementation of policies and guidelines backed by laws to enforce a more careful management of the land. Like other Lesser Antillean countries, St. Kitts and Nevis continue to struggle with the challenges of Small Island Developing States, while seeking to develop to their fullest potential. The fundamental importance of its landscape and the impact of its geology on all facets of life on the island remain evident. Maintaining an appropriate balance between the demands of economic development while minimizing harmful impacts on the environment will continue to be a challenge well into the future.

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8 Antigua and Barbuda

Amy E. Potter, Sean Chenoweth and Mick Day

Abstract

The country of Antigua and Barbuda comprises two islands located in the Lesser Antilles of the Caribbean. While both islands are positioned on the Barbuda Bank, they each consist of a unique geologic setting: Antigua is composed of volcanic rock, clay, and limestone, while Barbuda is largely limestone with prominent cave features. Their unique attributes are not just geologic, as the two islands also have differing histories that developed in part due to environmental constraints—Antigua's enslaved African population grew sugarcane as a British colony, while enslaved Barbudans raised livestock as a leased entity of the British Codrington family because of shallow soils resulting from the island's karst topography. Today, Antigua is much more developed relative to Barbuda in terms of tourism and has a greater population density. Barbuda's population is small and development is limited as a result of Barbuda's unique land tenure of common property. Still, despite their differences, both islands face similar environmental hazards including drought, hurricanes, soil erosion, flooding, and the long-term risks posed by climate change.

Keywords

Antigua and Barbuda • Caribbean • Common property • Tourism • Karst

8.1 Introduction

Antigua and Barbuda have land areas of about 280 and 160 km^2, respectively, with coastlines some 153 and 107 km in length (Loveless 1960; UN 2002; Carr and Heyman 2009; GA&B 2015a; Figs. 8.1 and 8.2). Geologically, they are part of the Limestone Caribbees (Martin-Kaye 1969; Blume 1974)—the Cenozoic carbonate-rock-dominated outer band of the Lesser Antilles island arc. Barbuda is dominated by carbonate rocks, primarily limestones of Pliocene age. Antigua consists of limestones, volcanic rocks, and clays ranging in age from mid-through late Oligocene (Wadge 1994; Donovan et al. 2014).

Elevations range from sea level to 402 m at Mount Obama (formerly Boggy Peak) in Antigua and to 38 m in the Highlands of Barbuda (GA&B 2015a). On and within the Antiguan limestones have developed karst landscapes, produced essentially by carbonate dissolution, containing dolines/sinkholes, dry valley systems, residual hills, and calcareous mollisols and vertisols systems. A discontinuous escarpment marks the boundary between the limestones and the Antiguan clays, on which a rolling central plain has developed, and the volcanic rocks of the southwest persist as prominent, steep-sided peaks and valleys bordered by a narrow coastal plain (CCA 1991). Barbuda is almost entirely limestone, similarly karstified as Antigua, but with extensive

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Fig. 8.1 General physiographic map of Antigua with major surrounding islands. The highest point, Mt. Obama, was renamed from Boggy Peak in 2009. Cartography by K.M. Groom

overlying sands (Martin-Kaye 1959; CCA 1991; UNEP 2010).

The easterly trade winds help moderate the Lesser Antilles summer temperatures. Because of the prevailing northeasterly trade winds, the eastern sides and windward slopes of Caribbean islands, such as the Barbuda Highlands, receive more rainfall. Overall, the climate is dry, sub-humid with average temperatures ranging seasonally between 24 °C (75F) and 29 °C (84F) (CCA 1991; ABMS 2015), though Barbuda can be classified as a dry-winter tropical climate (Rudloff 1981). Antigua's annual rainfall from 1981 to 2000 averaged 1187.5 mm/46.75 in (Antigua and Barbuda Meteorological Services 2016). Annual rainfall is characterized by extreme inter-year variability, with a distinct dry season from January through April and an August-November wet season (Barragne-Bigot and Yearwood 1991; CCA 1991: UNCCD 2005). Soils reflect the underlying geologic substrates, being dominantly shallow calcareous mollisols and vertisols over the limestones, sands, and clays in the Central Plain of Antigua, and acidic clay loams on the volcanic rocks (Hill 1966; CCA 1991). The annual cycle of temperature exhibits a summer-winter variation with a small range. Low temperatures around 20 °C in February and high temperatures during September about 32 °C result in an annual range of 12 °C for Barbuda (National Ocean Service 2015). The annual rainfall range for Barbuda is 750–900 mm (Oliver 2005), and hurricane season is from June to November with a peak of activity in September, prior to the rainfall maximum in November for the Caribbean.

Fig. 8.2 General physiographic map of Barbuda. Since St. John's, Antigua, serves as the administrative capital for both islands, Barbuda has no capital city. Codrington Village is the population center for Barbuda. Cartography by K.M. Groom

Barbuda has a resident population of about 2000 and Antigua 90,000 with population densities of about 13/km^2 (32 per square mile) and 321/km^2 (833 per square mile), respectively (GA&B 2015a; CIA 2015). Annual population increase is currently about 1.3% (CIA 2015), but visitor numbers have increased steadily to about 800,000 annually (GA&B 2015b), effectively doubling the population during peak season. The population, about 24% of which is urban, is concentrated in northwestern Antigua, particularly around St. John's (22,000) (CIA 2015; GA&B 2015a).

Human impact on the landscape has been long term and profound, resulting in wholesale environmental changes (Watts 1987; Day 2010a, b). Drought and water supply are fundamental problems, as is accelerated erosion and, paradoxically, occasional flooding. Hurricanes, occasional earthquakes, and potentially volcanic ash fallout and tsunamis pose additional threats (Wadge 1994). Environmental issues are intensified by the combination of limited land area, high population density, and mass tourism.

8.2 Antigua

8.2.1 Setting

Representing an exposed portion of the extensive Barbuda Bank, the volcanic basis of Antigua is mid-Oligocene, with overlying sedimentary rocks of later Oligocene age (Martin-Kaye 1959; Donovan et al. 2014). The stratigraphic succession is the most complete in the Limestone Caribbees,

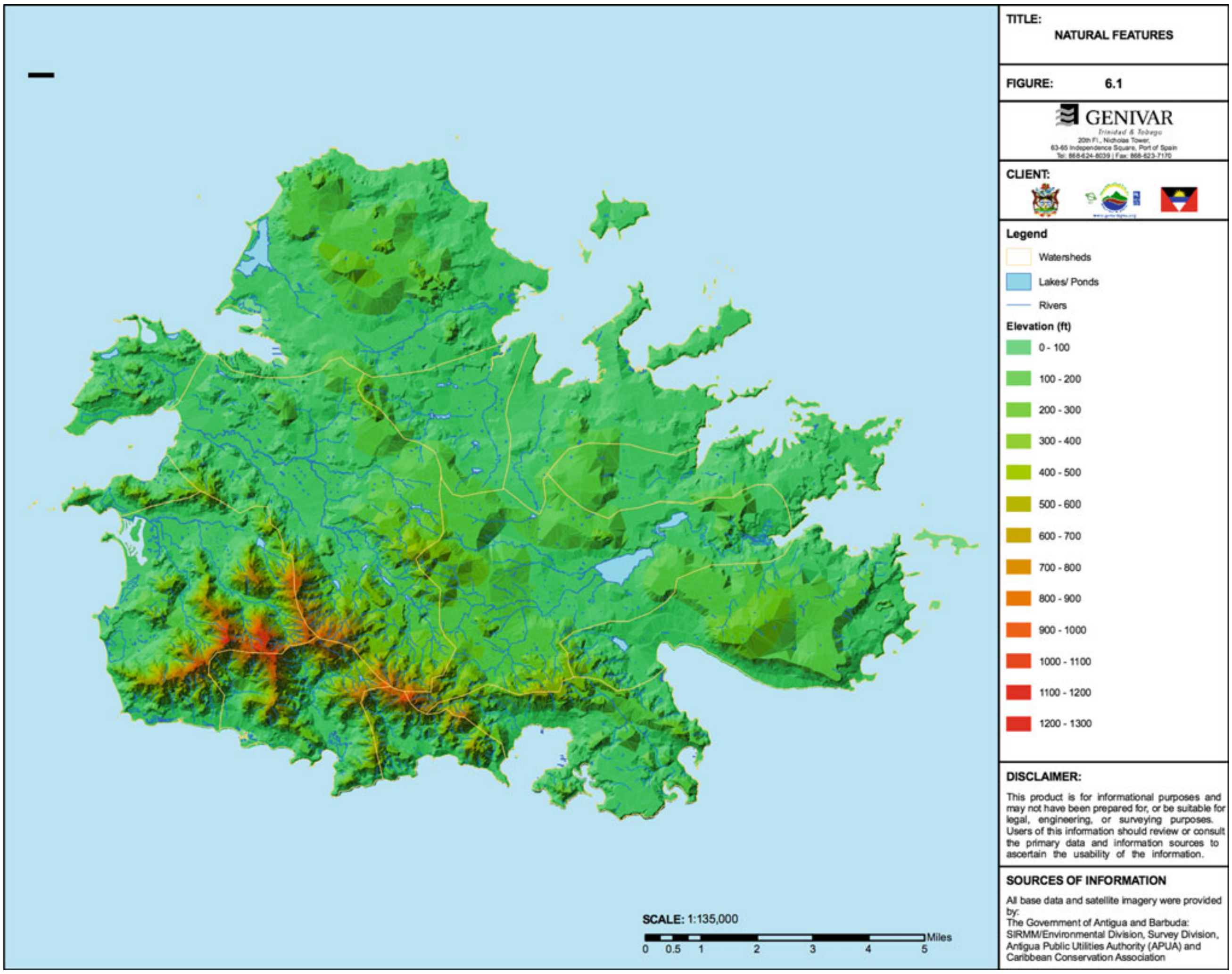

Fig. 8.3 Topographic map of Antigua, demonstrating a general dipping trend toward the northeast at an average of about 10, with the oldest outcrops in the southwest. The two main NW–SE-running valleys (between the island's high points) represent extensive strike-slip faulting. Figure courtesy of GENIVAR, Trinidad & Tobago (http://www.environmentdivision.info/wp-content/uploads/2012/01/NPDP-SIRMZP-2012.pdf)

demonstrating declining episodic volcanism and intermittent but increasing marine transgression throughout the Oligocene (Weiss 1994; Donovan et al. 2014) (Fig. 8.3).

The mid-Oligocene basal volcanics of southwestern Antigua are a suite of mostly calcalkaline andesites, although ranging from quartz basalts to dacites (Christman 1972; Weiss 1994; Tomblin 2005). Many are extensively metamorphosed, transported, decayed, and eroded, although volcanic cones and debris flows are still evident (Tomblin 2005). The rocks are dominantly blocky agglomerates, incorporating pyroclastic tuffs, lava flows, and intrusives. There are also some marine deposits, including carbonate lenses, and the total accumulation may exceed 2000 m in thickness (Martin-Kaye 1959).

The Central Plain Group is composed of perhaps a 1000 m thickness of agglomerates, mudstones, volcanic tuffs, and conglomerates, of both marine and terrestrial origin, with considerable local variability and local deformation. Terrestrial agglomerates and tuffs dominate, but there are also chert beds and limestone lenses, together with basaltic intrusions (Martin-Kaye 1959; Tomblin 2005).

The limestones and marls of northeastern Antigua belong to the Oligocene-aged Antigua Formation (Martin-Kaye 1959; Weiss 1994; Donovan et al. 2014). Older facies represent shallow-water coralline biostromes and patch reefs, but younger limestones are fine-grained, deeper-water deposits (Weiss 1994). The Antigua Formation attains a thickness of at least 550 m and dips generally at <15° toward the northeast (Martin-Kaye 1959). The limestones are highly variable, ranging from (bio)micrites through (bio) sparites, and many are highly fossiliferous. They also vary considerably in both purity and mechanical strength, reflecting rhythmic depositional sequences and variations in diagenesis (Weiss 1994; Day 2007).

8.2.2 Landforms

On and within the limestones, carbonate dissolution and associated processes have developed a karst landscape in Antigua dominated by dolines/sinkholes, dry valleys, residual hills, and springs (Day 1986, 2007). Surface water is rare here, except during particularly intense rains, when sinkholes may fill with localized ephemeral runoff, and normally dry valleys may channel dangerous floodwaters (Fig. 8.4a). Except during these events, drainage is predominantly subterranean, via rapid infiltration into, and percolation through, the thin soils, then transmission at various rates via pores, fissures, and conduits in the limestones to shallow, lenticular groundwater aquifers (Martin-Kaye 1956, 1959).

The most conspicuous landforms in the limestone area of Antigua are the discontinuous southwest-facing escarpment, which marks the boundary with the Central Plain, and the four northeast-trending dry and seasonally active allogenic valley systems that breach the escarpment and dissect the limestone upland into distinct blocks (Day 2002, 2007). Within the limestone blocks occur shorter autogenic dry valleys, generally shallow and without distinct stream channels, and mostly in agricultural use. These valley systems are significant geomorphologically in that they represent earlier phases in the karst development when secondary permeability was not sufficiently developed to permit total subterranean drainage, and runoff was via "normal" fluvial valleys (Smith 1975). As secondary permeability has increased through carbonate dissolution, drainage has increasingly been diverted underground, and the valleys have been essentially abandoned, only to be activated during intense rainfall, when the capacities of the karst plumbing system and its overlying soils are exceeded (Smith 1975; Day 2002). As such, in a sense, they are ephemeral or "occasional" drainage systems, and their persistence indicates that karstification has not yet progressed to the extent that surface drainage has been completely abandoned and the valleys obliterated by doline/sinkhole development, as appears to be the case in older karst landscapes elsewhere in the Caribbean (Day 2002).

Dolines/Sinkholes are often regarded as diagnostic of karst landscape (Ford and Williams 2007), and at least 45 occur in Antigua (Day 2007). In Antigua, dolines are most numerous in the central and southeast parts of the karst, although densities are generally low (Fig. 8.4b). Antiguan dolines, for the most part, are broad and shallow, with a tendency toward clustering. It has been suggested that smaller, individual dolines are near-circular, and probably dissolutional, but larger ones are asymmetric and probably represent constructional variability in the carbonate depositional environment (Weiss 1994; Day 2007).

The relationship between the autogenic dry valleys and the dolines/sinkholes is not entirely clear, although it is probable that formation of the former precedes that of the latter (Smith 1975; Day 2002). They may be competitive, in the sense that they have developed preferentially under different hydrological conditions, or they may reflect spatial variations in surface slope and/or carbonate lithology.

Many of the cliffed limestone slopes on Antigua have "ledge and notch" profiles, which reflect erosional exploitation of rhythmic carbonate depositional sequences (Weiss 1994). Depositional variations may also be manifest in the littoral karren (Lundberg 2004) and in the "…scattered, rather abrupt hills…" (Martin-Kaye 1959, p. 1) that also occur within the limestones (Multer et al. 1986; Weiss 1994; Day 2007).

There are few known caves in Antigua, since their development is restricted by the impurity of the limestones and the limited allogenic recharge (Martin-Kaye 1959; Gurnee 1961; Day 2002). Five types of carbonate island karst caves have been recognized in Barbados (Kambesis and Machel 2013), although these have not been identified

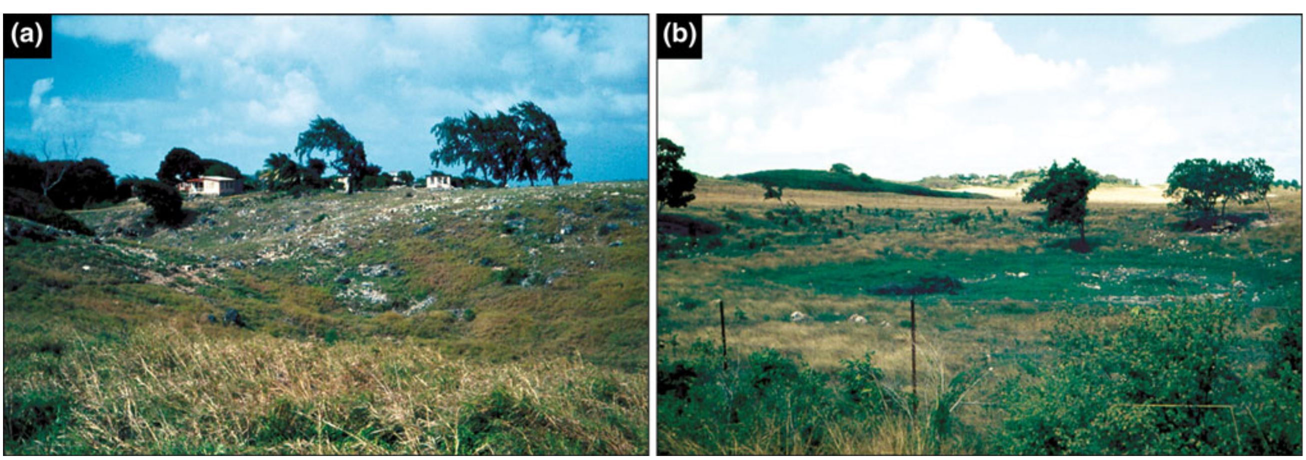

Fig. 8.4 Example Karst features on Antigua. **a** Typical dry valley in Antigua, typified by drought-resistant grasses and trees. Photograph by M. Day, 1975. **b** Typical small, circular doline/sinkhole manifested by the darker green area in the image's center. Photograph by M. Day, 1975

categorically in Antigua (Day 2009): (1) epigene caves formed by freshwater dissolution in the upland interior; (2) flank margin caves formed by mixing-zone dissolution along modern and older coastlines; (3) littoral caves formed by contemporary marine corrosion; (4) mechanical caves formed by bedrock mass movement; and (5) hybrid (polygenetic) caves, which constitute the majority, often involving modification of flank margin caves. There are natural bridges, which may be cave remnants, at several locations, including Soldier Point and Devils Bridge (Donovan et al. 2013).

Antigua exemplifies the composite type of the Carbonate Island Karst Model (Mylroie and Vacher 1999). The geologically young carbonate rocks have not been buried beyond the range of meteoric diagenesis, and they interact both with fresh and saline groundwater that is affected by glacio-eustatic and tectonic changes in sea level, forming immature (essentially Neogene) eogenetic karst.

The most prominent landforms in the volcanic terrain of southwestern Antigua are pronounced residual hills, often conical in overall morphology, dissected by steep-sided alluviated valleys displaying a radial drainage pattern moderated by the northeasterly dip (Martin-Kaye 1959). Steeper slopes are marked by various types of slope failure scars, particularly those resulting from debris flows.

The Central Plain is more varied than the name suggests, with rolling topography and relative relief in excess of 100 m culminating in the elongated central ridge of Belmont/Drews Hill and the southwestern escarpment overlooking the Bendals Valley (Martin-Kaye 1959). The overall morphology is that of a faulted monoclinal valley, transitioning southwestward to a monoclonal ridge (Martin-Kaye 1959).

Coastal landforms illustrate the multifaceted interaction between terrestrial and marine geomorphic processes, with restricted tidal platforms, cliffs with wave cut notches, littoral caves, stacks, arches, and extensive sand bars, spits, dunes, and beaches. The carbonate coastline in particular is deeply embayed and cliffed. Antigua's sand beaches are renowned (de Albuquerque and McElroy 1995), and there are marked energetic and morphological contrasts between beaches with a Caribbean aspect versus those subject to long-fetch Atlantic wave action.

Fringing, patch, and bank barrier reefs off the west, north, and east coasts represent contemporary analogues of the older features now exposed on the island itself, although the species composition differs (Multer et al. 1986).

8.2.3 Landscape

Human impact on the landscapes of Antigua and Barbuda has been long term and severe, as throughout the Caribbean (Watts 1987; Day 1993, 2010a, b). Amerindians perhaps arrived by 3500 BCE, and Antigua, in particular, has a rich legacy of pre-Columbian settlements, having been an important regional source of chert/flint for tool-making (Davis 1993). Native populations had profound influences on the natural vegetation (Harris 1965; Watts 1987). The island was colonized by the British in 1632 and was strongly fortified subsequently, resulting in a rich military heritage (CCA 1991; Museum of Antigua and Barbuda 2015).

The physical landscape of Antigua was devastated during the early colonial period by almost complete clearance of the natural vegetation and the institution of cotton, then sugar cane monoculture (Barker 1981; Watts 1987, 1988; Cooper and Bowen 2001). A few cave entrances, sinkholes, steeper-sided gullies and hillsides, and offshore islands were spared from clearance, and these represent important ecological remnants, although invasive species are highly competitive and increasingly challenging (FAO 2003; Gore-Francis 2013). Destruction of the natural vegetation undoubtedly changed the hydrologic regime and may have contributed significantly to historical aridification (Fig. 8.5; UNCCD 2005).

Antigua maintained its agricultural basis until the end of the twentieth century, shifting to livestock production and intensive production of produce for hotels and restaurants. Tourism is now ascendant, and much agricultural land has been converted to other uses (Barker 1981; CCA 1991; UNCCD 2005; Gore-Francis 2013).

8.2.4 Heritage and Tourism

Tourism is the leading economic activity in the country (CCA 1991; CIA 2015), and much of it focuses on the coastal zone, particularly beaches and reefs (Gore-Francis 2013). Annual tourist arrivals in 2014 totaled about 800,000 (Government of Antigua and Barbuda 2015b), and tourism accounts for 70% of GDP, 85% of foreign exchange earnings, and 40% of employment (Government of Antigua and Barbuda 2004; Gore-Francis 2013; CIA 2015). Mass tourism places major demands on the water supply system (CCA 1991) and on coastal zone resources (de Albuquerque and McElroy 1995).

Efforts have been made to encourage heritage tourism, agro-tourism, and ecotourism (Cooper and Bowen 2000; UN 2012), but these remain subsidiary to traditional tourism. Nelson's Dockyard, Shirley Heights, and other sites capitalize on colonial naval and other military heritage, with the former also being an important regional sailing center.

Antigua and Barbuda have only 11 formal protected areas, in which some 15% of the land area is at least theoretically conserved, primarily under the National Parks Act of 1984. Other areas, such as Santa Maria Hill, Corbison's

Fig. 8.5 Goat grazing near a denuded limestone slope in Antigua. This type of aridification has not been halted, as livestock and agricultural production have become somewhat more prevalent in recent decades. Photo courtesy of the Environment Division, Ministry of Public Works and Environment, Government of A&B

Point, and the Potworks and Collins reservoirs, are accorded variable levels of informal protection, and an integrated national protected areas system has been proposed, although not implemented, under the auspices of the National Biodiversity Strategy and Action Plan (GA&B 2001; Gore-Francis 2013). Antigua and Barbuda lag behind other Caribbean countries in protection of their karst landscape (Kueny and Day 1998; Day 2011), although important conservation efforts are being made on Great Bird Island and at other sites within the karst. The southwestern volcanic terrane also has considerable ecotourism potential, although this has not yet been fully realized.

8.2.5 Hazards and Environmental Issues

Drought and tropical storms, including hurricanes (with associated floods), are the major natural hazards affecting Antigua and Barbuda (GFDRR 2010), and projected anthropogenic climate change increases these threats, as elsewhere throughout the Caribbean karst (Farrell et al. 2007; Cambers 2009; Day and Chenoweth 2009a, b). Increased hurricane and drought frequencies have been experienced in recent years, with consequences including increased flooding, erosion, sedimentation, and decline in agricultural productivity (UNCCD 2005). Institutional, legislative and societal shortcomings, and questionable economic and development priorities exacerbate these problems (CCA 1991; Lorah 1996).

8.2.5.1 Drought

Drought (meteorological, agricultural, and hydrological) is a perennial, although increasing problem, particularly within the karstlands, where serious or severe drought historically occurs every 5–10 years (Martin-Kaye 1956; Lewis 1984, CCA 1991; Jackson 2001; OAS 2001; FAO 2004; A&BMS 2015). Severe drought, produced by little rainfall and intense evapo-transpiration, has occurred 15 times since 1928, most recently in 2002/2003, and serious drought has occurred 16 times, notably in 1983–1984, and currently since July 2013 (A&BMS 2015).

8.2.5.2 Hurricanes and Flooding

Tropical cyclones, including storms and hurricanes threaten Antigua and Barbuda regularly, with 50 hurricanes and 59 tropical storms recorded since 1851 (A&BMS 2015).

Notable damage occurred during category 4 hurricanes: Hugo in 1989, Luis in 1995, and Omar in 2008 (A&BMS 2015). Localized flooding is a considerable risk in Antigua because of the combination of cyclonic rainfall intensity, shallow soils with limited permeability, dense drainage networks, over-grazing, and urbanization (Cooper 2001). Flooding in the karst is a particular danger, since sinkholes and dry valleys contain water only occasionally, and the potential risk of flooding is often underestimated.

8.2.5.3 Soil Erosion

Accelerated soil erosion and land degradation is a severe local problem, particularly in areas with large numbers of goats, and where trees and shrubs are cleared or burned on slopes to encourage pasture grasses (UNCCD 2005; UN 2012). The problem is further exacerbated because 60% of the land in Antigua is government-owned, giving farmers little incentive to invest in land improvement (Lemel et al. 1988; FAO 2003).

In the volcanic rock areas, hazards include accelerated soil erosion, gullying, landslides, and other mass movements, many of which are human-induced through over-grazing and other disturbance (UNCCD 2005). Impacts on human residents have so far been minimal, but slope failures represent a potentially significant hazard, although they are considered generally to be “not a pressing problem” (GFDRR 2010, p. 87).

8.2.5.4 Earthquakes

There is a moderate earthquake risk in Antigua and Barbuda, with particularly notable events in 1690, 1843, and 1974 (McCann et al. 1982; CCA 1991). Regional tectonism and volcanism elsewhere in the Caribbean also pose potential risks of tsunami impact and volcanic ashfall (CCA 1991: Donovan and Jackson 1994; GFDRR 2010).

8.2.5.5 Water Supply

Water supply difficulties are largely a function of the contemporary and historical rainfall regime and the islands’ various landscapes. Surface drainage is usually of short duration, and water runs off quickly, particularly from impervious surfaces in urban areas, causing flooding and non-point pollution, and being effectively lost to human use through poor conservation practices (Barragne-Bigot and Yearwood 1991; Williams 1994; Mylroie and Carew 1997). Seawater intrusion into the shallow coastal aquifer is also an ongoing threat (Sandberg and Barnes 2004).

8.2.5.6 Degradation of Coastal Ecosystems

Degradation of coastal ecosystems is particularly acute around the St. John’s urban core and in tourism areas along the coast, where wetlands are being degraded and infilled, coastal water quality is decreasing, coral reefs are in decline, and unapproved sand mining remains problematic (CCA 1991; de Albuquerque and McElroy 1995; Carr and Heyman 2009). Tourism and other infrastructure is infringing upon beaches, and beach erosion has become significant and endemic (Baldwin 2000). Such environmental impacts adversely affect residents and tourism alike (Lorah 1996; Carr and Heyman 2009).

8.3 Barbuda

8.3.1 Setting

Although separated by a mere 42 km of water, Antigua and Barbuda are quite unique in terms of their history and geography. This section captures some of the nuances that make the island of Barbuda altogether similar, yet also distinctly different, from its sister-island counterpart. The two islands are bathymetrically connected by the Barbuda Bank along the 200 m isobath. Earthquakes that occur in this region are associated with plate boundary subduction zone tectonics. The Leeward Islands of the Lesser Antilles (Limestone Caribbees) were formed during the Tertiary. Barbuda is composed of Pleistocene coral limestone, lying about 50 km east of the extinct volcanic chain arc axis but, rather than at its center, Barbuda lies uniquely on the northeast margin of its bank. The rocks are nearly flat-lying and limestone sequences are thin. Between each marine stage, depositional hiatuses occurred with karstic erosion creating an environment of offlapping carbonate units (Brasier and Donahue 1985).

The land area of Barbuda is approximately 150 km^2, with an east–west extent of about 13 km, and northwest to southeast axis of about 22 km. Codrington Lagoon is approximately 20 km^2 with an east–west extent of about 2.5 km and north–south range of 9 km. Barbuda has little relief except for the Highlands in the east rising to a height of only 38 m in the north, and gradually decreasing in elevation toward the south (Fig. 8.6). Still, four main geologic formations are found: Highlands, Beazer, Codrington, and Palmetto Point. These span the geologic time scale from Miocene to Holocene.

The Highlands Formation was deposited between the depths of 20 and 100 m during the mid-Miocene to early Pliocene. This unit forms the table-like inlier of the Highlands landscape, represented by lime wackestone—a cream-colored, fine-grained, and porcellaneous rock (Brasier and Donahue 1985). The Beazer Formation, comprised of a fine-grained, porcellaneous, hard, compact, creamy-white limestone, represents an older Pleistocene deposit, while the Codrington Formation—composed of well-preserved fossiliferous mollusk and coral sediments that have recrystallized to a lesser degree, was most likely deposited during a

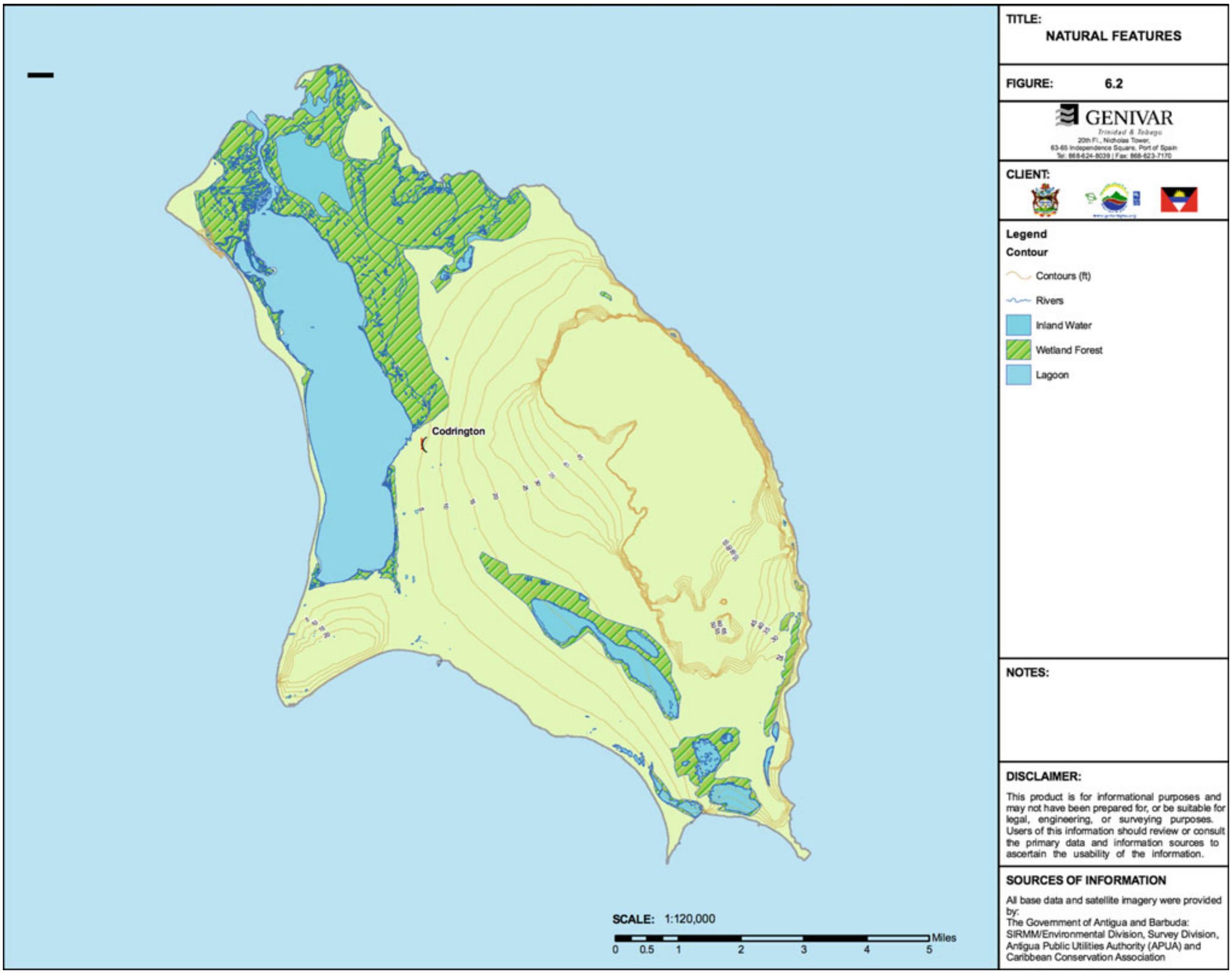

Fig. 8.6 Topographic map of Barbuda, displaying the lack of topographic variation. The mean and median elevations are both 26 m (with a mode of 7 m), with approximately 58% of the island being less than 10 m above sea level (USGS 2004). Figure courtesy of GENIVAR, Trinidad & Tobago (http://www.environmentdivision.info/wp-content/uploads/2012/01/NPDP-SIRMZP-2012.pdf)

high stand of the Last Interglacial in the late Pleistocene (Brasier and Donahue 1985; Brasier and Mather 1975).The Palmetto Point Formation representative of post-Pleistocene accumulations of sand, occurs at several locations on the island: Palmetto Point, Cedar Tree Point, Cocoa Point, dunes of the windward coast, and the sand bar forming the western enclosure of Codrington Lagoon (Brasier and Mather 1975).

8.3.2 Landforms

Sinkholes (dolines) are found in the Highlands and in an area called the Caves (local name for a sinkhole) south of Hog Point and east of Two Foot Bay (Fig. 8.7). The entrance surface trail to Darby Cave is a talus slope that leads to the bottom of the sinkhole similar to those found in the Jamaican Cockpit Country (Day and Chenoweth 2004). Even though Barbuda's karst landscape has no known surface streams, large trees and ferns cluster on the damp soil, reminiscent of a tropical rain forest (Harris 1965). There are sinkholes several times larger in surface area than the deepest (Darby Cave, see Fig. 8.8) located to the west-southwest and along the eastern Highlands near Pigeon Cliff (D.O.S. 1970, Sheet 1D). Care must be taken when walking around the eastern edge of the Highlands because many of the sinkholes are the collapsed roof of escarpment caves.

The Caves area is characterized by flat-lying outcropped limestone beach ridge facies of the Codrington Formation (Braiser and Mather 1975), with thin patches of soil and sinkhole clusters. Sinkholes are usually round or oval shaped in plan form and steep sided ranging in depth from 0.8 to 2.5 m. Length measurements range from 0.6 to 8.4 m and width dimensions from 0.5 to 5.6 m. Sinkholes with water present have a typical salinity range of 2.2–2.6 parts per

Fig. 8.7 Two Foot Bay is the site of caves and a view of the Atlantic side of Barbuda. (Photograph by Amy Potter, 2007)

thousand. There are several caves located in the interior of the Highlands: Garling Cave, Bryant Cave, Keyser Cave, and Dark Cave. Of these, only Dark Cave displays a sinkhole entrance that connects a series of large rooms, one of which contains freshwater pools with blind isopods (Nicholson 2007; Lawrence 2015).

There are a series of saline salt flashes in the southeastern portion of the island. Spring tides and storms intermittently flood these low-lying areas with sea water which evaporates to form thick layers of white and pink colored salt.

Barbuda is fringed by reefs primarily along its eastern and northern coasts. From Spanish Point in the southeast to Hog Point in the northeast, the windward coast is protected by a continuous reef structure absorbing the energy from the Atlantic Ocean waves. North of Hog Point lie Cobb and Goat Reefs which are important for local fishing due to ease of access from Codrington Lagoon through the Creek and the large area of calm, shallow water behind the reefs in this area. The leeward coast consists of patch reefs creating isolated navigational hazards. Along the south coast from Martello Tower to Spanish Well Point are groups of coral reef near the shore. South of Cocoa Point and Gravenor Bay are patch reefs and a large offshore assemblage called Palaster Reef.

The use of these landscape and landform formations including the island's coastal resources has figured notably in Barbuda's human occupation. The first evidence of a human settlement occurs around 4000 BC by the Siboney. A second more prominent occupation by the Saladoid peoples from what is today Venezuela dates to around 150 BC (Watters et al. 1992; Perdikaris et al. 2013). These early Barbudans left behind prominent shell middens along the island's southern coast. In their research exploring Barbuda's eastern coast caves, Perdikaris et al. (2013) documented the longitudinal importance of these karst features from the Archaic period to present as a place of shelter, ritual, and feasting. Their research uncovered evidence of Archaic lithics, as well as artifacts and faunal material that could have been produced by Obeah (local Caribbean folk religion) rituals.

Fig. 8.8 Though larger caves can be found on Barbuda, Darby Cave represents the deepest sinkhole on the island, measuring approximately 25 m deep and 120 m in diameter. Photograph by Amy Potter, 2010

8.3.3 Landscapes

The Marginal Plain includes all elevations less than 25 m which is approximately 80% of the island. Besides the sandy beaches, there are two soil series in the Marginal Plain: the Blackmere, a gray-brown loam, and the Codrington, a black clay (Charter 1937; Harris 1965). These two soil groups are poorly drained and alkaline, supporting mainly thorn-scrub evergreen woodland.

The Highlands are a limestone plateau dominating the eastern portion of Barbuda (Fig. 8.9). The north and eastern slopes are demarcated by an escarpment. The base of the escarpment initiates around the 8-m contour and steeply extends upward about 15 m. The escarpment is riddled with numerous caves of various dimensions facing the Atlantic Ocean. Intricate tropical rillenkarren and pankarren karst formations cover the outcropped limestone along the escarpment. Another dominant feature of the escarpment base are large boulders (>5 m) detached from the cliff face. The uplands are covered with dense woods, red soil, and rough rock outcrops. The Barbuda (terra rossa) soil series is reddish-brown, slightly alkaline, and well drained (Charter 1937; Harris 1965).

On the western side of the island lies Codrington Lagoon. It is shallow, hypersaline, and fringed by red mangrove trees, with a depth range of 1–4 m, and a salinity typically around 40 parts per thousand. The Lagoon's bottom is covered with sea grasses, algae, and a few scattered coral species. There is a narrow entrance to the lagoon from the ocean in the north locally known as "the Creek."

8.3.4 Heritage and Tourism

Barbudan heritage and identity are inextricably tied to a form of communal-land tenure that was formalized into law in 2008 (Antigua and Barbuda 2008) but developed over several hundred years of land use. For nearly two centuries

Fig. 8.9 The view looking out from Barbuda's Highlands region at the site of "Willy Bob," the ruins of the Codrington residence. The Highlands hosts the highest elevations on the island. Photograph by Amy Potter, 2007

(1680–1870), the British crown leased the island to the Codrington family of England who used the enslaved African population to grow food crops and raise livestock to provision sugar plantations (Betty's Hope) on neighboring Antigua. Unlike its Caribbean counterparts, the island was not suited to large-area agriculture due to its semiarid climate and karst topography (Harris 1965; Berleant-Schiller 1977). The Codrington family's and others' repeated attempts to establish plantations for cotton and other crops failed, in part due to the shallow soils, limited average annual rainfall, a long winter-dry season, frequent droughts, and a scarcity of surface water (Berleant-Schiller 1977). The enslaved and eventually free African-descended Barbudans overcame these perceived limitations developing an economy of subsistence agriculture, fishing, charcoal, and open-range livestock (Berleant-Schiller 1977; Lowenthal and Clarke 2007) centered on the communal-land tenure.

Over time, Barbuda's traditional economy of cattle herding and agriculture work began to wane as wage labor on the island expanded in the areas of sand mining, lobster export, and tourism (Potter and Sluyter 2010, 2012; Potter 2011, 2015a). In the 1960s, the first luxury hotel, Coco Point Lodge, provided construction jobs and then steady employment in the form of service jobs during the winter-tourist season.[1] Other luxury resorts on the south coast followed suit in the 1980s and 1990s, particularly the K-Club and The Beach House, providing additional seasonal employment.[2] Lighthouse Bay Resort, an endeavor by a Barbudan descendant, opened in 2008 across the lagoon, and smaller tourist accommodations have also sprung up on

[1]The resort employs approximately 80 Barbudans seasonally. This estimate is based on a conversation with an employee in December of 2013.

[2]Barbuda's tourism industry is wrought with failed initiatives; the K-Club has been vacant for years while The Beach House sits in disrepair. Perdikaris and Hejtmanek (2015) have described this as a boom/bust mentality.

Fig. 8.10 A major attraction in Barbuda is the Palmetto Point pink sand beach. The sand is a mix of coquina shell and coral fragments and is bottled and sold as a souvenir in Codrington Village. Photograph by Amy Potter, July 2010

North Beach. As economies rebound after the 2008 financial crisis, there has been a flurry of activity as the Barbuda Council entertains greater development of Barbuda's commons by the tourism sector, with the most recent approval of a $250 million investment by Robert DeNiro (Paradise Found) of the former K-Club Resort. These development initiatives are increasingly reliant on outside investment capital, which provide the funds for tourism infrastructure. The communal-land tenure has stunted Barbuda's tourism development relative to its Caribbean neighbors because of the limitations placed on foreign land ownership. Resorts that invest in Barbuda must lease land rather than buy outright.

In comparison with Antigua, Barbuda only receives a small percentage of the larger visitor total that travels to the twin-island country. Barbuda welcomed roughly 10,804 visitors in 2014, if you combine data including aircraft, ferry, and other watercraft. If you factor these numbers alongside the 249,316 total visitors counted in Tourist Stop Over statistics from the Caribbean Tourism Organization for the entire country (Antigua and Barbuda), roughly 4% of visitors in 2014 made their way to Barbuda.

Barbuda's stay-over tourism is small, attracting high-end guests.[3] In addition, day trips entice visitors via catamaran, ferry, and airplane from Antigua to experience the island's heritage sites (Amerindian petroglyphs in the caves at Two Foot Bay), the frigate bird sanctuary, and beaches. Two of the centerpieces of Barbudan tourism are the frigate bird colony as well as the island's pink sand beaches (Fig. 8.10). However, tourism initiatives often collide with the protection of these resources. A more recent tourism development at Cedar Tree Point cleared mangroves in the spring of 2014 in an area within the Codrington Lagoon National Park in close proximity to the Frigate Bird Colony (Butler 2013). Residents

[3]Room rates during off-peak season for Coco Point (rates are per room per night, based on double occupancy, and quoted in U.S. currency) range from $1050–1680 depending on the type of room. (See: http://cocopoint.com/guest-information/rates/, accessed July 2015).

Fig. 8.11 Sand mining has historically served as an important source of revenue for the Barbuda Council but has come with serious environmental and economic consequences as sand supplies dwindle through overuse. Photograph by Amy Potter, 2007

raised concern that the $1.9 million project did not properly consult the people of Barbuda and could ultimately disrupt the frigate bird habitat over the long term (Butler 2013).[4]

Tourism in Barbuda is not without its challenges. Until now, employment at resorts has largely been seasonal (December to April). The Barbuda Council was able to provide jobs to offset this seasonal employment in the past during the slow summer months because of revenues from sand mining; however, as this economic stream disappears, the Council has limited funds to keep this employment practice in place (Fig. 8.11).

Transportation infrastructure to the island is often fraught with problems. Several of the high-end resorts have their own landing strip outside of the main airport in Codrington, but sea-going vessels can experience mishaps, as in 2013, when an inoperable ferry impacted the number of tourists (2258 via ferry visitors in 2013 versus 8226 visitors via ferry in 2014). In addition, certain months of the year are particularly difficult for watercraft traveling the Caribbean Sea, where rough waters can impact the daily operations of the ferry to and from the island (particularly in the month of December). The daily flights from V.C. Bird International Airport (Antigua) to Codrington have not been without their headaches either (Observer Media 2014a; Webmaster in Local 2015). Flight cancellations and plane maintenance all impact island accessibility for not only tourists, but also Barbudans.

Barbuda is facing the usual pressures that come with tourism as a Small Island Developing State. The wages available to islanders are generally low, and there is fierce competition for jobs from non-Barbudans as new resorts necessitate skilled labor. Unique to Barbuda, however, are the negative impacts caused by tourism development in relation to the island's common property (loss of traditional resources and limited land access).

8.3.5 Hazards

Historically, Barbudans have shown tremendous resilience in coping with various hazards, be it drought, hurricanes (flooding), or earthquakes (Boger et al. 2014). For example, Hurricane Donna of 1960 and Luis of 1995 caused significant damage to homes within the village. Luis was one of the

[4]Despite expressed environmental concerns, the project proceeded.

major impetuses for the expansion of homes outside the traditional core of the village of Codrington. Hurricane Luis even breached a narrow strip of land across the lagoon that has since filled in.

Outside intense rainfall events wrought by tropical storms and hurricanes, Berleant–Schiller (1977, p. 87) documented cycles of drought and how these periods historically impacted past land use:

> Commercial cultivations disappeared in a dry spell, whereas subsistence cultivations contracted and stock-keeping expanded. Barbudans gave up attempting to control animals during drought because the crop production with which they might interfere is less important. During wet periods, when crop production is more successful, more human control is applied to animals.

A growing concern on the island not only centers on the cost of imported food, but also for those who continue to produce agriculture in line with the islanders' historic land uses suffering from increasing water salinity in their ground water sources (Boger et al. 2016). Boger et al. (2014) highlight how water quality is intimately tied to food production and food security. If Barbudans are going to produce food they have to contend with predicted decreases in annual rainfall and rising sea levels that will increase the salinity of the ground water for parts of the island.

Anthropogenic activities have also accelerated natural hazard risk. While Cambers (2009) notes these activities are certainly problematic in most Caribbean islands, Barbudans are particularly feeling the effects of sand mining, erosion, and overfishing.

Beginning in the 1970s, Red Jacket Mines, a company based out of Louisiana, began to mine in an area located near the southwest coast (Palmetto Point). Over time, the sand export revenue has served as an important source of employment for Barbudans and revenue (upwards of $5 million ECD) for the federal government and local governing body the Barbuda Council[5] (Potter and Sluyter 2012; Observer Media 2014b). While valuable to the Barbudan economy, mining has destroyed the ecological integrity of the natural sand dune system leaving the island vulnerable to hurricanes (de Albuquerque and McElroy 1995), typhoons, groundwater contamination (Campbell 2006), and climate change.

Beach erosion is also a concern. A 2010 *Observer* piece calls attention to threatened tourism developments following Hurricane Earl and Igor that severely eroded beaches in both Antigua and Barbuda (Observer News Observer News 2010a, b). Local environmentalists even question how development projects cause harm to the natural dune system.

Barbudans have traditionally relied on fishing in both the lagoon and surrounding ocean waters for subsistence and economy. Overfishing in the lagoon has put pressure on Barbudans to fish in waters further away from the island's shores, and there is currently a ban on fishing in the lagoon and surrounding waters.

[5]The Barbuda Council is the locally elected governing body established in 1976.

8.4 Conclusion

While the islands of Antigua and Barbuda comprise one country, we have sought to highlight their considerable differences in geology and historical development. Larger in land area and with greater elevations, Antigua is comprised of limestone, clay, and volcanic rock, while Barbuda is predominantly limestone, with caves on the Atlantic coast. Both islands exhibit little in the way of surface water and suffer from drought. Limited water supply is a constant concern, accelerated by erosion, and flooding during rainy times.

The long-term human impact is much more pronounced on the island of Antigua, with an agricultural legacy that incorporated enslaved African labor to grow sugarcane. Barbuda's karst topography posed certain difficulties to large-scale agriculture, with a colonial economy dominated by the use of enslaved labor to graze livestock. At present, Antigua is much more developed, particularly in terms of its tourism economy, which makes it especially susceptible to reverberations felt during global economic downturns. Barbuda's land tenure of common property has in some ways delayed this economic direction but limited revenues have shifted its leaders' attention toward an economy centered on tourism development of the commons. Barbuda's common property is a unique feature that has given islanders access to their lands when other Caribbean peoples are increasingly priced out of their island homes as they face competition and rising costs associated with tourism development. The question remains, however, whether Barbuda's unique land tenure will persist against the backdrop of this increasingly tourism-driven economy (Potter and Sluyter 2012; Potter 2015b).

Despite their differences, Antigua and Barbuda face many of the challenges common to Small Island Developing States (SIDS) especially in terms of climate change. These challenges include changing rainfall patterns, flooding, warming sea-surface temperatures, increased occurrence of natural disasters (such as hurricanes), and accelerated coastal erosion (Brown 2005). Environmental issues are then intensified by the combination of limited land area, high population density, and mass tourism, particularly for Antigua. These challenges aside, both islands showcase fantastic geomorphology, and a population that mostly understands effects of resource overuse. With enhanced programming and management driven by local leadership, Antigua and Barbuda could address these pressing issues associated with their apparent economic shortcomings.

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9 Montserrat

Elizabeth Nelson

Abstract

Montserrat, a smaller Caribbean island of the Lesser Antilles island arc, has a considerable contribution to the regional geomorphology: the active Soufrière Hills Volcano. The volcano consists of a cluster of andesite domes with flanks of sediment deposited by pyroclastic lava flows. The Soufrière Hills Volcano eruptions can be traced back thousands of years, but more recently the volcano became active again in 1995 with the latest recorded eruption in 2013. The volcanic activity involves both eruptive and dome collapse processes creating ashfalls, debris avalanches, and pyroclastic deposits. Coastal advancement occurs through mudflows, floods, and wind. The Soufrière Hills volcanic eruptions are among the largest volcanic events to occur in the Lesser Antilles and have created substantial exclusion zones on the island for safety. The seismic activity on and near the island and the Soufrière Hills Volcano are monitored closely by the Montserrat Volcano Observatory.

Keywords

Volcano • Andesite domes • Pyroclastic flow • Soufrière hills • Exclusion zone

9.1 Introduction

The sleeping Soufrière Hills volcano awakened in 1995 with a catastrophic explosion. The island at the time was still recovering from 1989 Hurricane Hugo and now faced the decades-long process of living life with an active volcano. Since the initial eruption, the former capital city of Plymouth has been completely destroyed and buried by volcanic material. Two-thirds of the island's 1995 population—12,000—left the island, though some continue to trickle back, and today around 4500 live there (Donovan et al. 2013; UNICEF 2013). These persevering islanders live on a small portion of the land area in the north, while the southern part of the island consists of a large, uninhabitable exclusion zone, though much of the area is still accessible during the daytime under governmental permission.

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Montserrat is an Overseas Territory of the United Kingdom of Great Britain and Northern Ireland (UK) in the Lesser Antilles (Fig. 9.1). Before the 1995 eruption, it had a thriving economy and was nearing independence from the UK. Now, Montserrat is dependent on aid from the UK and other foreign aid agencies (Skelton 2000). The capital city-now ghost town and exclusion zones created by volcanic devastation are in the place of a once-bustling Caribbean locale—now quiet, eerie, and despondent, mere remnants of a culture once achieved—taken over by a series of volcanic events, and finally left to survive and eke out an existence on the remaining inhabitable portion of the island. The proud island residents who have stayed behind include native Montserratians and migrant populations. Together, they make up a most unique culture in a landscape of at once lunar-like desolation and lush rainforest, spawning the island's moniker, the "Emerald Isle of the Caribbean" (Fig. 9.2).

There is a complex intertwining of physical and human geographies, of geomorphology and volcanology in Montserrat. Due to the relatively recent developments,

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Fig. 9.1 General physiographic map of Montserrat. While Plymouth is still officially the Island's capital, it is no longer habitable—much like most of the island's southern half. Other cities in the southern region, such as Kindsale, are also abandoned. For more information on the extent of the established volcanic extrusion zones, see Fig. 9.3 and the corresponding Table 9.1. Cartography by K.M. Groom

literature and current assessments of various aspects of the island are no longer relevant. This chapter thus relies heavily on the post-eruption research of a small group of scientists, most heavily centered at the Montserrat Volcano Observatory (MVO). Additionally, information is included from scientists conducting ground-breaking research of an active volcano and simultaneously work with local, colonial, and international audiences. Before the 1995 eruption, geologic interest in Montserrat was limited to a small amount of literature, most notably by British scientists, geologist MacGregor (1938), and physicist Powell (1938), who together developed a foundational understanding of the geology of Montserrat. Post-eruption, many groups collected and published information on the island, including the University of the West Indies (UWI) (see *Volcanic Hazard Atlas of the Lesser Antilles*, UWI 2005), the Geological Society of London (2002), and the MVO.

This chapter begins with a geologic overview of the island, followed by an outline of its major landforms. With the island's physical features established, it then delves into the island's cultural landscape, drawing from an anthropo-geomorphological approach in addition to traditional geographic landscape inquiries and how the general landscape has changed over time. This leads into an overview of the heritage and tourism aspects of the island before finally ending with a discussion regarding the hazards of the island, including past, present, and future outlooks for these hazards and their potential mitigation for inhabitants of Montserrat.

Fig. 9.2 A ground view of the Soufrière Hills Volcano on the Emerald Isle, with lush green land cover visible, and the volcanic peak is covered by clouds, as it is most days. Notice the extensive lava flows to both the *right* and *left* of peak. Photograph by J. Davenport

9.2 Setting

Montserrat (16°45′N, 62°10′W) is situated toward the northern end of the Lesser Antilles island arc (Le Friant et al. 2004). The humid tropical marine climate is moderated by the prevailing northeasterly trade winds. Because of the topography, annual and seasonal precipitation varies dramatically. The rainy season is typically between July and December (Weaver 1995, p. 597).

As a result of the subduction of the North American plate beneath the Caribbean plate, this island experiences the combined outcomes of tectonic plate activity of both strike-slip and subduction in addition to volcanic processes (Le Friant et al. 2004). The Lesser Antilles island arc includes the outer and inner arcs, both with characteristically different landforms and land-creation processes (Le Friant et al. 2004). The island lies at the western edge of the shallow platform between these arcs and has a shallow (less than 140 m) submarine shelf, with steep margins that fall off to the Grenada Basin in the west and to the Atlantic in the east (Fig. 9.3; see also Deplus et al. 2001). The sea floor around Montserrat has numerous fault scarps and coastal coves. On the east, south, and west coastal areas, hummocky topography has been identified as debris avalanche deposits due to major volcanic landslides (Deplus et al. 2001).

Montserrat is one of the smaller islands in the Antilles. The subaerial portion of Montserrat is 16.5 km long from north to south and 10 km wide from east to west (Le Friant et al. 2004; Hincks et al. 2005). Composed nearly exclusively of volcanic rock, there are four volcanic massifs that make up the 100 km^2 of total land area. The youngest massif, collectively called ‘the Soufrières’, consists of the Soufrière Hills and South Soufrière Hills (the active volcano), and these are sometimes referenced as one massif (Le Friant et al. 2004). However, for the purpose of clarity in this chapter, they are considered separate massifs. The other massifs, in order of youth, are the Centre Hills and Silver Hills. The erosional maturity of the massifs decreases progressively from north to south, indicating a southward migration of volcanism over time, and following the movement of the underlying tectonic plates (Harford et al. 2002). Migration in accordance with the tectonic plates occurs at a time averaged rate of ~6 km/Ma parallel to the trench and ~2 km/Ma perpendicular to and away from the

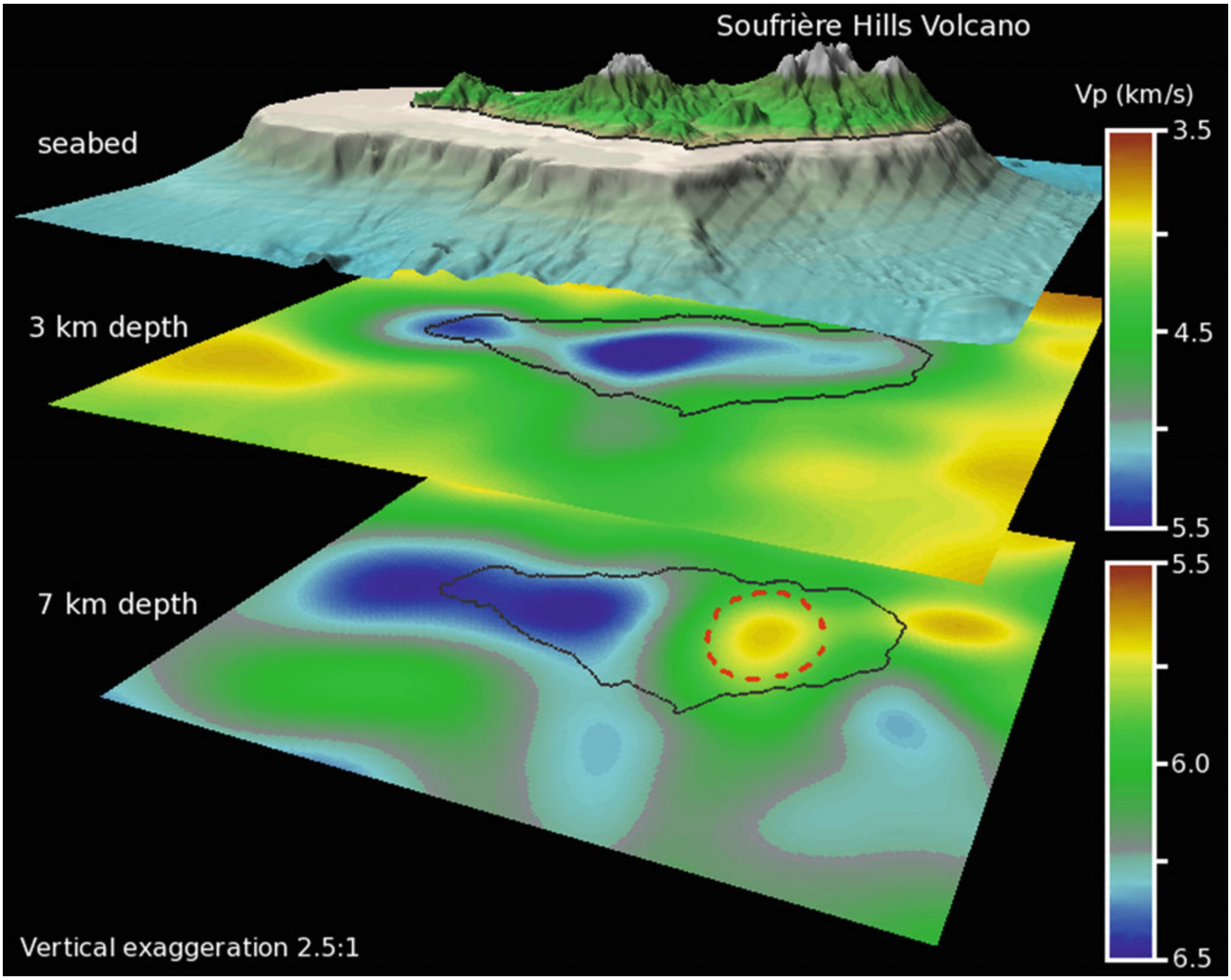

Fig. 9.3 Three-dimensional seismic velocity model of Montserrat at seabed, 3 and 7 km depths. (Animated model also available online from https://geoazur.oca.eu/spip.php?article1544). Model created by M. Paulatto in 2015, based on data from Paulatto et al. (2012)

trench, and the long axis of the island is aligned approximately north–south (Hincks et al. 2005).

Montserrat is mountainous with small areas of coastal lowlands and a densely vegetated interior of tropical rainforests. There are a limited number of beaches and no inland bodies of water. Rock exposures exist in road cuttings, coastal areas, quarries, and the steep inland cliffs (Hincks et al. 2005). After 20 years of volcanic activity, the fallout and subsequent landscape changes have created vast expanses on the flanks of the Soufrière complex, buried by pyroclastic flows, lahars, and ashfalls, particularly in the deep valleys. Local researchers call these “ghauts” (sometimes referred to as “guts” on non-French influenced islands) as clefts in the hills that commonly function as drainage paths for water and low-lying areas (Hincks et al. 2005). The infill of the major ghauts by pyroclastic deposits and deposition at the mouths of several ghauts has extended the coastline, adding new areas of land (Hincks et al. 2005).

Nearly all of this additional coastline lies in the exclusion zone, which covers two-thirds of the island and has access organized by level of danger, concluding with the absolute exclusion zone that is accessible only by helicopter and only with the express permission of the local police commissioner (Fig. 9.4). The hazard levels are jointly determined by the MVO and the Disaster Management Coordination Agency (DMCA) of Montserrat (Table 9.1).

Before the volcanic activity began, the Soufrières consisted of prehistoric lava domes, and the upper flanks were divided by ghauts that fed rivers on the outer flanks. The sustained volcanic activity, however, has significant impacts on the landscape of the Soufrière complex and, in many places, the preexisting vegetation has been completely

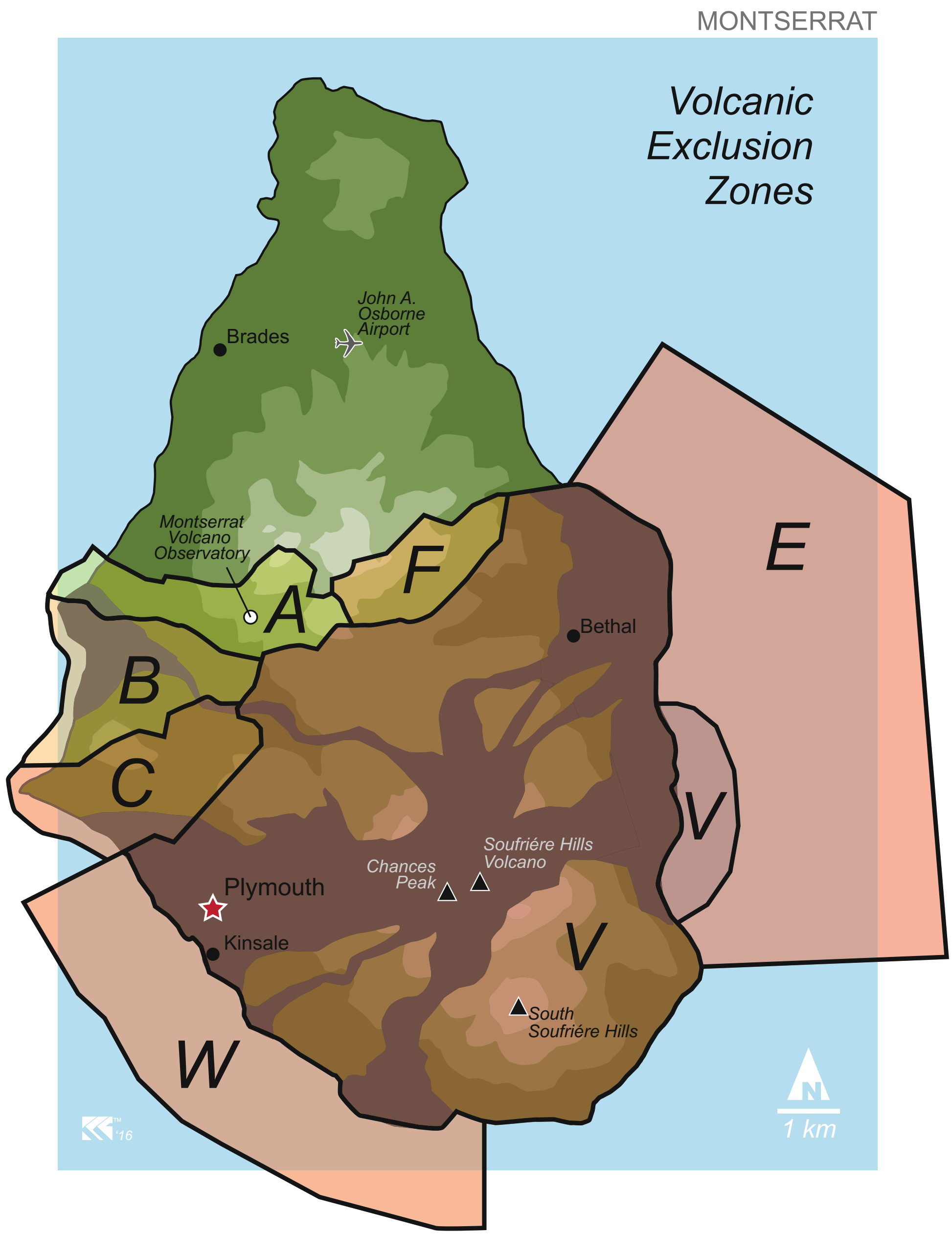

Fig. 9.4 Volcanic exclusion zones on Montserrat. Zones are divided into terrestrial and oceanic designations along with varying degrees of risk/hazard level. Some of the oceanic zones protrude several kilometers from the coast. Any sea vessel wishing to circumnavigate the island must travel around these zones. For further explanation of each zone, see Table 9.1. Cartography by K. M. Groom

destroyed by pyroclastic flows, ashfall, and acidic gas (Hincks et al. 2005).

9.3 Landforms

The island of Montserrat has undergone incredible landform changes during its volcanic activity. The volcano changed both terrestrial and marine ecosystems and, unlike many current marine habitats of the world where detrimental effects are mostly anthropogenic, it has been the pyroclastic flows of the Soufrière Hills Volcano that has most greatly affected Montserrat's marine environment (Myers 2013). The island has varying underwater topography containing, for the most part, untouched and unexplored reefs (Myers 2013). Above ground, the main subaerial landforms on Montserrat today are Silver Hills, Centre Hills, the Soufrière Hills Volcano, South Soufrière Hills, Roche's Bluff, Garibaldi Hill, and St. George's Hill. Prior to the initial eruption, the highest point on the island was Chances Peak (included in the Soufrière Hills volcanic complex) at 914 m above the sea level. Since April 22, 2003, however, the Chances Peak dome has measured 1098 m (Hincks et al. 2005).

Across the island, the Silver Hills volcanic massif was active between 2.6 and 1.2 million years ago (MacGregor 1938). It is composed of porphyritic hornblende andesitic

Table 9.1 Government-monitored exclusion zones. Time of access and personnel restrictions depend on the time of day and hazard levels defined by the Montserrat Volcano Observatory (MVO) and Disaster Management Coordination Agency (DMCA)

Hazard level		0	1	2	3	4	5
		More than one year with no measured activity	No surface activity for an extended period. Low measured activity	No surface activity that threatens the north or west. Low measured activity	Mild surface activity that threatens the west. Significant change in measured activity. High levels of activity	Lava extrusion that threatens the north or west. Large unstable dome to the north or west	Threat of large pyroclastic flows to the north or northwest. Threat of lateral blast or sector collapse
Inland zones	A	Unrestricted	Unrestricted	Unrestricted	Unrestricted	Unrestricted	Controlled access
	B	Unrestricted	Unrestricted	Unrestricted	Unrestricted	Controlled access	Controlled access
	C	Unrestricted	Unrestricted	Daytime Access	Controlled access	Controlled access	Essential workers
	F	Unrestricted	Unrestricted	Daytime Access	Daytime Access	Controlled access	Controlled access
	V	Access to some areas	Controlled access	Essential workers	Essential workers	Essential workers	Essential workers
Maritime zones	W	Unrestricted	Daytime transit	Daytime transit	Daytime transit	Essential workers	Essential workers
	E	Unrestricted	Daytime transit	Essential workers	Essential workers	Essential workers	Essential workers

lava, as observed in the eroded lava domes and sequence of volcaniclastic beds (Hincks et al. 2005). The highest point reaches 403 m above sea level. The submarine shelf is well developed around Silver Hills, and it is believed that this area is the eroded remains of a previously much larger volcanic massif (MacGregor 1938).

In the middle of the island, the Centre Hills area has extensive coastal cliffs and includes a mountainous interior with dense rainforest cover (Hincks et al. 2005). Like the Silver Hills, the mountains are made of porphyritic hornblende andesitic lava, the remnants of lava domes that collapsed to produce the pyroclastic deposits on the flanks. The material is predominantly pyroclastic flow deposit, but also includes pumice-and-ash flow, pumice fall, lahars, debris avalanche, and fluvial deposits (Harford et al. 2002). The highest point is 741 m above the sea level (Hincks et al. 2005).

The Soufrière Hills Volcano is a Peléen-type volcano and the only active volcanic massif on the island. Pre-1995 eruption, the massif contained five steep-sided andesitic lava domes, many of which are now covered by new material that has buried landforms during the volcanic activity. At the point of publishing, the volcano is still active, yet displays aprons of volcaniclastic deposits that flank the four remaining lava domes. The deposits are, according to Hincks et al. (2005:150), "…predominantly pyroclastic flow deposits related to dome collapse and lahar deposits, with subsidiary debris avalanche deposits, pumice flow deposits, fluvial deposits, stratified fallout tephras and paleosols." Existence of two-pyroxene andesite and a hornblende-hypersthene andesite indicates a transition from a period of basaltic volcanism (Harford et al. 2002). Additionally, three deposits of debris avalanches have been identified on the lower submarine flanks offshore from the Tar River valley, White River valley, and the once-capital city of Plymouth (Le Friant et al. 2004).

The smaller South Soufrière Hills are formed of lava flows and volcaniclastic beds of breccias, as well as some scoria-fall deposits, yet the lavas and pyroclastic flow deposits are of basaltic to basaltic–andesite composition. The area displays scars of an earlier dome collapse, and today its highest point is 756 m above sea level (Hincks et al. 2005).

A non-massif, Roche's Bluff, on the southeast side of the Soufrière Hills Volcano, is an important landform on Montserrat because the rocks of the bluff are "…cross cut by numerous faults, and it is interpreted as being an uplifted beach" (Hincks et al. 2005, p. 150). The bluff consists of steeply dipping submarine volcaniclastic rocks associated with thin limestones. The ages of both coral and foraminifera fossils, in addition to the coarse grained nature of the deposits, indicate deposition around one million years ago in an offshore shelf environment with an andesitic center. This is consistent with a link to the Centre Hills volcanic massif (Hincks et al. 2005).

Finally, the non-massif Garibaldi Hill and St. George's Hill are significant landforms, in that they have a distinctive geology on the flanks of the Soufrière Hills. Composed of andesitic lavas, lahars, pumice fall deposits, and laharic breccias in addition to pyroclastic flow deposits, this area has also been cut by numerous faults. This is consistent with the Centre Hills volcanic massif or an early product of the Soufrières (Hincks et al. 2005).

9.3.1 Soufrière Hills Volcanic Activity

The events of the Soufrière Hills Volcano during the timeframe of 1995–2013 were dramatic, near-constant, and often violent in experience. The Montserrat Volcano Observatory remains a world-renowned volcanic observatory, and the Soufrière Hills Volcano is one of the most researched, monitored, and actively managed volcanoes in the world. While a summary of events can be found in Table 9.2, the following subsections outline in greater detail the type of volcanic activity occurring on Montserrat, as well as the effects and consequences of those events, over the past ~20 years.

9.3.1.1 Modern Volcanic Activity: The Soufrière Hills Volcano 1995–1999

On July 18, 1995, the Soufrière Hills Volcano sprang to life with a burst of phreatic activity (Young et al. 1998). Small explosions were followed by ash and steam, and on August 21, 1995, larger phreatic explosions generated cold base surges and engulfed the capital city of Plymouth, prompting the first evacuation of the capital (Hincks et al. 2005).

Table 9.2 Timeline of activity on Montserrat. Data collected from MVO Web site (http://www.mvo.ms/), October 2016

Volcanic activity	Time period
Seismic activity	January 1992–July 1995
Phreatic explosions	July 1995–November 1995
Dome growth and collapse	November 1995–August 1997
Vulcanian explosions	August 1997
Dome growth	August 1997–September 1997
Vulcanian explosions	September 1997–October 1997
Dome growth	October 1997–December 1997
Major collapse	December 1997
Dome growth	January 1998–March 1998
Dome degradation and residual activity	March 1998–June 1999
Major Collapse	July 1999
Dome degradation and residual activity	August 1999–February 2000
Dome growth	November 1999–February 2000
Collapse	March 2000
Dome growth	March 2000–July 2001
Major collapse	July 2001
Dome growth	August 2001–July 2003
Major collapse	July 2003
Cessation of dome growth	July 2003–January 2009
Vulcanian explosions	November 2009–February 2010
Dome collapse	March 2013–April 2013

Phreatic explosions with steam and ash columns up to 3 km high lasted several months, and the largest of these ash clouds engulfed Plymouth in total darkness for up to 30 min (Young et al. 1998). A full evacuation of southern Montserrat was ordered in December 1995. As slopes destabilized, the first pyroclastic flows began in March 1996, increasing in magnitude and culminating in a massive dome collapse on September 17, 1996 (Young et al. 1998). This collapse triggered the first magmatic explosion of the eruption. It also removed an estimated 40% of the dome, depositing this material southward and extending the coastline where Plymouth once stood (Young et al. 1998; Hincks et al. 2005).

In October 1996, a second phase of dome growth began, triggering multiple smaller dome collapses. In December 1996, the first pumiceous pyroclastic flow accompanied by cyclic inflation and deflation of the dome caused periodic partial dome collapses into January 1997, sending pyroclastic flows down the Tar River valley (Young et al. 1998, p. 3391). On June 25, 1997, another massive dome collapse occurred to the east, sending an estimated 5 million cubic meters of material in a sustained pyroclastic flow down Mosquito Ghaut, killing 19 people in its wake (Hincks et al. 2005; Young et al. 1998). In August 1997, pyroclastic flows again travelled to the sea, through Fort Ghaut, and further destroyed and buried Plymouth, triggering Vulcanian explosions for more than a week. On September 21, 1997, another major dome collapsed with an estimated volume of 14 million cubic meters and a second round of 75 Vulcanian explosions occurred over the course of the following month. All of these events led up to December 26, 1997, when a failure of the upper flanks of Galway's Wall created a debris avalanche that triggered a volcanic blast that added 10 km^2 to the southwest of the island and covered the former airport and St. Patrick's village (Fig. 9.5; see also Hincks et al. 2005).

From March 1998 to November 1999, there was no measured dome growth, and the dome was continually degraded by small collapses, rockfalls, and pyroclastic flows. On July 03, 1998, another major dome collapse occurred, taking off about 25% of the dome and sending 20–30 million cubic meters of material down the eastern Tar River valley in pyroclastic flows, carrying ballistic blocks up to one kilometer (Hincks et al. 2005). After this event, heavy rains in September, November, and December created voluminous mudflows down all flanks of the volcano. Relentlessly, activity increased again in the spring of 1999 with a series of explosive ash-venting occurrences and another dome collapse on July 20, 1999 (Fig. 9.6).

9.3.1.2 Modern Volcanic Activity: The Soufrière Hills Volcano 1999–2005

Two hurricanes swept through the island in 1999: Hurricane Floyd in September and Hurricane Lenny in November,

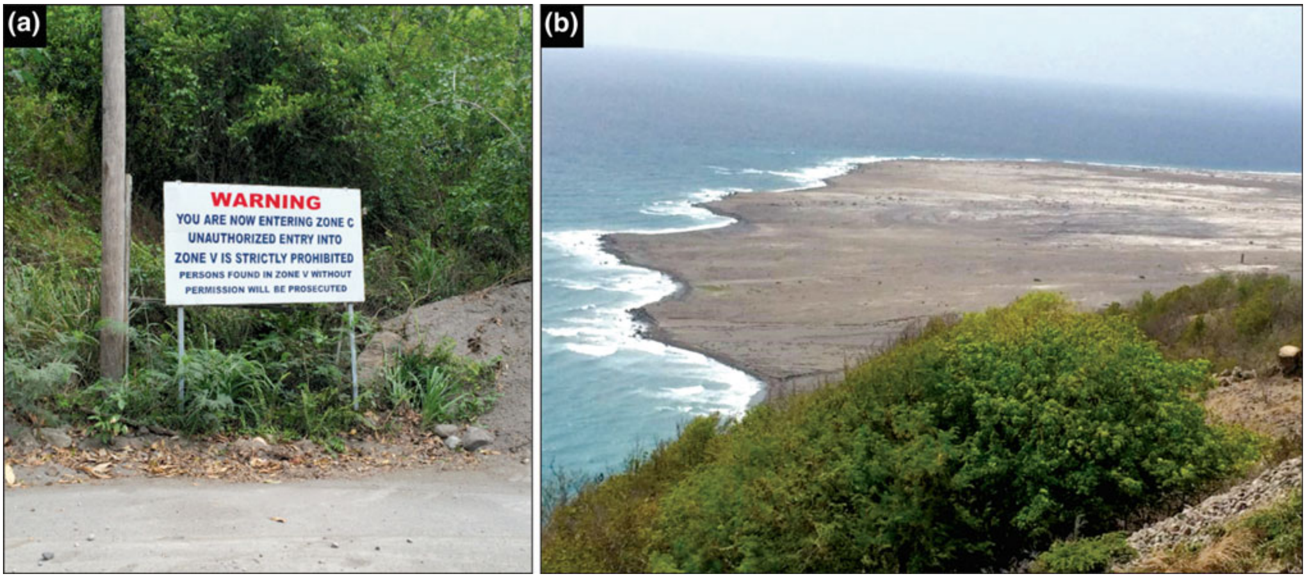

Fig. 9.5 Examples of life ever changed by volcanic destruction. **a** An Exclusion Zone sign at the entrance of Zone C. All Exclusion Zones are readily identifiable by signs that indicate which zone you are in and gates that close when access is not permitted. Photograph by E. Nelson. **b** Buried village of St. Patrick's and site of former airport, Brambles Airport; the aviation tower is barely visible at the *right* of the photograph. Photograph by J. Davenport

triggering mudflows that were followed by small explosions from the volcano (Hincks et al. 2005). These were the first hurricanes to hit Montserrat since the devastating Hurricane Hugo in 1989.

On November 27, 1999, a new lava dome was measured in the base of the old dome crater and was the first sign of extrusive growth in 20 months. After months of growth, large pyroclastic flows from the new dome again poured down the Tar River valley in February 2000. Heavy rains in the spring of 2000, initiated another major collapse on 20 March that year, with a volume of 20 million cubic meters (Hincks et al. 2005). The growth of the dome continued moderately into 2001 with minor collapses, some pyroclastic flows, and rockfalls, and on May 18, 2001, a new lobe extrusion occurred to the south. In the following months, near-continuous rockfall activity occurred until, in July, torrential rainfall and mudflows down the Belham River valley were followed by the second collapse of the new dome (July 29, 2001). This near-continuous nine-hour event shed 45 million cubic meters of earth and sent pyroclastic flows down the Tar River valley, out to sea and into the air where particulate matter from Montserrat was recorded as far away as Puerto Rico and the Virgin Islands (Hincks et al. 2005). In November 2001, the direction of growth changed from east to west, but activity remained low for the rest of the year.

The following year 2002 was characterized by the impressive production of large spines. Lava spines are characterized as abrupt expulsions of volcanic material, most often shaped as a column (spine) or as a slab. Spines are forceful in creation yet are weak structures as landforms and erode very quickly. On February 25, 2002, for example, one 90-m spine appeared overnight at an altitude of 1080 m (Hincks et al. 2005, p. 156). In the spring of 2002, rockfall and seismic activity escalated but then declined and remained at low levels until July 21, 2002, when a new lobe began to form on the north face. By September, small collapse events generated pyroclastic flows that reached the east coast, and in October 2002, growth switched again to the northeast and prompted the evacuation of the margins of the Belham Valley on October 06, 2002.

By 2003, now in its eighth year of activity, the Soufrière Hills Volcano continued its rumblings with dome growth in the directions of north and northeast. In March of 2003, the dome reached its greatest altitude in recorded history, 1098 m, and by July had increased in volume to about 22 million cubic meters (Hincks et al. 2005). On July 12 and 13, 2003, the dome collapsed again, this time with an estimated collapse volume of 120 million cubic meters. This, coupled with heavy rainfall on 12 July, triggered mudflows in the Belham Valley. Low-volume pyroclastic flows now travelled down the Tar River, increasing in frequency and intensity (Hincks et al. 2005, p. 160). The larger flows reached the sea and produced phreatic explosions, alongside an estimated 1.2 million tons of ash falling over the populated areas of the island. The pyroclastic flows slowed on July 13, 2003, but three volcanic explosions occurred after the collapse and produced an ash cloud that rose 15 km into the sky with gravel and large rock fragments falling over the populated areas of the island —"raining gravel" again on the island (Hincks et al. 2005).

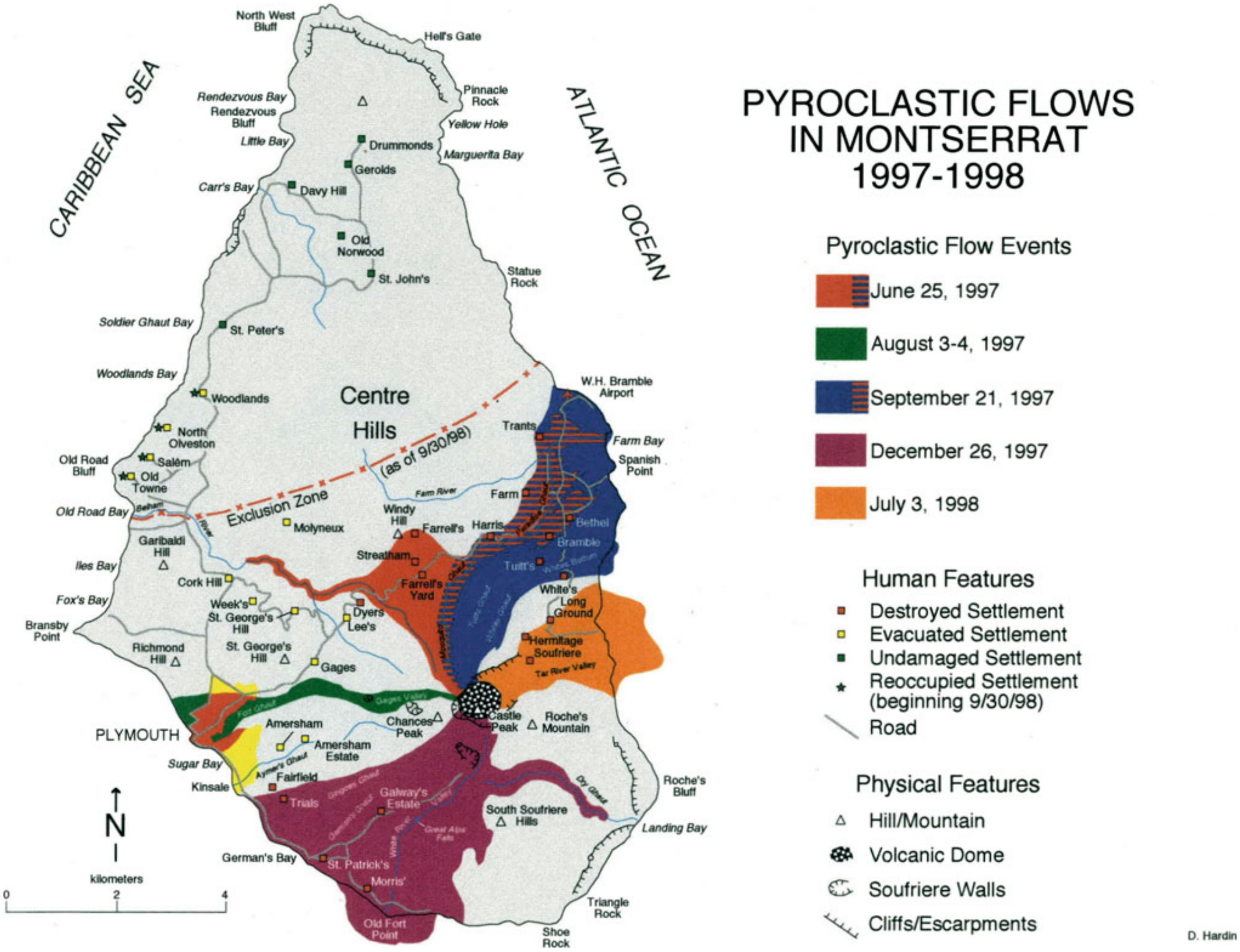

Fig. 9.6 Map of areas of pyroclastic flows on the island of Montserrat during the years 1997 and 1998. From Hardin, retrieved from: http://www.hoeckmann.de/karten/amerika-nord/montserrat/index-en.htm

For the rest of 2003 and 2004, only tremors and minor ash venting occurred until March 03, 2004, when another explosion and dome collapse occurred. This time, it sent pyroclastic flows down the Tar River and into the sea, and ash clouds reached nearly 7 km into the air (Hincks et al. 2005, p. 160). The spring of 2004 brought moderate-to-low tremors, but on May 21, 2004, intense rain triggered massive mudflows in the Belham Valley with waves reaching up to 2 m high (Hincks et al. 2005). In August of 2005, an eruption created a 1.8-km plume into the sky (MVO 2015).

9.3.1.3 Modern Volcanic Activity: The Soufrière Hills Volcano 2005–2013

On December 24, 2006, pyroclastic flows became visible again, and on January 08, 2007, an evacuation order was issued for the Lower Belham Valley (MVO 2015). On July 28, 2008, pyroclastic flows again reached Plymouth, caused by a dome collapse on the lava dome's eastern side, creating an ash cloud 12 km tall (Chardot et al. 2010). During 2009 and 2010, extrusion of the lava dome triggered the most recent large event at the Soufrière Hills Volcano, and included the several rapidly developed spines and lobes that extruded from the volcano. On February 05, 2010, pyroclastic flows rapidly filled surrounding valleys on multiple sides of the volcano, and on February 11, 2010, a partial dome collapse again sent large ash clouds into the sky (MVO 2015; Stinton et al. 2014).

Volcanic activity began again in November 2009 and continued through February 2010 with ash venting and an explosion that created pyroclastic flows in several directions down the sides of the volcano (MVO 2015). In 2013, the MVO reported a pyroclastic flow that travelled down the Tar River Valley in March. The deposits indicated a failure of a large slab that had been moving away from the dome (MVO

2015). Heavy rainfall occurred after this event triggering lahars in the surrounding valleys (MVO 2015). Figure 9.7 displays some visual evidence of these events.

9.3.2 Rivers and Beaches

The rivers of Montserrat have been affected by the volcanic activity, and some have been filled by pyroclastic debris, many are conduits for lahars that also affect the sedimentation of the river basin. Montserrat has 11 rivers (including tributaries) that include Farm River, Lee River, Paradise River (altered by pyroclastic flows), Tar River valley (destroyed by pyroclastic flows), Hot River, White River (destroyed by pyroclastic flows), Belham River, Dyer's River, Nantes River, Collins River, and Lawyers River.

The beaches and bays on Montserrat vary in size, location, and material makeup. The island has both black sand and white sand beaches. The bays of Montserrat include Bunkum Bay, Carr's Bay, Foxes Bay, Isle Bay Beach (Old Road Bay), Lime Kiln Bay, Little Bay, and Marguerita Bay (Montserrat Tourist Board 2012). Many of these beaches are inaccessible post-eruption, as they are located in the exclusion zones, for example, Foxes Bay has only recently been declared safe, located in Zone B (see zone reference chart). However, the volcano also caused coastal advancement that extended the Isle Bay Beach (Old Road Bay). Little Bay is the only bay deep enough to accommodate for small watercraft, and there are no bays on the island capable of accommodating large cruise ships. The only white sand beach on the island is Rendezvous Beach; this beach is located in an uninhabited area of the island and is only

Fig. 9.7 An aerial view of the Soufrière Hills Volcano looking north. Volcanic processes that altered the physical landscape of the island of Montserrat—such as pyroclastic flows, coastal advancement, previous dome collapses, and an ash plume—are all visible in this image, including the deltaic pattern, some lava flows created at their termini, and the partially buried remnants of the small village of Bethel (*center-right*). Photograph by J.-M. Bardintzeff, 2010. Retrieved from http://44.svt.free.fr/jpg/volcanologue.htm

accessible by boat or hike. Woodlands beach is the most notable black sand beach, with the material makeup of volcanic sand, one of the few in the Lesser Antilles region.

9.4 Cultural Landscape

The ongoing eruption has had a significant impact on both the physical and cultural landscapes of the island. Across the island, vegetation and much of the tropical rainforest has been destroyed or damaged by pyroclastic flows, ashfall, and acidic gas. Low-lying areas and ghauts have been filled in by pyroclastic flows, lahars, and ashfalls; additionally, these flows have created coastal expansion (Hincks et al. 2005).

This physical standpoint provides an entry point to frame an understanding of Montserrat's physical and social landscape interplay. It offers a manifestation of "…complex and emergent relationships that can be used as a platform" to understand multiple, converging viewpoints and understandings (Wilcock et al. 2013, p. 573). Ethnogeomorphology, for this study, is used as "…a geomorphic lens to discuss 'relationality'—or the way in which processes emerge in nondeterministic and non-causative ways" (Wilcock et al. 2013, p. 574). Landscape analysis builds on the delineation of landforms, processes, evolutionary adjustments, and the associated applications of these understandings (Brierley et al. 2013). Expanding on this foundation, within human geography, relations at a landscape scale form connections between place and home and strongly influence land use, following historical settlement patterns, social, and cultural interactions (Wilcock et al. 2013).

The ethnogeomorphology of Montserrat, because of the volcanic history and subsequent destruction of the former capital, economy, and way of life for Montserratians, requires concepts of connectivity and space–time relationality to frame the understanding. This perspective is grounded on the literature and on the experience of Montserrat pre- and post-eruption, and engagement with the community of Montserratians to examine knowledge production and concerns for environmental negotiation and decision-making.

9.4.1 Background

Montserrat, one of Britain's oldest colonies, was a quiet and relatively prosperous island in the Caribbean before the volcanic eruption, with good levels of employment, and high standards of education and health care. Montserrat held one of the highest standards of living in the Caribbean (Skelton 2000). The capital city of Plymouth was a flourishing town with a mature infrastructure of municipal functions including schools, a medical university, medical resources, heavy tourist traffic, and other successful commercial and industrial activities. It was a mainstay on the stopover itinerary of major cruise lines, had a large number of second homes for expats, and ran multiple hotels ranging in luxury with ocean views that were competitive and easily accessible (Weaver 1995).

The first modern disaster to strike was Hurricane Hugo, a category four hurricane which passed over the island in 1989 and destroyed 90% of the island's structures (Harden and Pulsipher 1992). Millions of dollars in aid poured into the recovery of the island with a major focus on rebuilding the port city of Plymouth. Yet only a few years later, the island, and specifically the city of Plymouth, would again come under attack by a natural disaster.

In July 1995, the long dormant the Soufrière Hills Volcano became active, triggering a chain reaction of events for the residents to evacuate and make decisions and life changes, in most cases permanently (Skelton 2000). The volcanic event brought immediate worldwide attention to the island, and while thousands of the resident population out-migrated, hundreds of scientists in-migrated to study the volcano, to advise on evacuation, and to quickly address the changing status of an active volcano and evacuation plan (Donovan et al. 2013).

The areas now enclosed in the exclusion zones to the east, south, and central areas include the former capital city of Plymouth (Fig. 9.8), the original airport, and many villages that were once agricultural villages, although most residents had paid work in Plymouth (Skelton 1996). The north of the island, currently the only inhabited area, is much dryer and less fertile. It was designated as a safe zone from the volcanic activity although ash is regularly blown over the region. The areas now included in the exclusion zone made up 74% of the households in Montserrat pre-eruption. These residents had to relocate to makeshift accommodations in shelters, churches, and schools, or with friends and family in the north, on other Caribbean islands, or the UK (Skelton 2000).

Scientists from the UK and around the world descended upon Montserrat after the initial eruption, participated in the monitoring of the volcano, the decision-making processes about the evacuation, and other safety concerns. This mix of local and foreign participants in a time of crisis became a dysfunctional process, spawning infighting and resentment on both sides. The typically risk-averse western scientists and UK officials, feeling responsibility on the part of the colonial holding, were quick to issue large evacuation orders, where local and non-western decision-makers were more contentious of the effects of false orders of evacuations and the emotional impact they had on local residents (Donovan et al. 2013). Where foreign visitors had the readily available option of leaving the island and going home at any time, those actually being evacuated had to make quick decisions and experience the excruciating trauma of a rapid departure from their beloved homes.

Fig. 9.8 Desolated capital city of Plymouth, covered by pyroclastic flow. Collapsing houses, in stark contrast to the barren ashfall and the lush greenery surrounding the flow path, now dominate the landscape. Photograph by J. Davenport

9.4.2 The Landscape of Past-Present

A visit to the exclusion zone and seeing a street of abandoned houses leaves an outsider with a sense of voyeurism. The sadness and loss, while intangible, descend heavily, almost like the pyroclastic flow that caused the abandonment. The feeling is intense, unforgiving, and overwhelming. Entering the derelict homes is indicative of a forceful, hurried, and frantic departure. Swimming suits still hang to dry over shower curtain rods, magazines from 1995 lay open to the last page of reading, closets still full of clothing, drawers left open with items from around the house, a collection of random items that make up a life, scattered about in the rush to evacuate, captured in a moment in time, when the residents had to leave. Many homes have been inundated with mudflows, destroyed by the hot gases of the pyroclastic flows, yet as with most disastrous events, oddities in the destruction remain. Where the chemical reactions of the pyroclastic material melted safes and swallowed metal desks and furniture, cloth curtains and paper documents remained. When a pyroclastic flow-delivered ballistic did not ignite a home, a boulder may have cracked the side wall and stayed there forever captured in this moment of time and location. The abandoned homes hold indications of the unknown and sporadic evacuations. Some storefronts have actual signs of their "temporarily relocated" businesses (these became permanent relocations). A mass of debris collected outside one home, it was the stopping point of a flow of trees and other debris. In another home, someone took off a pair of glasses, set them on the counter and just left (Fig. 9.9).

This arrival of the past, of the thriving city of Plymouth, arrives in the present in a preserved and respected way—a type of arrested decay. Arrested decay is a concept by Western scholars to preserve "ghost towns" or other abandoned areas in a way that stabilizes the existing infrastructure and allows organic decay as the buildings slowly give way to weathering and decaying processes, where the general appearance and layout of the streets and houses are retained but not repaired (DeLyser 1999). Arrested decay also addresses the particulate matter that accumulates in preserved or abandoned sites, mandating that neither the artifacts or the dust, or in this case the ash, that covers the entire area of abandoned homes is removed (DeLyser 1999). The ash-covered neighborhood had air of authenticity, many

Fig. 9.9 Select images exemplifying the urgent and sudden evacuation of Plymouth during the 1995 eruption. **a** A swimming suit hanging over the shower to dry in 1995. This is a very common sight in the abandoned houses. **b** Closest *left* with clothing and items still hanging on the door in an abandoned house. **c** A pair of glasses, set on the counter and *left* behind when the evacuation was ordered. **d** East Caribbean coins minted in 1994, just before the volcanic explosions began, lay untouched in an abandoned house. All photographs by E. Nelson

homes had footprints, also preserved in the ash, and some homes had no footprints (DeLyser 1999).

It was the homes without footprints that offered a visitor a true glimpse, again a voyeuristic glance, into the island lifestyle of the former residents. There are no written signs or organized tours of the areas surrounding the exclusion zones, and arrested decay is not an enforced policy in this particular neighborhood, a relatively unregulated area. This lack of written interpretation leaves the visitor with a sense of authenticity through the power of visual appearance to create meaning (Strazdes 2013). Authenticity engages with the historical and cultural landscapes and often leaves questions of an "authentic heritage," yet this landscape in Montserrat leaves no thought to interpretation, like many of the features of the island, the abrupt and violent nature of this town's abandonment, and the 20 years of ash, dust, and volcanic material that have collected in a very convincing way that leaves no questions of authenticity.

9.5 Heritage and Tourism

The island was first inhabited by Arawak people, and subsequently by the Carib, or Kalinago Amerindians. The Caribs called the island Alliouagana, meaning "Land of the Prickly Bush" (Fergus 1975). In 1493, Christopher Columbus claimed the island for Spain on his second voyage to the new world. He named the island "Santa Maria de

Montserrat" after the Virgin of Montserrat in Catalonia, Spain (Minahan 2009). In 1632, Irish-Catholics from nearby Saint Kitts colonized the island, fleeing anti-Catholic violence and indentured servitude. These Irish immigrants were followed by Irish-Catholics from Virginia, also fleeing religious persecution (Skelton 2000). Montserrat's nickname, "The Emerald Isle of the Caribbean," comes from its Irish heritage and interpreted resemblance to the other Emerald Isle, Ireland (Fergus 1984).

Despite the Irish colonists, it was Britain and France who fought for possession of the island for most of the 18th century. The island has hallmarks and regions named for the historical battles that raged on its soil. Runaway Ghaut was the site of a bloody colonial battle between the British and the French, which as its name implies, ended with one side retreating. In 1783, the battles ended, and Montserrat was declared a British possession (CIA 2015).

Like other Caribbean islands, Montserrat had a thriving slave trade linked to plantations. The first African slaves arrived in the 1660s (CIA 2015). While Montserrat has an Irish heritage as well, including the Irish indentured servants, the modern population is overwhelmingly of African descent, albeit with Irish surnames, creating an interesting confluence of history (Messenger 1994). The slave trade gradually increased from approximately 1000 slaves in 1678–7000 in 1810, when the enslaved population outnumbered the white settlers (Fergus 1984). These slaves became free in 1834 after slavery was abolished in British Overseas Territories, following the passage of the Slavery Abolition Act of 1833 in the UK (Fergus 1984).

Numerous slave rebellions occurred during the time of slavery, most notably one led by a slave named Cudjoe. Local legend claims that Cudjoe plotted a rebellion, escaped, and was caught by white slave owners. They beheaded him and hung his head from a silk cotton tree as a warning to other slaves. The silk cotton tree still stands today in a village aptly named Cudjoe Head. In honor of this rebellion and the island's strong African heritage, the island holds a Cudjoe Head celebration every summer (Montserrat Tourist Board 2011).

Another celebrated slave rebellion took place on St. Patrick's Day in 1768, when slaves rebelled, but failed to achieve freedom (Fergus 1984). This controversial depiction of the holiday is portrayed in tourist literature:

> Montserrat is the only country in the world apart from Ireland that observes St. Patrick's Day with a holiday. The weeklong celebration highlights Montserrat's local culture and Irish heritage that culminates with St. Patrick's Day on March 17 (Montserrat Tourist Board 2011).

While the festival is full of typical St. Patrick's Day revelry, complete with shamrocks and leprechauns, the locals consider the festival a solemn honor to the slavery history of the island.

The development of the tourism industry in Montserrat has, for the last 20 years, taken a back seat to the redevelopment of the island's infrastructure and, quite plainly, to the restarting of life as a new island. The volcanic eruption altered the island forever, destroying touristic activities and the previous capital city. Nonetheless, it has also created touristic activities in the exploration of the abandoned city, and has attracted hundreds of social, physical, and environmental scientists. The island holds a story of survival through its volcanic past and will undoubtedly continue to thrive and grow while maintaining a sense of seclusion that is particularly appealing to many tourists. Montserrat is truly a gem, the Emerald Isle, an exciting and different locale in the Caribbean, albeit a potentially dangerous gem. Looming in the background, rarely visible, even on sunny days, is the Soufrière Hills Volcano. Unseen, but always felt, a constant reminder of danger, of the unknown, of fear. The hazard of the volcano has become a way of life for Montserratians, from explosion to pyroclastic flow, from evacuation to revival.

9.6 Hazards

Montserrat is a volcanic island, and the active Soufrière Hills Volcano represents its most relevant hazard. But volcanism involves additional hazards of earthquakes (seismicity), volcanic blasts and explosions, dome collapses, pyroclastic flows, tephra falls, ballistics, and mudflow (Hincks et al. 2005). Additionally, the island remains geographically located in an area with a high incidence of hurricanes, making Montserrat an exceptionally likely place for catastrophes.

Since 1900, seven hurricanes have affected Montserrat. Of those, Hurricane Hugo in 1989 was the most devastating, and it destroyed a majority of the island (Weaver 1995, p. 597). Previous to Hugo, an entire generation had been living a disaster-free existence, since the last destructive storm of any kind had occurred in the late 1920s, and the volcano was still dormant (Harden and Pulsipher 1992). However, after 12 h of unrelenting wind and rain, "Every structure on the island suffered damage and 90% of the 12,000 inhabitants were left homeless, at least temporarily. All roads were rendered impassable by fallen trees and downed power lines; and the schools, churches and hospitals were badly damaged or destroyed" (Harden and Pulsipher 1992, p. 9).

Yet, the descriptions of Hurricane Hugo, and local references to it, were all pale in comparison with the volcanic activity. As terrible as Hurricane Hugo was, the difference between a hurricane and volcanic fallout is access. After the hurricane, inhabitants could rebuild. After the volcanic eruption, inhabitants were evacuated permanently.

An introduction to the volcanology of Montserrat, and the various hazards within the larger hazard of a volcanic eruption, must be given for understanding the Soufrière Hills Volcano. A major factor in determining the level of hazard across the island is the dome formation and eruption, the rate and direction of those processes, and the associated topography of the projected hazardous area (Hincks et al. 2005). For this section then, after a brief explanation of these phenomena, a quick review of the island's history of monitoring is offered before ending with an in-depth report of the volcanic events leading up to today.

9.6.1 Volcanic Activity

Dome collapse is caused by two mechanisms: first, an endogenous collapse involving internal forces within the volcano that destabilizes the dome by causing a surge of lava that always occurs in the direction of the dome growth (Watts et al. 2002); and the second mechanism is specifically rainfall-induced, creating an environment for a weakening of the dome and subsequent collapse (Matthews et al. 2002). Both of these mechanisms occur on Montserrat.

Pyroclastic flows typically follow a dome collapse and are high-speed, gravity-driven flows of debris, hot particles and gas (Hincks et al. 2005, p. 161). As gravity-based flows, they tend to follow the topography of the landscape, yet more powerful surges are capable of exiting a typical route and covering an unpredictable area and amount of land, much like the waters of a flooded river (Fig. 9.10).

Tephra fallout represents the most widespread volcanic hazard, caused from massive plumes of ash and rock created by phreatic explosions, pyroclastic flows, and explosions. The material enters the atmosphere and, depending on density and weight, falls back down to the earth. As Montserrat has predominately easterly low-level wind, much of the ash from tephra fallout is blown to the west, away from the currently inhabited areas. Yet occasionally, less common wind directions will cause significant ashfall and rock-fragment fall in the populated area—"raining gravel"—as the locals say (Bonadonna et al. 2002).

Ballistics are large blocks of rock, ejected from the volcano at speeds and temperatures high enough to cause significant damage within a 2.5 km radius of the dome. Also known as hot ejecta and volcanic bombs, the ballistics can cause fires when they come into contact with flammable material, like a wooden house (Hincks et al. 2005).

Volcanic mudflows, also called lahars, are caused by intense rainfall that mobilizes the loose deposits on the flanks of the volcano. These can move debris of all sizes and, because of their viscous nature, can completely bury cars, roads, and buildings, hampering access to critical services (Hincks et al. 2005, p. 161). On the island, near the mouth of the Belham River, deposits have been measured up to 3 m deep, and mud carried down Fort Ghaut continues to bury the city of Plymouth (Hincks et al. 2005).

9.6.2 Volcanic Monitoring on Montserrat

The most significant hazards involved with a volcano, because they underlie everything else, are the eruptions themselves. Volcanic monitoring began in Montserrat in 1936 by two geologists, C.F. Powell and A.G. MacGregor, sent by the Royal Society of London. These geologists produced the first detailed description of the geology of Montserrat (MacGregor 1938). Powell set up a seismograph network that was in operation until 1951 (Hincks et al. 2005; Powell 1938). The Seismic Research Unit of UWI (SRU) installed four seismograph stations in 1966 and piloted studies of ground-deformation measurement. Subsequent installations occurred between 1966 and 1986 (Hincks et al. 2005). The seismograph network was destroyed by Hurricane Hugo in 1989 and was restored in 1992 and has been greatly enhanced since the eruptions began in 1995.

After the initial eruption of the Soufrière Hills Volcano, the Montserrat Volcano Observatory (MVO) was established to provide constant, intensive monitoring of the volcano. During the early stages of the crisis, through 1999, the MVO brought in scientists from the British Geological Survey (BGS), universities from the UK and the USA, and the SRU team, all working with local technical teams. Beginning in 1998, the scientific contributions of the MVO have been managed by the BGS and in 2003, the MVO moved into a purpose-built building observatory with a full view of the volcano (Hincks et al. 2005). Volcanic reporting continues daily with reports from the MVO Web site and on the MVO Facebook page that reaches across informational boundaries to reach the widest audience possible, both scientist and non-scientist alike, with up-to-date information about the volcano (MVO 2015).

The MVO conducts visual, deformation, gas, and environmental monitoring. These techniques involve aerial- and ground-based photography, as well as topographic surveying. They use leading technological advancements of photography to model the dome and dome growth (MVO 2015). Using GPS measurements and Electronic Distance Measurements (EDM), the MVO monitors the deformation of the flanks of the volcano, within a variable of a few millimeters (Hincks et al. 2005).

Earthquakes are common on Montserrat. Between 1933 and 1937, 3290 earthquakes were reported (Young et al. 1998). After these years of heightened activity, only 200 earthquakes were reported in 1937 and 1938 (Shepherd et al. 2002). This pattern of seismicity repeated itself nearly 30 years later in 1966 with heightened activity but it declined severely, and by

Fig. 9.10 Extended coastline from a pyroclastic flow as it enters the ocean creating new landmass for the island. Notice the fluvial-like features in both the resulting erosional and depositional formations. Photograph by S. O'Meara 2004

November 1967, "it was no longer thought necessary to continue intensive monitoring" (Hincks et al. 2005, p. 153; Shepherd et al. 2002). Yet in 1992, after decades of inactivity, seismic activity increased sharply, and from the beginning of 1992 to July 1995, the average number of daily earthquakes was higher than at any time since the 1938 observations. The phase of eruptions between 1995 and 1999 coincided with shallow, low-frequency earthquakes originating in a small area, often occurring in swarms and lasting for hours (Hincks et al. 2005).

9.6.2.1 Future Outlook

The Soufrière Hills Volcano has been relatively quiet for the past few years. Currently, MVO scientists continue to monitor the changing conditions. Hazard and risk assessments are carried out at six-month intervals by a panel of MVO personnel and scientific advisors since December 1997 (MVO 2015). The panel's reports are shared with the Governor of Montserrat and provide a basis for decisions concerning the exclusion zones and emergency procedures.

As the island is vulnerable to multiple disasters, the DMCA and the MVO work together to create safe and reliable forecasts of disasters and prepare themselves and the population of Montserrat accordingly. With a state-of-the-art warning system in place, and in collaboration with the other Caribbean islands' warning systems, Montserrat stands ready for whatever disaster may befall them in the future. Yet they also patiently await a few decades of peacefulness. Perhaps years of quiescence and economic growth are in order after the past decades of struggle.

9.7 Conclusion

The convergence and urgency of the geomorphologic landscape of Montserrat and its effects on the residents of the island offer a story of survival. At a time when other islands and nations were struggling with different disasters and different political quandaries, Montserratians lived a moment-to-moment existence in reverence to the volcano. As the volcano erupted, towns were evacuated, scientists flew in from all over the world, and the island experienced an influx of people and knowledge while simultaneously experiencing widespread out-migration—first to neighboring islands and, in many cases, on to the colonial homeland of the UK. Before Hurricane Hugo struck in 1989, the island was on the verge of independence from the UK, yet after the hurricane and more permanently devastating volcanic events of the Soufrière Hills Volcano, they are today, completely dependent on aid from the UK and other foreign agencies.

This vacillation from quiet, beautiful, and peaceful Montserrat, to violent, desperate, and traumatized Montserrat was no easy transition. Montserratians carry their past with them and, while they are still a proud and strong people thankful for their precious resources, they carry with them a fear and respect for the unrelenting volcano as well. Many locals speak of nature as a force not to be questioned, for they well know that nature will do what nature will do and humans have very little to do with the processes.

Those processes of land accretion and erosion, as outlined in this chapter, have created a Montserrat of beautiful and breathtaking mountains, hills, and the volcano. Additionally, beautiful beaches, nearly untouched by the ravages of mass tourism, make the island spectacular in the Caribbean. It is these very processes, however, that destroyed their former capital city of Plymouth by pyroclastic flows following multiple dome collapses of the volcano, triggering land deformation on an enormous scale that has forever altered Montserrat's landscape. This, coupled with the peculiar engagement with a legendary music scene and desired destination for affluent resident tourists, makes Montserratians rather extraordinary, especially for such a small island. They are an everyday folk, yet are outstanding in their hospitality, their resilience, and their ability to adapt, embrace, and carry on. Through a violent history of colonization, slave trade, and modern natural disasters, this island is a place of wonderment for anyone daring enough to discover it. It takes a certain kind of person to travel to Montserrat, but an even more special kind of person to *be* Montserratian.

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Guadeloupe

10

E. Arnold Modlin Jr and Casey D. Allen

Abstract

Comprising a small set of several islands located at the southern end of the Leeward Islands in the Lesser Antilles, Guadeloupe is a French Overseas Department. The two larger islands are separated by less than 40 m in some sections giving Guadeloupe the geologic distinction of being part of both the Volcanic Caribbees (geologically younger) and the Limestone Caribbees (geologically older). Basse-Terre (the western main island) consists of a series of volcanically active andesitic massifs, while Grande-Terre is of lower terrain and a volcanic bedrock foundation overlain with carbonate sedimentary deposits. While various Amerindian groups visited and started settling in the islands between 4000 and 6000 BP, it was unknown to Europeans until Columbus' second voyage (November 1493). Once French colonists began settling the island after 1635, the landscape was dramatically transformed first by fighting with the Carib people for five years, and subsequently by bringing African slaves to cultivate sugar. Even today, Guadeloupeans represent a resilient people struggling with social and economic issues such as the high cost of living and high unemployment rates.

Keywords

Volcano • Basse-Terre • Grande-Terre • Marie-Galante • Soufriere • Vichy • Slavery

10.1 Introduction

With a land area of approximately 1628 km^2 and 581 km of coastline, as of 2015, the department of Guadeloupe had a total population of 400,132 people (INSEE 2016; Pruett and Cimino 2000). The island of Basse-Terre, Guadeloupe, sits 42 km north of Dominica and 56 km southeast of Montserrat, while the other major island Grande-Terre lies 61 km south of Antigua. A narrow channel 40–150 m wide and about five km long (*Rivière Salée*, or Salt River) separates these two largest islands of Guadeloupe. Sometimes Guadeloupe is referred to as *l'Île Papillon* (Butterfly Island), because Basse-Terre and Grande-Terre form a butterfly-like shape (Fig. 10.1). As an Overseas Department of France (also known as an Overseas Region since 2003), Guadeloupe is part of the European Union and uses the Euro as currency, although it is not a part of the Schengen area (US Department of State 2016). Citizens of Guadeloupe remain citizens of France, and the islands' inhabitants are represented in the French national government by officials elected locally on the island.

Geologically, Guadeloupe remains quite complex (Fig. 10.2). The islands have three basic geochemical compositions. Grande-Terre, Marie-Galante, and the Îles de la Petite Terre are part of the Limestone Caribbees, islands that represent an arc of volcanic activity that ceased millions of years ago, and are overlain by carbonate deposits. To the east is La Désirade which has a volcanic base that is older

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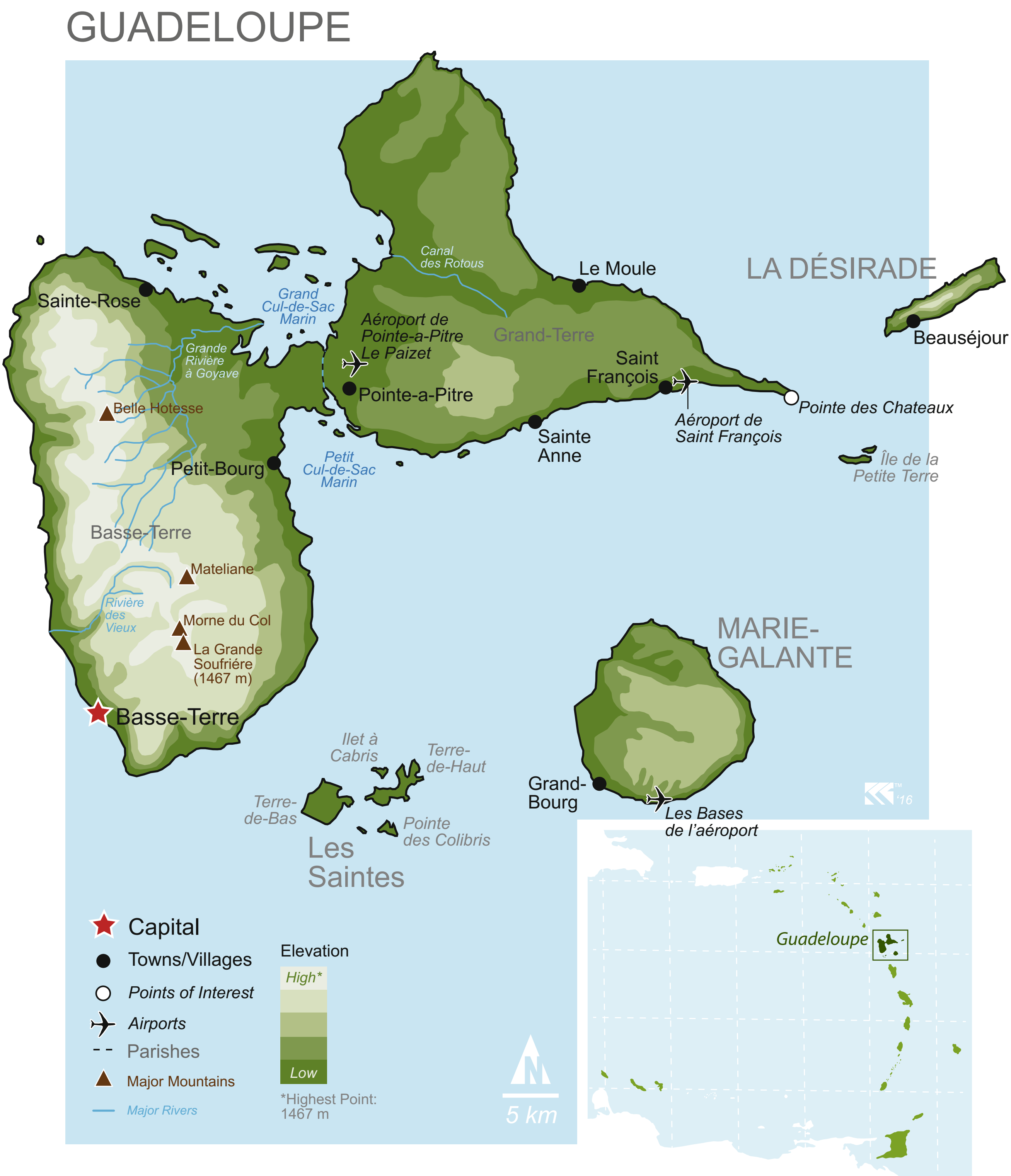

Fig. 10.1 General physiographic map of Guadeloupe and numerous surrounding islands. Many of the small neighboring islands are populated, such as Marie-Galante to the southeast. The bow-shaped main island of Guadeloupe is noticeably more mountainous in the western Basse-Terre region than the eastern Grande-Terre region. Cartography by K.M. Groom

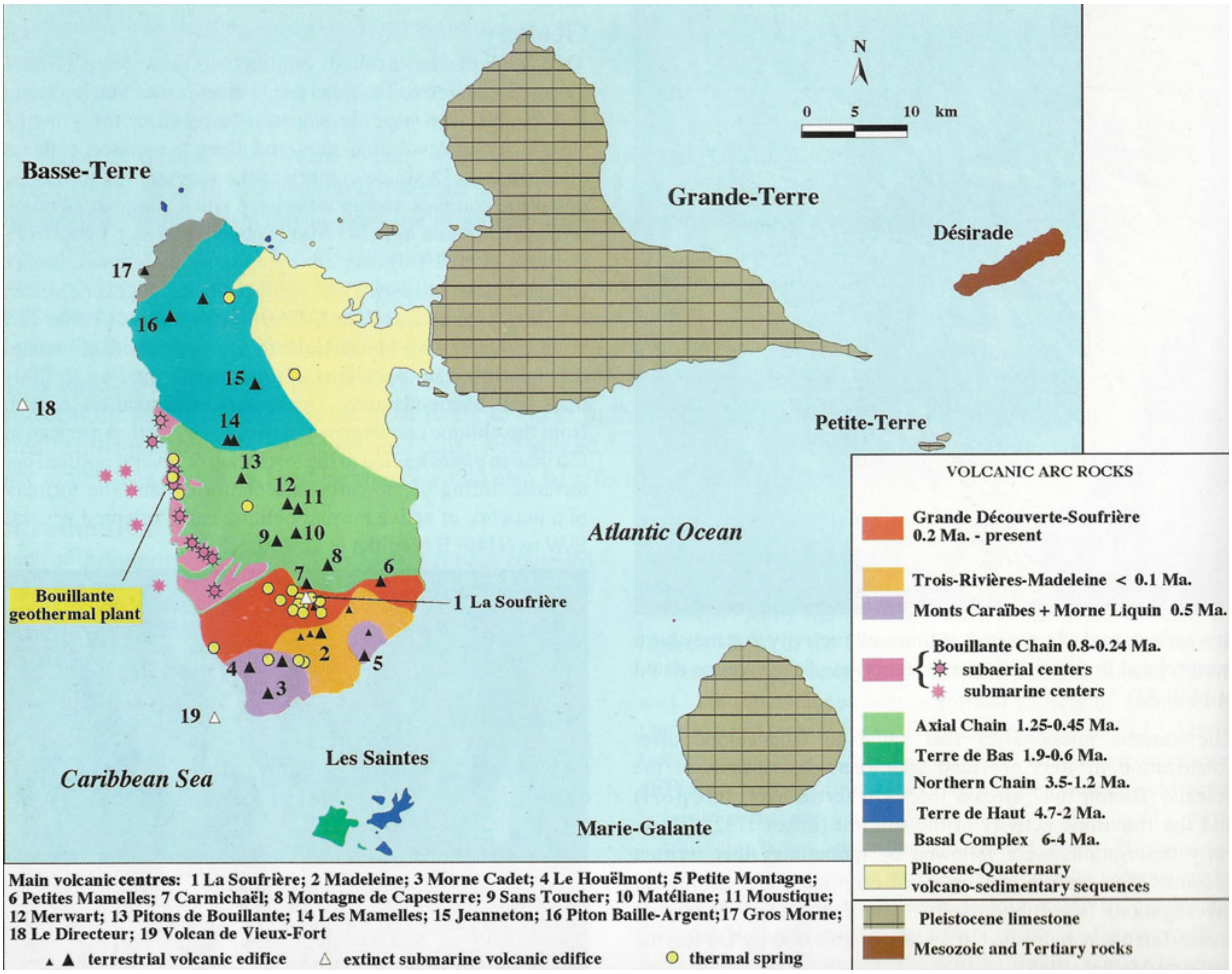

Fig. 10.2 Geological map of Guadeloupe displaying its distinctness across the major islands. Map courtesy of http://caribbeanvolcanoes.com/guadeloupe-map/. See also Bouysee et al. (1990)

and mineralogically different from the rest of the Limestone Caribbees. To their west, Basse-Terre and Les Saintes islands are part of the Volcanic Caribbees, which are the result of more recent volcanic activity and have a higher profile than the Guadeloupean Limestone Caribbees (Bouysee et al. 1990). La Grande Soufrière, a 1467-m-high volcano on Basse-Terre, although quiet at the time of this writing, represents the highest point in the Lesser Antilles and still considered an active volcano.

In addition to natural forces that shaped the landscape, anthropological forces transformed the islands that make up Guadeloupe. The first migratory waves of Amerindian groups passed through, and in some cases stayed, prior to 2000 B.C.E. (Allaire 1997). Columbus discovered and landed on the islands of Marie-Galante and Basse-Terre in November 1493. Caribs continued to inhabit on the islands until at least 1640 when the French largely displaced them. In 1635, the French settled the islands with the intention of raising tobacco. Sugar and slavery would shape the landscape from the 1660s to the abolition of slavery in 1848, when indentured servants would then take many of the formerly enslaved people's places in the sugarcane fields. Many Guadeloupeans would fight for the French in World War I and World War II (Jennings 2001). During the World War II years of 1940–1943, Vichy France maintained control of the island. In 1946, Guadeloupe became an Overseas Department of France. Today, tourism on the island takes a variety of forms, from cruise day-stops to sun-sea-sand visitors, ecotourism, and active tourism, although participating in one of these does not necessary preclude one from participating in other activities. As important as tourism is to the economy, other industries also contribute substantially to the local economy, and yet many Guadeloupeans see a need to further develop and diversify their local economy.

10.2 Setting

Guadeloupe comprises over a dozen islands—six of which are continually inhabited. The two largest islands, Basse-Terre and Grande-Terre, remain separated by the narrow Salt River. Basse-Terre hosts more mountains and is larger than its counterparts, even though the name literally means "lowland"—so-named by the French because the settlement of Basse-Terre was located on the leeward side of the mountainous island, which blocked the trade winds coming from the northeast (Rogoziński 1999). Forming the other half of the Caribbean Butterfly, Grande-Terre—though not as large as Basse-Terre—is large in comparison with all other islands under Guadeloupe's purview, including *Îles de la Petite Terre*, or Petite Terre—a two-island archipelago with a combined total area of approximately 1.7 km^2. The larger, southern island is Terre-de-Bas, and the smaller island to the northeast, Terre-de-Haut. While uninhabited by people, the surrounding water serves as a natural reserve for a number of Lesser Antilles Iguanas as well as sea turtle nesting areas (Réserves Naturelles 2016).

To the northeast of the Petite Terre Islands, and due east of southern Grande-Terre, is the inhabited island, La Désirade. The Petite Terre Islands are administratively cared for by the local government (commune) of La Désirade. La Désirade is located 8 km from Grande-Terre. Long and narrow (11 km by 2 km, on average), the island of La Désirade is the oldest part of Guadeloupe with research on the west end of the island and just offshore, indicating rock formation ages of over 140 Ma (Mattinson et al. 1980). La Désirade's major settlement is Beauséjour on the east end of the island. It is connected to Saint-Fraçois on Grande-Terre by ferry.

The third largest island of the archipelago of Guadeloupe is Marie-Galante, located about 26 km south of Grande-Terre and 30 km southeast of Basse-Terre. Ferries connect the island to Point-á-Pitre and Saint-Fraçois on Grande-Terre. The landscape was once dominated by sugar plantations, but the decline of sugarcane production on the island reduced job opportunities, and the population has dropped substantially to ~11,000 in 2012 (INSEE 2015b). One of the Limestone Caribbees, the island is made of limestone deposited, in some cases up to 200 m, on top of volcanic rock (Collina-Girard 2002; Fig. 10.3x).

To the west of Marie-Galante and south of Basse-Terre is *Îles des Saintes* ("Islands of the Saintes," often shorted to "Les Saintes"). Only two of the islands of this archipelago are inhabited by people. Resulting from volcanic activity, some of these islands are so small and located so close to each other that only a few feet of shallow water separate them from another island in the group. Finally, another often overlooked island lies between the northern sections of Basse-Terre and Grande-Terre; Ile à Fajou is an island located in the Grand Cul-de-Sac Marin.

10.3 Landforms

Despite the main islands' closeness—as little as 40 m apart in some sections—Basse-Terre (the western main island) and Grande-Terre are geologically quite different. Basse-Terre and Les Saintes islands are identified with the new or recent arc of volcanic activity aligned with the Volcanic Caribbees. Grande-Terre, Marie-Galante, and the Petite Islands are covered with calcium carbonate and considered part of the Limestone Caribbees, an older arc of volcanic activity, though the entire archipelago is moving at approximately 20 mm a year (DeMets et al. 2000).

Basse-Terre consists of a series of volcanic andesitic massifs (Samper et al. 2007). Generally speaking, on Basse-Terre, the older the massif, the further northwest it is located (Fig. 10.3). Starting from the northwest, the Basil Complex was active between 2.0 and 6.0 Ma. Heading south, the Septentrional Chain, active 3.5–1.15 Ma, covers over a third of the island. The next massif to the southeast is the Axial Chain which was active from ~1.0 to 0.44 Ma. The Bouillante Chain to the west of the Axial Chain hugs the Caribbean coast and was active between 1.2 and 0.9 Ma. The Monts Caraïbes massif is at the southern tip of Basse-Terre and was active between 600 and 400 Ka. North of Monts Caraïbes and south of the Bouillante and Axial Chains is the Composite Volcano of La Grande Découverte (CVGD), a still-active massif of La Grande Soufrière volcano. It has been active from 8.5 Ka to present. Other parts of the CVGD massif have been active for the last 200,000 years (Feuillet et al. 2002, Samper et al. 2007). Traveling from the northwest edge of Basse-Terre toward the south-central part of the island, Basse-Terre's profile increases in height until the highest point, La Grande Soufrière. The northeastern corner of the island is its lowest part, on average (Fig. 10.4).

Basse-Terre's mighty La Soufrière dominates the landscape (Fig. 10.5). The resultant steep slopes created by numerous eruptions and subsequent erosion events has led to steep, almost feral reliefs in some areas. Surrounding La Soufrière is Guadeloupe National Park, which hosts numerous natural features, including geothermal vents, a crater lake (Lac Flammarion, Fig. 10.6), and majestic waterfalls such as those along the Carbet River (Fig. 10.7). Although these types of features remain typical of many Lesser Antillean volcanic islands, what sets Guadeloupe apart is the ability to capitalize on them in terms of

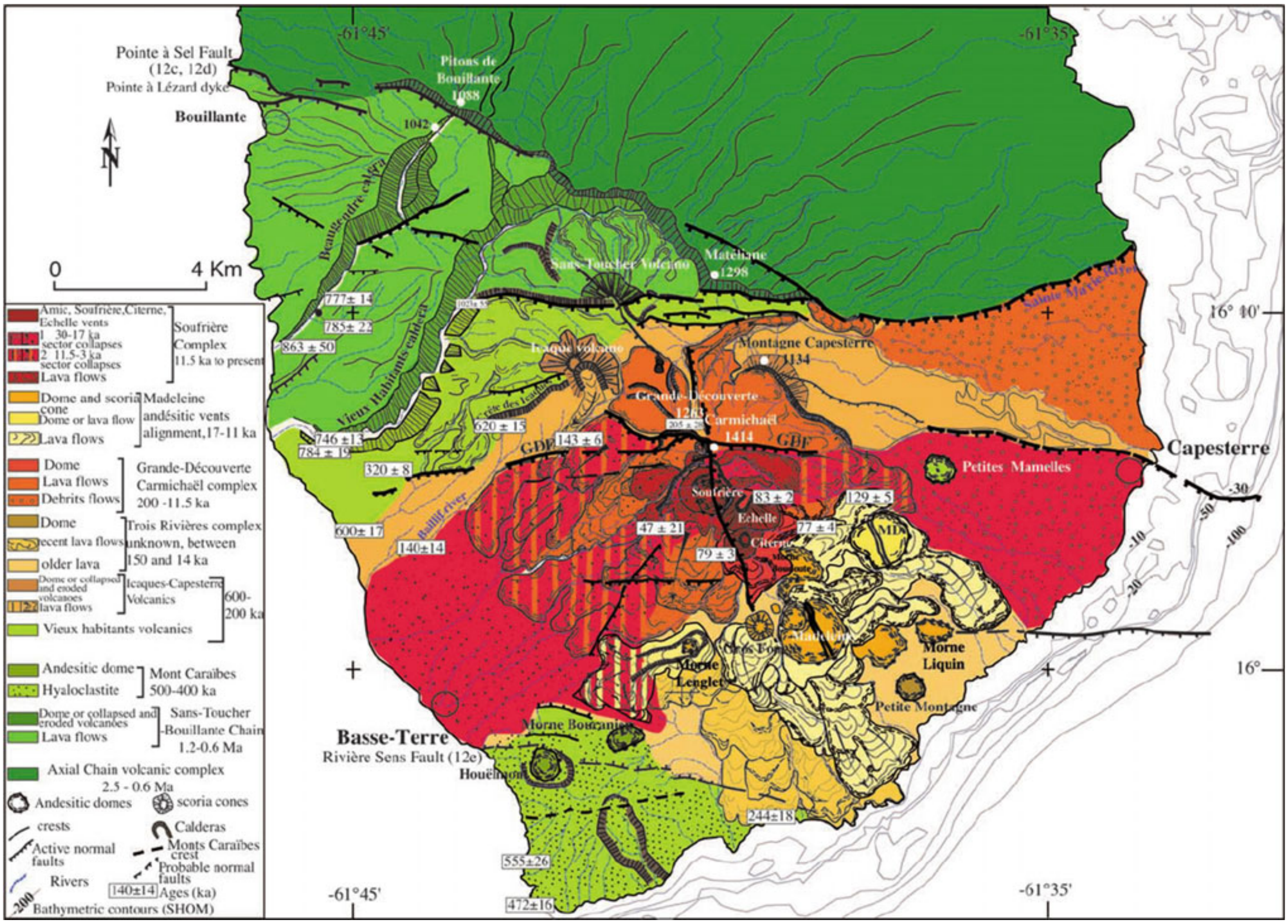

Fig. 10.3 Geological map of the southern portion of Basse-Terre surrounding La Soufrière. Note the general age trends (southeast to northwest, white boxes). Figure from Feuillet et al. (2002), available online at https://www.researchgate.net/publication/228472964_Arc_parallel_extension_localization_of_volcanic_complexes_in_Guadeloupe_Lesser_Antilles, and compiled from various sources

economics (e.g., tourism), protection (national parks and reserves), and energy production (a functioning geothermal power plant; see Jaud and Lamethe 1985).

While not flat, Grande-Terre consists of lower terrain than most of Basse-Terre (Fig. 10.8). The foundational bedrock of the island is volcanic, with the last 5.0 Ma being an active period of carbonate depositing (Cornée et al. 2012). Being at the south end of the eastern arc, Grande-Terre—and Marie-Galante—became inactive more recently than the northern Limestone Caribbees such as Sombrero, Anguilla, and Barbuda (Robertson 2009). On Grande-Terre, Cornée et al. (2012) identified four periods of sedimentary buildup—four unique sedimentary sequences—each of which is separated by a period of subaerial erosion.

Grande-Terre represents one of the major areas of Caribbean karst lands in the Lesser Antilles. On the islands of Guadeloupe, most caves associated with the karst landforms are on or near the coast (Lenoble et al. 2015). Among karst type caves, only one wet cave appears in interior Marie-Galante while two wet caves and one dry cave appear in interior Grande-Terre. The majority of karst caves are on the eastern side of Grande-Terre, and southeastern Marie-Galante (Fig. 10.9), while over a dozen dry caves are on the southeastern two-thirds of La Desirade (Lenoble et al. 2015).

La Désirade on the other hand represents a geologically unique island within the Guadeloupean archipelago (Fig. 10.10). Current understanding about the movement of the Caribbean Plate recognizes that it shifted from the area now associated with the Pacific region (Corsini 2011). Research on rock formations on the east end of La Désirade and just off of its eastern coast dates some of the igneous rocks in that area at over 140 Ma (Mattinson et al. 1980; Mattinson et al. 2008; Corsini 2011). That is, even though the island is overlain by carbonate deposits—a characteristic shared with Grande-Terre and Marie-Galante, two of the Limestone Caribbees—La Désirade reveals its own complex geology and geologic history.

The Grand Cul-de-Sac Marin, a shallow water area with coral reefs, mangroves, and seagrass beds, rests between the northern sections of Basse-Terre and Grande-Terre. This

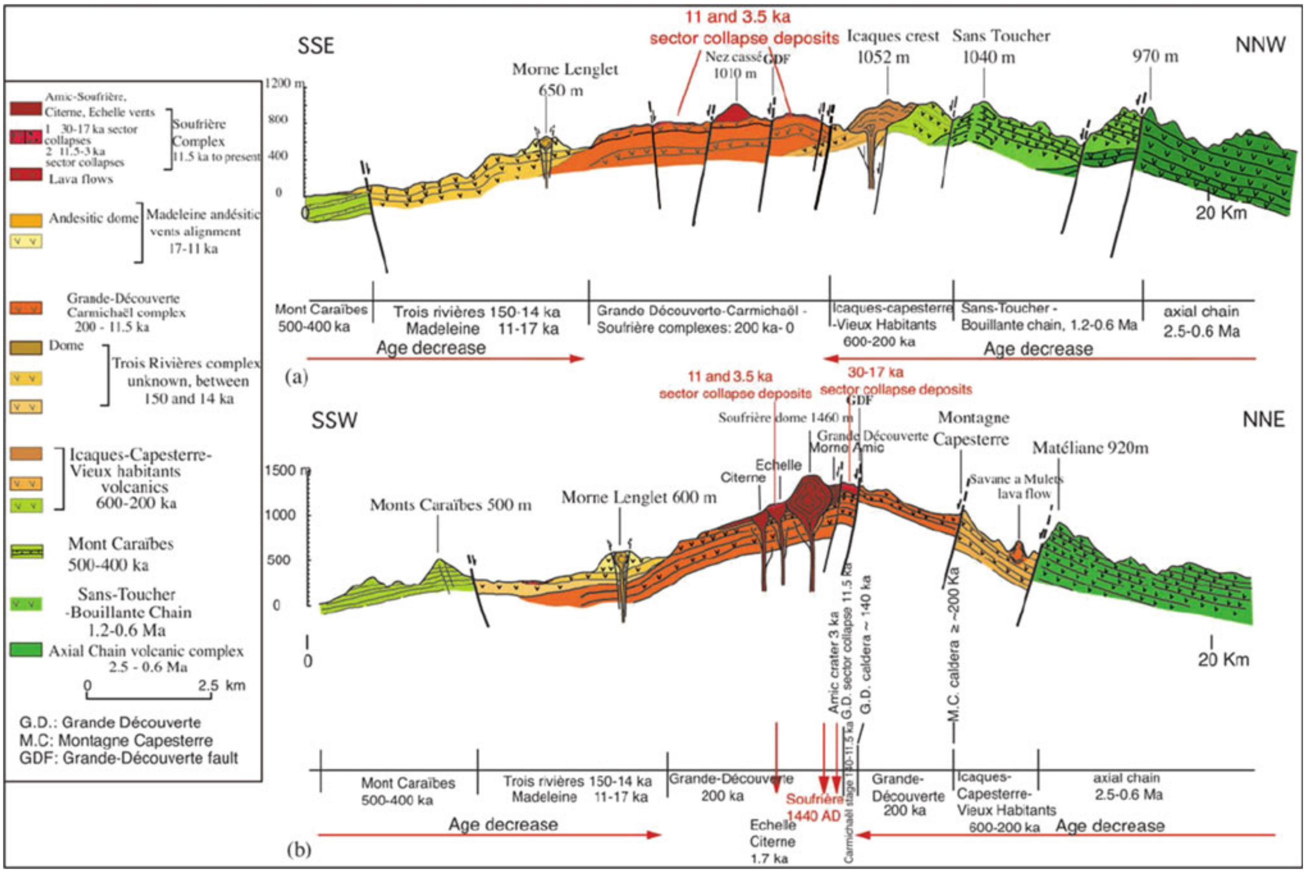

Fig. 10.4 Geological profile of Basse-Terre's southern portion, demonstrating the island's volcanic complexity. This profile runs south–southeast to north–northwest (**a**) and south–southwest to north–northeast (**b**), bisecting approximately 1.2 km south of La Soufrière. Figure from Feuillet et al. (2002), and available online at https://www.researchgate.net/publication/228472964_Arc_parallel_extension_localization_of_volcanic_complexes_in_Guadeloupe_Lesser_Antilles

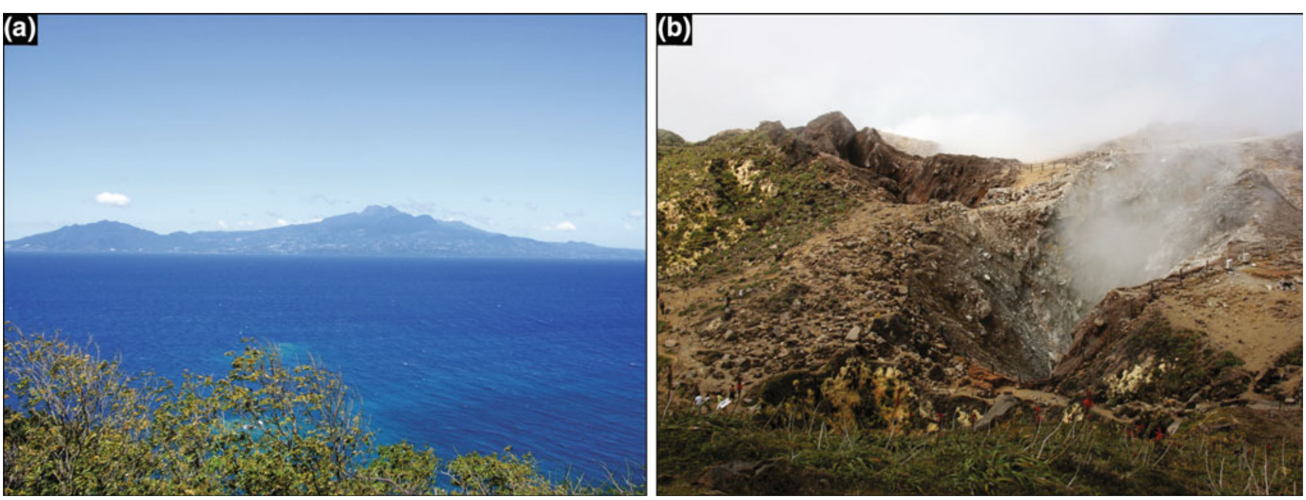

Fig. 10.5 Views of La Soufrière Volcano. **a** Basse-Terre as seen from Les Saintes. La Soufrière, just *right* (east) of center is the highest point. The other peak to the *left* (west) is the Monts Caraïbes massif. Photograph taken by Wikiuser Friman on February 26, 2008. Uploaded to Wikimedia Commons and shared under a Creative Commons License on March 15, 2008. **b** On top of volcano La Soufrière at island Basse-Terre, Guadeloupe, looking toward La Découverte in the direction of Gouffre Tarissan, South Crater. Photograph taken by Wikiuser Miebner. Uploaded to Wikimedia Commons and shared under a Creative Commons License on June 19, 2011. Required tag for both images: http://de.wikipedia.org/wiki/Benutzer:Miebner

Fig. 10.6 Lake Flammarion in Guadeloupe National Park, a crater lake filled by rainfall, approximately 1.2 km southeast of La Soufrière. Though a volcanic island, Basse-Terre has few such lakes, most likely due to its rugged topography. Image courtesy of Guadeloupe National Park: http://www.guadeloupe-parcnational.fr/fr/galeries-photo/paysages-de-la-guadeloupe

area contains mangroves known to exist for at least two millennia (Lallier-Vergés et al. 2008). Within this broader ecological zone are numerous smaller zones with species of flora and fauna that are sensitive to changes in salinity. Sea level rise will be a challenge for this area causing changes in the chemistry across this bay and wetlands. Because of the environmental sensitivity of this area, further research is needed to understand how this region in general will react to sea level rise and climate change, as well as how incremental changes in one smaller area will affect neighboring areas.

10.4 Landscapes

Like all of islands in the Lesser Antilles, there was a sense of both crossroads and destination for many of the early peoples to Guadeloupe. Early native people migrated to and through the territory prior to 2000 BCE (Higman 2011), but archaeologists have not found much evidence of these peoples' existence in Guadeloupe prior to 300 BCE. When Columbus met the Caribs in Guadeloupe, they lived in small communities of 20–30 houses situated around a central square and buried their dead in ways that reveal cosmic beliefs and the existence of an afterlife and respect for ancestors (Rodríguez 1997). By the time of Columbus' second voyage, Caribs lived on parts of Guadeloupe–the double island had fresh water, and the Caribs were most likely in regular contact with other Caribs and native people elsewhere in the immediate and larger Caribbean world.

The French colonized Guadeloupe in 1635, not only encroaching on land first settled by native peoples, but also taking food from them. The ensuing violent struggle for the islands of Guadeloupe costs many French and Amerindian lives, culminating with the confinement of Caribs to the mountainous section of Basse-Terre in 1641, and eventually

Fig. 10.7 The third waterfall along the Carbet River, which begins on the lower slopes of La Soufrière, and flows in a southerly direction. A popular tourist attraction in Guadeloupe National Park, this series of three falls (125, 110, and 20 m high, respectively) traverses the rugged rainforest and volcanic terrain, decreasing in height as the river makes its way to the sea. Image courtesy of Guadeloupe National Park: http://www.guadeloupe-parcnational.fr/fr/galeries-photo/paysages-de-la-guadeloupe

allowed or forced to migrate to Dominica and/or St. Vincent (Pons 2013; Watts 1987). Meanwhile the French started growing their tobacco-based colony, switching to a sugar-dominated colony a few decades later (Dunn 2012). The few thousand Europeans were soon joined by tens of thousands of enslaved Africans whose work made the island one of the French Sugar Islands (Curtain 1969). Clearing the land was a key requirement of sugar cultivation, and even more pressure was put on the original forests as wood was initially used as fuel for sugar refining—a practice the French quickly discouraged before denudating the landscape permanently (Watts 1987).

Following a false abolition period from 1794 to 1802, a drop in sugar production occurred alongside many slaves entering the field of piracy (Rodigneaux 2015). Still, after this period, sugar planters resurrected their business with the import of thousands more indentured servants (Northrup 2000). By 1900, the indentured system came to an end, and fields began to fallow. By World War II, fallow land was seen not as resting and regenerating land for future exploitation, but as unpatriotic. The Vichy representatives on the island pushed for extracting food from everywhere on the island, even while many Guadeloupeans suffered from hunger (Jennings 2001).

Fig. 10.8 A view along Grande-Terre's coast from Anse-Betrand cliff in the far north, demonstrating its lower relief in comparison with Basse-Terre. Image courtesy of Guadeloupe National Park, available online: http://www.guadeloupe-parcnational.fr/fr/galeries-photo/paysages-de-la-guadeloupe

Since then, the Department of Guadeloupe has made major changes to the landscape. The international airport, Pointe-à-Pitre Le Raizet, was designed to handle a much higher volume of air traffic than it does, in hopes of expanding tourism options. Pristine beaches and a range of hotels dot many of the islands, and modern, paved roads are often crowded with vehicles. Agriculture still represents a significant portion of the economy and continues to shape the landscape. Offshore, large parts of the water between northern Basse-Terre and Grande-Terre are preserved as the Grand Cul-de-Sac Marine Nature Reserve, while additional land in central Basse-Terre has been set aside as a national park. Many of the past landscape moments are still reflected in areas as relict or historic landscapes and often serve as touchstones for memory and heritage on the island.

10.5 Heritage and Tourism

While heritage and tourism are often connected, heritage goes beyond history by making personal and emotional links to the past, considered unique to the social group. But they can become tools for tourism promoters to market to outsiders. This commodification of the past (and heritage sites) over time can become contentious, where some locals feel that their heritage is being cheapened, while visitors might not understand the full value and deep meaning of these past moments, events, and locations to the local population (Compare Nuryanti 1996 for some of the issues associated with the relationship between tourism and heritage).

Fig. 10.9 Limestone features in Saint-Louis de Marie-Galante, Guadeloupe: Gueule Grand Gouffre, a geomorphological complex including a littoral chasm (from a roof collapse) and a natural arch (bottom-center of image). Sometimes called "Trou a Diable," this coastal sinkhole is a popular tourist destination. The trail/road leading to the viewpoint is visible along the northern rim of the chasm. Photograph taken by Wikiuser: Thesoulfulwriter. Uploaded to Wikimedia Commons and shared through a Creative Commons License on January 5, 2009

10.5.1 History and Heritage

For Guadeloupe, initial Columbian contact occurred from 3 to 10 November 1493, on Columbus' second voyage. He did not leave settlers to colonize the island, but over the next century, Europeans stopped for water from the islands after crossing the Atlantic and for occasional slave raiding of the Caribs (Delpuech 2011). In 1635, the French created a settlement with 550 settlers led by Charles Lienard and Jean Duplessis Ossonville (Pendery 2010). Sick, hungry, and viewing the natives' lives as of less value than their own, some of the French followed Governor Liénarde's advice and started raiding the Caribs gardens and reserved food stores (Boucher 1992). The French and the Caribs fought over the island for four years, with the French finally prevailing by the addition of French soldiers from St. Christopher in 1640 (Boucher 1992).

By the beginning of the eighteenth century, Guadeloupe made the transition from an uncertain business interest of a few French citizens to a colony of the French King (Higman 2011). It also transitioned from a society with slaves to a slave society (Curtain 1969). During the mid-eighteenth century and into the early nineteenth century, Guadeloupe was captured by the British from the French a number of times, and also spent 15 months in Swedish hands—though largely in name only as British governors remained as administrators (Tingbrand 2002). In 1794, the French government decreed that slavery was abolished in all colonies, only to have that decree reversed in 1802 by Napoleon—who was married to a Martinican planter's daughter (Bélénus 2015). When the news reached Guadeloupe, the once-enslaved population did not allow themselves to so easily be subjugated again. Napoleon sent troops to Guadeloupe who killed thousands of free Blacks who refused to be re-enslaved. Instead, they chose to fight until their deaths (Bélénus 2015). Still slavery was violently reinstituted on the island and would not be abolished until 1848.

Many formerly enslaved people started subsistence farming, building their own homes on land that they worked for their own needs (Fig. 10.11a). Planters continued to use coercive labor, importing indentured servants from West Africa, Vietnam, China, and India (Northrup 2000). By

Fig. 10.10 View of La Désirade (Background, left of center) from the east coast of Grande-Terre, Guadeloupe. The small island, only 2 km by 11 km, is dominated by its distinctive central plateau and unique geology. The white sand beach and sea stump in the foreground are indicative of the picturesque coastal landforms found on many of Guadeloupe's islands. Photograph taken by Wikiuser: Jayen466 on August 22, 2007. Uploaded to Wikimedia Commons and shared through the photographer releasing it to the public domain on January 12, 2009

1900, the indentured servant system was almost over, though Guadeloupe was still a colony of the French with an economy based on exporting agricultural crops such as sugar, pineapples, and bananas (Fig. 10.11b). During the first half of the twentieth century, agriculturally the economy was reconfiguring of toward Guadeloupean food self-sufficiency by leaving no field fallow (Jennings 2001).

While Guadeloupe was declared an Overseas Department shortly after World War II—like Martinique, French Guiana, and Réunion—its citizens' relationship with Paris unfolded in different ways than the other Overseas Departments. In some ways, Guadeloupe and Martinique shared important moments in history because of their close geographic relationship and because Guadeloupe was administered through Martinique for much of its colonial history. Recently, Guadeloupeans have been more vocal about their economic difficulties, and on January 20, 2009, forty-eight organizations came together under the name Lyannaj Kont Pwofitasyon (LKP) and listed 165 demands that included a 200-euro per month increase in pay for those working at minimum wage (Bonilla 2009). Though not seen as a colony in the eyes of the French government, the insular economy of Guadeloupe is unlike the economy of Continental France. Because of the cost of importing goods, taxation, and limited competition in certain industries, items in Guadeloupe can cost 20–170% more than in Metropole France (Bonilla 2009). Bonilla's (2009) report on the strike reveals not only just how workers in Guadeloupe got important concessions, but also exposes the struggle between those running small and large businesses on the island. Large employers refused

Fig. 10.11 Historic postcards displaying the lives of freed slaves in Guadeloupe. **a** Title: Guadeloupe—Cabane d'Indiens. Postcard was created prior to February 1907. Images like these show how some Guadeloupeans were forced to live around the turn of the twentieth century. This image should be considered with a critical eye, as the assumptions that images like this encourage the viewer to make tell more about the viewer than the lives of those pictured in the image (Modlin, 2015). This is an unused postcard from the author's personal collection. **b** Title: Compagnie des Antilles.—Propríetaire de la marque Rhum Chauvet. (English: "Company of the Antilles—Owner of the Rhum Chavet brand") Bottom text: 54—Récolte d'ananas à la Guadeloupe (English: "Pineapple harvest in Guadeloupe"). Image shows workers harvesting pineapples. Photograph taken prior to December 1915. This is an unused postcard from the author's personal collection

to negotiate with the strikers, but the UCEG, "which represented smaller, local Guadeloupean business owners" stepped forward and used the chance to challenge the dominance of businesses owned by the white elites (Bonilla 2009:10). On March 4, 2009 a final agreement was signed for Guadeloupe.[1]

[1]Other Overseas Departments followed Guadeloupe's lead. Martinique signed an agreement on March 11, 2009. Réunion had labor unrest shortly afterward and a general strike also occurred in France starting March 19, 2009 (Bonilla 2009).

10.5.2 Tourism

For many of the islands in this volume, tourism remains a staple in their economies. This often means either attracting more tourists, or getting them to stay longer. As a commodity—what the tourism experience is—there are few ways to make attractions fit a solid cost-benefit model. In the Caribbean, many islands compete for the same set of tourists. Guadeloupe, like other Lesser Antillean islands, benefits in a number of ways from longer-staying tourists: More money is spent, a greater respect for the environmental impact can be engendered in tourists, and some of these tourists will move away from the high-volume tourism areas, spreading out the possible economic benefits of their visits. In places such as Marie-Galante, Les Saintes, and La Désirade, longer stopovers are a necessity, as just getting to those islands can be an ordeal requiring arriving by air to Point-á-Pitre, clearing the airport, getting transportation to the appropriate ferry dock, and then continuing on to the destination hotel on one of these islands. Finding a balance of locals' and tourists' needs and wants will probably be one of those issues constantly under negotiation.

Still, Wong (2015) makes a strong argument that Caribbean tourism can repeat colonial exploitation, as many of the jobs created are low-wage jobs employed by multinational hospitality companies that pressure islands to keep minimum wages low to boost their own profits. However, tourism is now such a significant part of many Caribbean economies that major changes in its role locally need to be thought through with solid plans about what will replace it. This is true of Guadeloupe. Over 100,000 cruise tourists visited Guadeloupe each year between 2009 and 2011, and over 150,000 cruise tourists each year in 2012 and 2013, but in most instances, these tourists stay for less than 24 h (Table 10.1). However, "stopover tourism" in Guadeloupe, while showing some reaction to European financial issues, is interesting, especially when compared to other places in the Caribbean. For example, French tourists, who make up between 70 and 80% of the tourists to Guadeloupe tend to take longer vacations than tourists from other countries, and this potentially affects the number of days on average that a stopover tourist spends in the Overseas Department. According to UNWTO (2015), however, stopover tourists on average spend between 13 and 14 days in Guadeloupe. Yet, it is at this point that a qualification has to be made about these data. Five years of data are not enough to project the direction of trends.[2]

Cruise ship tourism, while bringing in hundreds or even thousands of tourists at once, does not necessarily contribute large amounts of income per passenger to the local economy. Part of this is because tourists have the choice to eat on the ship or the island, to wander the island on their own, or participate in prepackaged shore excursions arranged by and paid for through the cruise company. Additionally, many tourists return home via airlines from the cruise's final destination with weight limits on what they can carry home in their bags, thus limiting what they purchase at each stop. Further, ports of call compete with each other, and cruise companies can decide to stop visiting a port for reasons ranging from simply trying a new destination or concern over port infrastructure to perceptions of tourists about the value or safety of certain places. Generally, but not always, negative events such as unrest or local violence can cause a drop in the number of ships that visit a port one to two years later.

Tourism also remains susceptible to macroeconomic events, such as political upheavals or financial crises, and these undoubtedly affect the number of cruise passengers and stopover visitors to Guadeloupe. The twentieth century found Guadeloupeans still in the midst of international political, ideological, and economic forces, leading to challenges that revolve mainly around tourism at the human–environment interface. With a population of 400,000—and another 400,000 or more stopover visitors and dozens of cruise ships stopping annually—for example, plenty of challenges remain, such dealing with waste disposal and fresh water consumption. As one of the larger, more spread-out territories of the Lesser Antilles, Guadeloupe also encourages an increase in car ownership and rentals, leading to potential pollution problems.

10.6 Hazards

Like other Lesser Antillean islands, Guadeloupe is at risk of a number of hazards including hurricanes and other tropical storms, volcanic eruptions, earthquakes, tsunamis, and longer-term hydrologic and climatic changes such as sea level rise. The following subsections focus on how each of these has, and potentially will, affect the Guadeloupean islands.

10.6.1 Tropical Storms and Hurricanes

Hurricanes and tropical storms have struck or brushed the Guadeloupean islands dozens of times since the first European settlement. Just since 1851, over three dozen tropical storms or hurricanes have grazed or crossed part of the group of islands that make up Guadeloupe[3] (NOAA 2016). Some of these storms have caused significant damage and loss of life. The "Great Hurricane" of 1928 claimed 1200 Guadeloupean lives, and a hurricane in 1776 killed over 6000

[2]Despite searching through numerous sources, the only reliable data of tourism numbers for Guadeloupe are from the UNWTO. These data were limited to the years between 2009 and 2013, and the detailed report that the UNWTO produced for Guadeloupe contains significant gaps.

[3]Thirty-seven tropical storms or hurricanes have come within 70 km of Pointe-à-Pitre. This radius includes all of the territory of the department without including neighboring islands. As such some larger storms have had effects on the island such as storm surge, wind, or excessive rainfall events. As an example, Hurricane David in 1979 passed south of Dominica but was close enough to the island to caused major damage in Les Saintes, Marie-Galante, and Basse-Terre with crop damage estimated at over $100 million (NOAA 2016; Lawrence 1979).

Table 10.1 Estimated number of tourists (Stopover) by year. Data from United Nations World Tourism Organization (UNWTO 2015). Data for all years of cruise passenger arrivals and Overnight Stopover tourists for 2011 and 2012 rounded to nearest thousand by UNWTO

Year	Total overnight stopover tourists	Total cruise passenger arrivals
2009	346,507	111,000
2010	392,282	105,000
2011	317,000	102,000
2012	325,000	162,000
2013	487,416	158,000

Table 10.2 Significant Earthquake recorded events in Guadeloupe since 1690 with a Mercalli Intensity of IV or higher (Most Data from Dorel 1981: 694)

Date earthquake was felt in Guadeloupe	Mercalli intensity
April 5, 1690	IX
January 11, 1839	VI
February 8, 1843	IX
May 16, 1851	VII
April 29, 1897	IX
December 25, 1969	VI
October 8, 1974	VII
November 21, 2004	VIII*

Understanding the differences in Mercalli Intensity, the rating of VIII applies to the island of Terre-de-Bass, Les Saintes. It would be lower on parts of Basse-Terre. However, the magnitude was still M_w 6.3
*Intensity of VIII is based on magnitude and reports of damage in Les Saintes on November 21, 2004. This intensity would be lower in Basse-Terre, the capital and even lower in Point-á-Pitre

(Lawrence 1979; NHC 2005). Tropical storm activity does not have to directly “hit” the islands of Guadeloupe for there to be a substantial impact. For examples, Hurricane David destroyed the banana crop on the island, although the eye of the storm passed south of Dominica and west of Guadeloupe causing substantial damage to crops on the islands.

The introduction of more reliable, satellite-based tropical storm tracking and warning systems have substantially reduced the likelihood of extreme human casualty numbers, allowing people time to prepare and occupy more durable structures which are not likely to be destroyed by high winds or flooded by storm surge and high waves. Yet, this does not eliminate the potential damage to agriculture, nor do such warning systems reduce the likelihood or volume of landslides. For example, Tropical Storm Helena in October 1963, caused over 250 landslides of various sizes along the steepest slopes of the interior of Basse-Terre, mostly centered around the watersheds of Beaugendre, Vieux Habitants, Capesterre, and the upper parts of Bras-David and Goyave (Allemand et al. 2014). Allemand et al. (2014) extrapolated that this one extreme meteorological event caused a denudation rate of roughly 1.6 mm averaged over the few days, spread across the affected watersheds—the same amount of erosion that would take four to twelve years on average without extreme meteorological events in these watersheds (see also Le Bivic et al. 2014).

10.6.2 Volcanic, Seismic, and Tsunamic Activity

While each Guadeloupean island consists of base volcanic rock, today only La Soufrière on Basse-Terre is considered active. The volcano has erupted eight times since French settlement in 1635 (Global Volcanism Program 2013), most recently in between July 8, 1976 and March 1, 1977. This eruption period led to the evacuation of the Guadeloupean capital, and second largest city, Basse-Terre, as well as surrounding areas that ultimately displaced over 72,000 people for a few months (Fiske 1979). Even with better monitoring and advances in understanding of volcanos in general—and La Soufrière in particular—there are still risks, such as people settling a mere 2.5 km from of the summit.

Lying along and near many faults, each of the islands also remains susceptible to damage from earthquakes, recorded as far back as April 5, 1690 (Table 10.2). A relatively recent earthquake in Guadeloupe occurred on November 21, 2004. With the epicenter located approximately 15 km southeast of the Les Saintes archipelago, it killed a five-year-old girl in Trois-Rivières in southern Basse-Terre Island and injured one other person on Basse-Terre and ten people on the Les Saintes’ island of Terre-de-Bas (Nikolkina et al. 2010; Zahibo et al. 2005). Numerous buildings were severely damaged and destroyed on Terre-de-Bass and in Trois-Rivières, and the damaging effects were noted in

Portsmouth, Dominica (25 km from the epicenter), and Pointe-à-Pitre (65 miles from the epicenter). The most intense seismic events do not demonstrate a regular frequency, partly because the study of earthquakes in Guadeloupe is based on fairly short mechanically captured seismic histories and fairly recent historical records.

Connected to earthquakes and volcanic activity, Guadeloupe has experienced a number of tsunamis in its recorded history. Rogers et al. (2013) describe a number of factors that influence the likelihood and height of tsunamis. In researching for a predictive model of the tsunami that could have been felt after the February 08, 1843 megathrust event, the authors noted that while the earthquake was quite destructive on parts of Guadeloupe and recorded in historical records, they did not find anything in historical records about an associated tsunami. More recent events like the 2004 Les Saintes earthquake and three pyroclastic flows from nearby Montserrat reaching the sea (1997, 2003, and 2006), however, propagated one- to two-meter-tall tsunamis. Researchers indicate that distance from seafloor to sea surface, reefs, approaching direction of a particular tsunami, and even the locational relationship of some of the smaller islands of the Guadeloupean archipelago have significant influence amplifying or mitigated the damaging effects of a major tsunami (Rogers et al. 2013). This does not mean that tsunamis are insignificant events, as even the November 21, 2004 Mw 6.3 earthquake caused an 80-cm drop and 70-cm rise, which created a significant amount of water force striking the coast (Zahibo et al. 2005).

10.6.3 Hydrologic and Climatic Hazards

Research indicates that sea level rise and climate change are no longer processes predicted for the future. Evidence indicates that for decades, ocean and sea levels have risen and that this will continue to do so for at least the rest of this century. The rising levels of the major saltwater bodies of the Earth, like the Caribbean Sea and Atlantic Ocean, are due, at least in part, to anthropological forces such as major deforestation—often through burning—and the use of carbon-based fuels, leading to climate change on a global scale.[4] Understanding the full effects of climate change in a particular area requires a deep understanding of the global, regional, and local atmospheric, geologic, and hydrological processes.

Sea level rise (SLR) cannot be ignored on Guadeloupe and its many islands, but its effects will not be evenly distributed. Like some other Caribbean islands, Guadeloupe has a large population with a significant tourism industry that is, in part, based on its sea resources—beaches, food, and hospitality venues, as well as coral reef diving and mangrove habitats. Scott et al. (2012) predict an SLR range of 18–59 cm between 1900 and 2100, noting SLR does not follow a global pattern, but that the Caribbean in general will experience it more dramatically (Compare Tamisiea and Mitrovica 2011). While trying to understand all of the processes associated with sea level rise and attempting to predict it, these numbers—as small as they seem—will affect mangroves and coral reefs causing damage in some areas that will remove or degrade some of the coastal protections from which the islands of Guadeloupe have benefited. The damages of SLR can include saltwater intrusion, beach erosion, and even the endangerment of seaside buildings and infrastructure (Scott et al. 2012).

Just as the effects of SLR will vary from location to location, so will the effects of climate change, especially in terms of Guadeloupe's karst landscape. As a dissolutional landscape, karst regions remain at the mercy of precipitation. As precipitation increases, so does erosion in karst landscapes, beginning slowly, but eventually giving way to collapse (e.g., Fig. 10.9). Day (2010) notes that not only will climate change affect Caribbean karst landscapes, but the eroding landscape will, eventually, also affect biological systems as well as social and economic systems. Thus, climate change will have an impact on the broader set of processes of environmental change. Scientists expect biodiversity to decrease (May 2010). The acceleration of karst damage will affect karst hydrology with the potential for more seasonal flooding and prolonged drought (May 2010). The cause of the more frequent dry season drought will be due to a reduction in soil moisture budgets, with soil having more difficulty holding moisture for longer periods of time. Collapsing stone deposits and the denuding topsoil due to increased flash flooding—events that start and end quickly, yet are devastating when they occur—can also open up points of quick infiltration of water into the local water tables. Rapid infiltration of water into subterranean water conduits makes these karst water sources vulnerable to pollutants, including biological contaminants such as microorganisms.

10.7 Conclusion

Geologically, Guadeloupe remains representative of the Volcanic Caribbees and the Limestone Caribbees, as well as an older, Late Jurassic igneous formation on the eastern end of the easternmost island La Désirade. Traveling from east to west, the island group as a whole becomes more mountainous with the active volcano, La Soufrière at 1467 m,

[4]The use of the concept "climate change" is intentional. It recognizes that in some areas temperature might actually decrease as well as major changes in other climate factors such as rainfall, air quality, and power and direction of ocean currents.

serving as the highest point not only in Guadeloupe, but also in the entire Lesser Antilles. The main island of Basse-Terre with its mainly volcanic landscape sits juxtaposed next to Grande-Terre that, while also relatively flat, contains older volcanics overlain by more recent, thick lithologies of limestone. The other dozen or so inhabited islands that comprise Guadeloupe remain just as varied geologically as the two main (and much larger-in-size) islands: some igneous, others limestones, and varying in age from Late Jurassic to recent volcanic eruptions.

Humans visited Guadeloupe as early as 2000 BCE, and numerous Amerindian migrations occurred before Columbus sighted Guadeloupe in November 1493. In the late 1630s, hundreds of French Colonists arrived with the intention to exclusively exploit Guadeloupe, a goal they achieved barely a decade later. Tobacco farms gave way to sugar plantations in the late seventeenth century, and hundreds of thousands of enslaved Africans were imported to transform the landscape. Even after emancipation in 1848, tens of thousands of additional indentured servants were brought in over the next fifty years (Northrup 2000).

Tourism and agriculture represent important industries in Guadeloupe today, but there is still a need to further diversify the economy. While hundreds of thousands of tourists visit Guadeloupe's intriguing landscapes each year, it hosts a multibillion dollar agricultural sector. Yet, tourism and agriculture have not led to strong employment on Guadeloupe's islands. Even many of the residents who do work, find it difficult to live because the cost of living is so high, even though, along with Martinique, Guadeloupe retains the highest income for minimum wage workers in the Caribbean. These economic difficulties will remain a challenge facing Guadeloupe into the foreseeable future. Even among the young adults who doubtlessly feel the pull to places where they might have better economic opportunities, some return after getting their college degrees in Metropole France with the determination to help Guadeloupe meet its challenges in the future.

Though susceptible to common Caribbean island hazards (e.g., hurricanes, volcanic eruptions, tsunamis, and sea level rise), Guadeloupe remains a geomorphologically varied island. Visitors can encounter any number of landforms and resultant processes by taking a short walk from any of the main towns. Guadeloupe's complex geology yields many types of distinct volcanic, karst, and coastal landforms: from abundant geothermal springs, steep-relief slopes, and tall waterfalls to dolines, sea arches, and crater lakes. Indeed, when it comes to breadth of landform type, Guadeloupe may be one of the most varied in the Caribbean. Hopefully, its natural beauty continues to inspire researchers in the coming decades, to help more fully understand its geomorphologic diversity.

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Dominica

11

Vanessa Slinger-Friedman

Abstract
Located along the eastern boundary of the Caribbean Plate, Dominica is one of the most volcanically active countries in the Caribbean. Its volcanic nature results in a rugged mountainous landscape that is lush and fertile and creates the backdrop for a rich biodiversity of plants and animals. Dominica, with its mountain peaks, subaerial volcanoes, crater lake, coastal dike, and numerous rivers, has been shaped over millions of years by volcanic and hydrological processes, which have built up and worn down the island, respectively. Dominica's physical geography played a role in helping the native Carib Amerindians resist European colonization, and today contributes to Dominica's economy by supplying the landscape for the agriculture, fishing, and tourism that takes place on the island. Dominica's economy and parts of its culture are a reflection of its landscapes and landforms. Conversely, the influence of various cultures and economic activities on Dominica is reflected in impacts on the geomorphic landscape.

Keywords
Dominica • Volcanic • Biodiversity • Caribs • Ecotourism

11.1 Introduction

Dominica, the largest and northernmost Windward Island in the Caribbean, is located in the central Lesser Antilles (Fig. 11.1). The volcanic nature of this island means that it is replete with high, rocky coasts and a mountainous spine, peaked by the highest mountain in the eastern Caribbean, Morne Diablotins (1447 m). At least 60% of the island is covered in slopes of 30° or more. There are clear signs of geologically recent volcanic activity on Dominica, including hot springs, the warm bubbling waters of Champagne Beach, and the famous flooded fumarole known as the "Boiling Lake" in the Valley of Desolation (Caribbean Geology 1994).

While its 92 miles of coastline provides Dominica with domestic fishing grounds and some offshore reefs, the volcanically based, fertile mountainous interior of Dominica is covered by dense rainforest, which incorporates 60% of the island (Fig. 11.2). This forest and some of its inhabitants are protected by three national parks. The southernmost park, centered on Morne Trois Pitons, a UNESCO World Heritage Site, is considered to be one of the richest biodiversity spots in the Caribbean. The combination of steep terrain and high annual rainfall across the island provides the conditions for numerous rivers, streams, and waterfalls.

When Christopher Columbus tried to describe Dominica's appearance to the King and Queen of Spain, he supposedly threw down a piece of crumpled parchment to indicate its many mountains and rugged nature (Fig. 3.3; "Dominica" New World Encyclopedia 2013). The Caribs, the indigenous people residing on the island at the time of Columbus's arrival, had

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Fig. 11.1 General physiographic map of Dominica. Note the complex topography and various volcanic peaks positioned along a central mountain ridge that runs the length of the island. Cartography by K.M. Groom

Fig. 11.2 Hills of Marigot in the northeast of Dominica as seen from the air. These densely vegetated hills represent the rugged and forested landscape that dominates Dominica. Photograph by V. Slinger-Friedman

named the land "Wai'tukubuli" meaning "tall is her body" (Honychurch 1991). By the 1700s, control of Dominica changed hands from the French to the British, and the Caribs on the island were the only remaining indigenous group living in the Caribbean. Today, they live as a community on a 3700 acres (1500 hectare) mountainside reserve on the northeast of Dominica (Slinger 2000).

Dominica's economy has been dependent on agriculture, particularly bananas that thrive in the fertile volcanic soils. More recently, cruise ship tourism and ecotourism are the main drivers of Dominica's economy. Dominica's rugged landscape and volcanic black sand beaches deterred the creation of a traditional three "S"—sun, sea, and sand—mass tourism on the island. Instead, in the 1990s, the Dominican government began to focus on its varied and distinctive landscape, tropical vegetation, and unique cultural groups to develop Dominica as an ecotourism destination. Both agriculture and tourism have been adversely affected by the hazards of hurricanes.

11.2 Setting

11.2.1 Dominica's Interior

Dominica, and nearby Martinique and Guadeloupe, all have areas greater than 750 km^2 and lie at the center of the Lesser Antilles western, and geologically younger, Island Arc (Steiner 2003). Dominica was created starting with volcanic eruptions along the eastern margin of the Caribbean Plate. With the exception of some sedimentary rocks and corals along its west coast, Dominica is predominantly made up of andesite and dacitic volcanic rocks (DeGraff 1998). Rocks from three different periods or arcs—Miocene, Pliocene, and Quaternary—compose Dominica (Smith et al. 2013). Now deeply decayed, the oldest Miocene rocks, dating between 6.92 and 5.22 million years ago (Ma), form the basal portion of the island and are found along the eastern Atlantic coast (McCarthy et al. 2005). A huge stratovolcano, named the Cochrane-Mahaut Centre, was formed out of lava and ash during the Pliocene. This landform has eroded over time and now exists as remnants in the form of the mountain peaks of the south central part of the island (including Morne Cabrits Marons, Morne Cola Anglais, Deux Saisons, Morne Boyer, Morne Couronne, and Morne Negres Marrons). Further to the center and north, there are the highly dissected remnants of other Pliocene (2.83 Ma) volcanoes, including Morne Espagnol and Pelean, which are associated with Pliocene activity at Morne Diablotins. These areas of Pliocene rocks do not experience seismic or geothermal activity and are considered unlikely to become volcanically active again.

Older Pleistocene rocks and volcanoes are located in the north of Dominica, some built upon a Pliocene rock base. Examples of these areas include the peninsula of Morne aux Diables and the largest volcano on the island, Morne Diablotins. Seismic activity in these areas indicates that there is the possibility of future eruptions. However, about 1 Ma ago during the younger Pleistocene period, the center of volcanism switched to the south of Dominica with six major active volcanoes, including Morne Trois Pitons, Wotten Waven, Watt Mountain, Grand Soufrière Hills, Morne Anglais, and the Plat Pays volcanic complex. The youngest dated volcanic deposits on Dominica are on the large dome of Morne Patates, which is associated with the active Plat Pays Volcano (Roobol, J, and Smith, n.d.). Also active in the south is the Valley of Desolation, a major geothermal area. Steam explosions, or phreatic activity, last took place here in 1997. Dominica has nine active subaerial volcanoes, each with its own radial drainage system; however, it has not experienced a major magmatic eruption since the eruption of Morne Patates about 500 years ago (Steiner 2015). For this reason, Dominica has well-preserved tropical rainforest. Currently, the volcanoes in the south of Dominica are linked with geothermal and/or seismic activity and are considered likely to erupt again (Roobol and Smith, n.d.). This causes some concern since Roseau, the country's south-based capital, lies in the potential path of pyroclastic flows from the Wotten Waven caldera on its eastern side (Fig. 11.3).

11.2.2 Dominica's Coastal Setting

Dominica's coastal shelf is narrow, measuring less than 1 km wide in parts. Its narrow, stony, or black sand beaches exist mainly in embayments, separated by lengths of steep cliffs. Embayments on the south and west of the island generally have straight sections (Fig. 11.4). Comparatively, embayments on the north and east sides are more indented (Cambers 1996). There is an area of coral sand and volcanic sand beaches on the north coast between Hampstead and Woodford Hill. A narrow coastal shelf and the impact of fluvial sediment outfall from its many rivers limit Dominica's environment for reef development (Steiner 2003). The distribution of the island's reefs has been significantly influenced by the northeast trade winds and the impact of storm-induced waves. The eastern, windward side of Dominica lacks a wide island shelf and protective structures such as barrier reefs, and also experiences turbulent waters and the full force of Atlantic waves (Fig. 11.5). As a result, there is a contrast between the sessile communities on the windward and leeward (western) side of the island. The eastern side of Dominica has only a few coral reefs that can be found in north-facing sub-bays that give protection from the Atlantic's waves. The larger reefs exist on the calmer, southwestern section of the leeward side of Dominica, in areas with wide coast shelves and in some of the bays along the north coast (Steiner 2015).

Overall, the island is characterized by high-relief terrestrial topography such as domes, peaks, and ridges along with a narrow sublittoral zone. The country's central spine is a northwest–southeast axis of steep volcanic slopes and deep gorges with an elevation that varies between 300 and 1400 m. The narrow coastal plain is studded with sea cliffs, and typically has narrow volcanic stone or black sand beaches with limited development of coral reefs.

11.3 Landforms

11.3.1 Terrain Features

Many of Dominica's landforms relate to its volcanic nature. The interior of Dominica features rugged mountains and ridges, many of which are volcanic, the highest of which is Morne Diablotins (1447 m). Dominica has nine volcanoes, compared to the other volcanic islands of the Lesser Antilles that have only one each. Morne Trois Pitons (1387 m) is the second highest mountain on the island and a dormant volcano (Fig. 11.6). It is shaped by three peaks at its top and located in the south within the Morne Trois Pitons National Park, a UNESCO World Heritage Site (whc.unesco.org). The park is the site of verdant tropical rainforests, 50 fumaroles, many hot springs, a "Boiling Lake," and five volcanoes. The Morne Trois Pitons National Park was inscribed as a World Heritage Site based on the World Heritage List's Natural Criteria (viii) and (x):

> Criterion (viii): Be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features (IUCN 2008, p. 13)

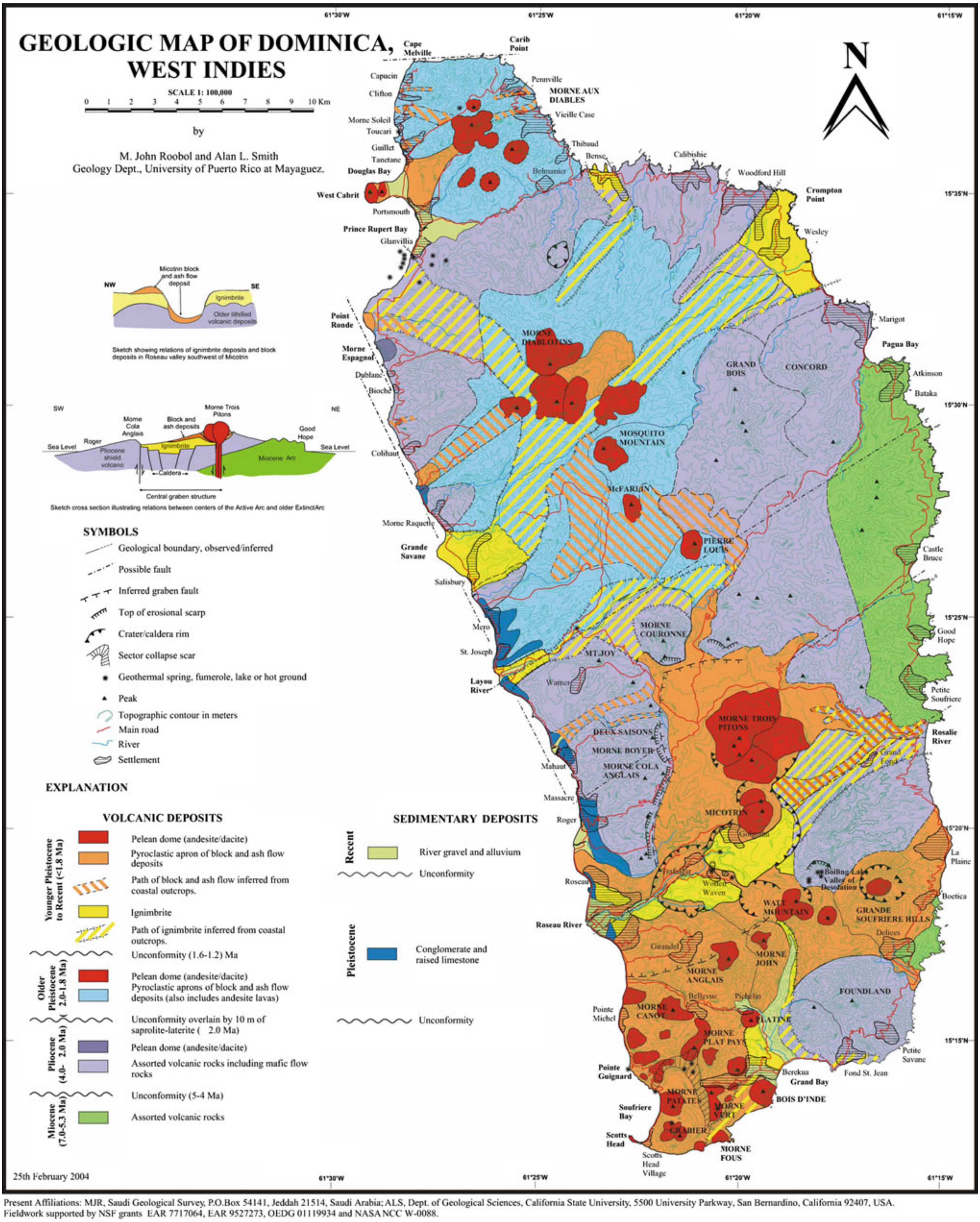

Fig. 11.3 Digital elevation model (DEM) of Dominica displaying its rugged topography. Image courtesy of http://caribbeanvolcanoes.com/green-volcanoes/, retrieved January 2017

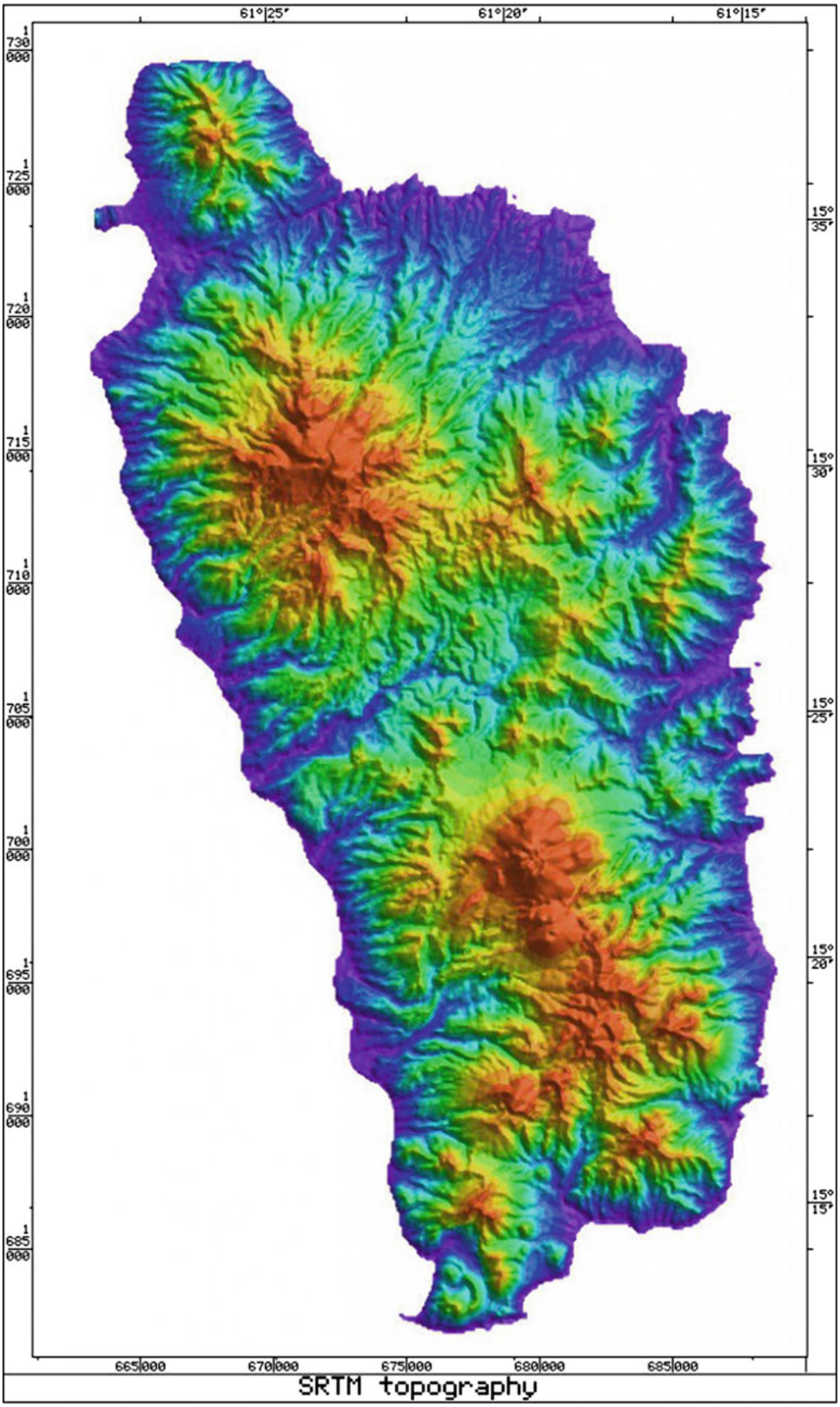

Fig. 11.4 Geologic map with accompanying profile of Dominica, demonstrating its complex geology and volcanics. Image courtesy of Caribbean Handbook on Risk Information Management, available at http://www.charim.net/sites/default/files/handbook/usecase/8/83%20dominica%20geological%20map.jpg (authorship embedded in map), retrieved January 2017

Fig. 11.5 Cove near the hamlet of Salibia on Dominica's east coast showing the island's narrow, steep-sided coast with exposed volcanic rocks, with a small rocky beach in the lower left corner of the image and the formation of sea caves along the cliffs in the background. Photograph by V. Slinger-Friedman

> Criterion (x): contain the most important and significant natural habitats for in situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation. (IUCN 2008, p. 15)

Found within the Morne Trois Pitons National Park at an altitude of 750 m, Boiling Lake is the world's second largest high-temperature volcanic crater lake after New Zealand's Frying Pan Lake, at approximately 63 m across (Fournier et al. 2009; Fig. 11.7a). The lake is an area of high hydrothermal activity generally considered to be very stable while maintaining a constant temperature (180–197 °F or 80–90 °C), occasionally punctuated by irregular periods of rapid draining and refilling. During these times, it can drain within 24 h and fill back up just as quickly (Fournier et al. 2009). The lake is a flooded fumarole, with a vent in the earth's surface that leads directly down to volcanic magma. Filled by rainwater and a perennial stream that feeds into it, Boiling Lake's exit flows into the Riviere Blanche (White River), so named because of its milky white color brought on by the Lake's high sulfur content. The White River is also the source for Victoria Falls, one of the many waterfalls in Dominica.

Along the trail to the Boiling Lake lies the Valley of Desolation (Fig. 11.7b). This active volcanic area has steam vents, fumaroles, hot springs, and boiling mud pools (Holahan 2009). There are almost always fumarolic clouds in the air, smelling of sulfur (Fontaine 2007). The hike to the Boiling Lake starts at Titou Gorge, a deep pool warmed by a hot spring. It then passes through an area of tropical rainforest before transitioning into the Valley of Desolation,

Fig. 11.6 Morne Trois Pitons …Photograph by J. Hains, available online at http://static.panoramio.com/photos/original/42592079.jpg, from http://www.worldtravelserver.com/travel/en/dominica/rosalie/gallery_rosalie/photo_42592079-Morne+Trois+Pitons+-+Dominica.html. Retrieved January 2017

whose harsh environment only supports limited vegetation in the form of mosses, lichens, and grasses. Hot springs arising from submerged fumaroles, and similar to the ones in the Valley of Desolation, can be also found in several other parts of Dominica, including those at Wotten Waven in the south, and in the dormant crater of Morne Aux Diables in the northern tip of the island.

11.3.2 Hydrological Features

Dominica has a humid tropical marine climate. Average yearly rainfall varies from 500 cm (196.9 in) on the windward coast, 900 cm (354.3 in) in the interior, and 180 cm (70.9 in) on the leeward coast. With 83 significant waterways, a total of 365 rills and brooks, and many freshwater lakes, Dominica is resplendent with water resources. Trafalgar Falls (Fig. 11.8) consists of twin waterfalls that have cold-water pools downstream and hot ponds to one side that are filled by springs from underground, and Middleham Falls (Fig. 11.9)—one of the Dominica's tallest—sits in a pristine setting in the northwest of Morne Trois Pitons National Park (Ralston 2014). Boeri Lake, a circular shape crater lake, is the highest lake in Dominica at 869 m. Both Boeri Lake and Freshwater Lake are located in the Morne Trois Pitons National Park, with Freshwater Lake in the lip of a volcanic crater (Ralston 2014). They are separated by Morne Micotrin (Macaque), which was formed in the crater of the old volcano. Dominica's widest river, the Indian River, originates from Morne Diablotins and exits out into the Caribbean Sea at Portsmouth in the north (Fig. 11.10a). Flowing through a coastal wetland and mangroves, and lined with buttressed Bwa Mang trees whose roots reach out up to 6 m, this brackish river is home to barracudas, crayfish, and the green heron (Love and Gabbett 2012).

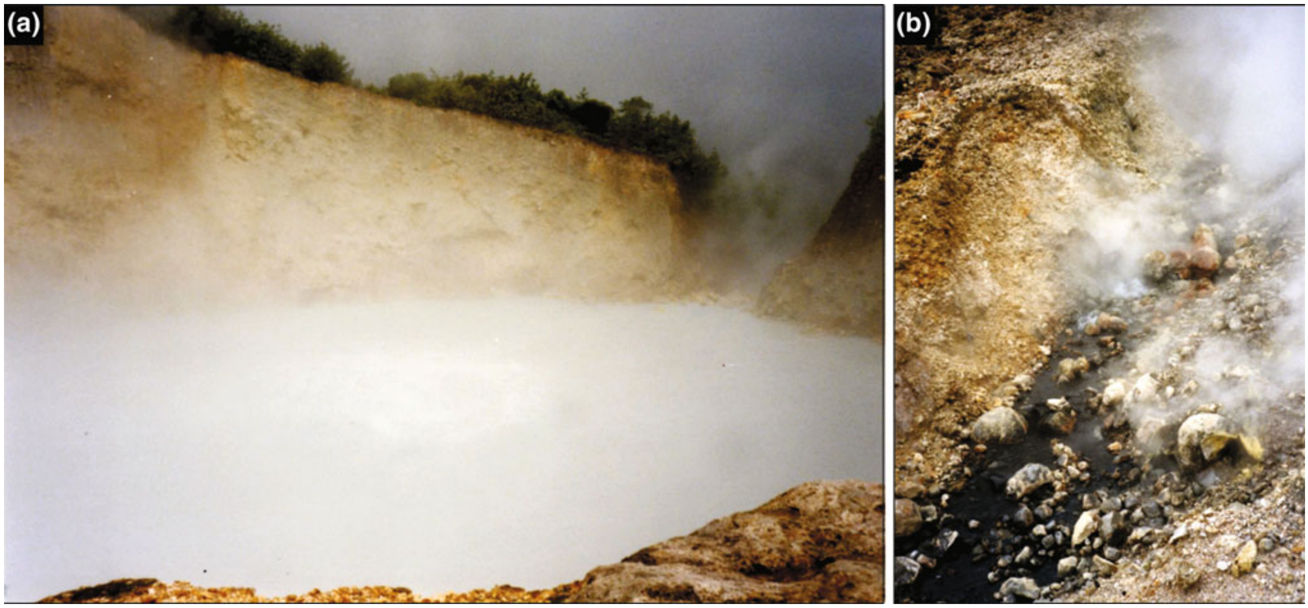

Fig. 11.7 Examples of geothermal/volcanic activity on Dominica. **a** Boiling Lake, a volcanic crater lake formed by the flooding of a fumarole, is a World Heritage Site and a popular tourist destination. The lake is located near Watt Mountain in the southern range. **b** Sulfuric river valley and steam vents in the Valley of Desolation, an active volcanic field with numerous vents and hot springs just south of Watt Mountain. Photographs by V. Slinger-Friedman

11.3.3 Coastal and Marine Features

The volcanic activity on Dominica extends to the coast and impacts some of the coastal and marine landforms. Dominica's narrow coastal zone is composed of steep rocky shorelines and volcanic black sand beaches such as Londonderry Beach and Castle Bruce Beach on Dominica's eastern coast. At Wavine Cyrique, water from a river plunges almost 46 m into the tidal surges of the Atlantic (Ralston 2014). Similarly, Crayfish (or Isulukati) River has a waterfall that cascades from rock pools into the ocean (Fig. 11.10b). In the northeast, an ancient volcanic rock formation known as L'escalier Tete Chien forms a natural staircase to the sea. This volcanic dike occurred when a sheet of rock formed in a fracture in the preexisting rock. The dike rock is impermeable and becomes more prominent as the surrounding rock forms erode over time. Off the southwest end of Dominica is Soufriere Bay, an extinct volcanic crater whose walls drop to an uncharted depth as a lava chute (Scott's Head Soufriere Marine Reserve 2003–2004). Dominica's Champagne Reef, located in this area, is so named due to the warm gases rising up from thermal vents on the ocean floor, which give the appearance of bubbles in a glass of champagne. It is a shallow submarine hydrothermal area (McCarthy et al. 2005). Beautiful coral reefs are located here, as are numerous underwater pinnacles, such as Scotts Head Pinnacle and Swiss cheese, as well as walls, such as Cachacrou and La Sorciere. East coast reefs consist of patch and fringing reefs characterized by low live cover and less diversity than west coast or leeward reefs (Steiner 2003).

11.4 Landscape

11.4.1 Impact of the Indigenous Caribs on Dominica's Landscape

Past and present cultures on Dominica have relied on the surrounding landscapes and landforms for their survival, livelihoods, and pleasure. As a result, they have had to modify and accommodate the natural environment in numerous ways. Dominica's Amerindians, including the Caribs and groups that existed before them, have been an integral part of the environment and natural cycles, because they relied on the environment for hunting and gathering and subsistence agriculture. Volcanic peaks took on particular significance as they were viewed as the life-giving source of all the natural resources on the islands. Volcanoes were represented in the conch shell, stone, and clay in the form of a religious object known as a zemi. Zemis represent the spirit that gives fertility to and brings rain to the land (Honychurch, n.d.).

The Caribs connected to their landscape in other ways. The Indian River is so named because of the known settlement of Caribs on the upper banks of that river at Prince Rupert's Bay in Portsmouth. This location provided for all of their needs with a "sheltered bay, fresh water, reefs and fishing banks, land for cultivation and abundant forests bearing … wood, thatch, bark, fruit and herbs…" (Honychurch, n.d.). The Caribs' fierce nature and Dominica's mountainous terrain helped them resist colonization for a

Fig. 11.8 Trafalgar Falls as seen from the trail. A set of falls, locally named "mommy" and "Daddy," the falls themselves remain difficult to reach. The resultant, nearby step pools—both hot and cold—however, are readily visited by tourists. Image courtesy of Hans Hillewaert, shared under Creative Commons, original available at https://commons.wikimedia.org/wiki/File:Rainforest_at_Trafalgar_Falls_(Dominica).jpg

longer period than on any other island in the Caribbean. When the French and British eventually colonized the island, the Caribs retreated to the very rugged, unoccupied northeast of Dominica. In general, the inaccessible coast and mountainous terrain provided a safe haven for the Caribs and a launching point to make raids against Europeans. The 3700-acre (15 km^2) area in the northeast was granted to the Caribs by the British Crown in 1903 and is today known as the Carib Territory or Reserve (Fig. 11.11; Slinger 2000). It is home to a small community of approximately 3000 Carib descendants who mainly make a living from agriculture and tourism (Fig. 11.12). Agriculture, in the form of bananas, coconuts, cassava, yam, sweet potatoes, and fruits, flourishes in the fertile volcanic soils of the region. Tourism in the Carib Territory stems from the tourists' desire to experience their indigenous culture, and see other major landform-related attractions including Crayfish or Isulukati River and L'escalier Tete Chien. The Caribs' intense use of their commonly owned land has created some concerns by having the worst soil erosion in Dominica. It has also experienced stream loss through deforestation (Dominica Export-Import Trade and Business Directory 2013).

Fig. 11.9 Middleham Falls, located in the northwest of Morne Trois Pitons National Park. At almost 100 m, these Falls represent some of the tallest on Dominica, but remain lesser touristed owing to their hour-plus hike through sometimes steep and rugged rainforest. Image courtesy of Hans Hillewaert, shared under Creative Commons, original available at https://commons.wikimedia.org/wiki/File:Middleham_Falls,_Dominica.JPG, retrieved January 2017

11.4.2 Colonial Arrivals and Their Impact on Dominica's Landscape

The European colonists, African slaves, and both of their descendants have also used the landscape for varying purposes. Wood was the predominant building material in colonial Dominica; however, colonial fortifications (such as the buildings on the Cabrits Garrison in Portsmouth), stone houses, and some foundations for wooden houses were constructed using volcanic stone found scattered in the hillsides. Coral limestone, collected on the nearby reefs, was used to produce a powder that was mixed with aggregate, water, and molasses and then used as a mortar to bind walls (Steiner 2015). This was practiced until the 1950s when cement became more available and cost-effective.

Most of the water sources for agriculture originate in Dominica's central mountain peaks. Dominica's lack of flat land has played an important role in colonial and modern agriculture. The high-producing plantations found on other Caribbean islands could not be as easily accommodated on Dominica. Early estates focused on coffee, sugar, limes, and cocoa, and later bananas, which became the major export crop. Dominica's mountainous terrain has always imposed physical limitations and transportation difficulties. To some

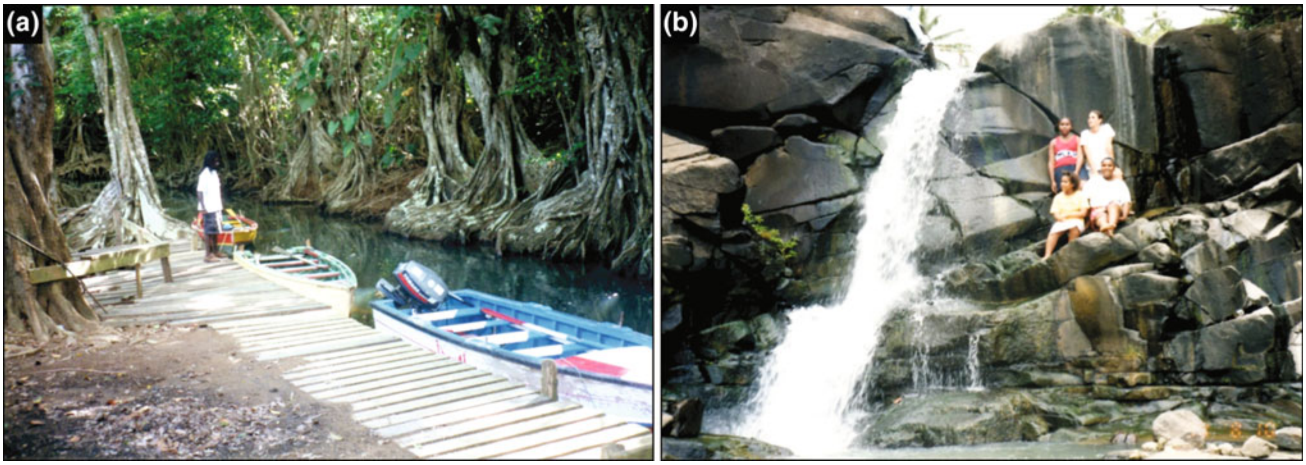

Fig. 11.10 Examples of Dominica's many rivers and fluvial landforms. **a** River guide and boats aside the Indian River, Dominica's widest river. Its course through picturesque coastal wetlands and mangroves, along with the fact that scenes from *The Pirates of the Caribbean: Dead Man's Chest* were filmed here, makes the Indian River a popular tourism attraction. **b** Cascading waterfall of Crayfish River (also known as Isulukati River) flowing into the Atlantic Ocean through a series of rocky, volcanic outcrops. Photographs by V. Slinger-Friedman

Fig. 11.11 Part of "Carib Territory," in the northeast of Dominica. Notice the small stretch of sandy beach in this image, a rarity on Dominica. Image courtesy of Hans Hillewaert, shared under Creative Commons, original available at https://commons.wikimedia.org/wiki/File:Carib_Territory_(Dominica).jpg. Retrieved January 2017

Fig. 11.12 A Carib woman selling *larouma* reed baskets to tourists. Tourists come to the Carib Territory to experience the indigenous culture and visit the landform-related attractions in the area. Photograph by V. Slinger-Friedman

extent, development in Dominica has gone hand in hand with agriculture. For instance, roads were constructed for the purpose of opening more land up to development and for transporting products to market (Nelson 2010). Agriculture has brought benefits in terms of jobs and livelihoods, but it has also had adverse effects on the environment. Much of the littoral woodland, on the exposed eastern or windward slopes of the island, has been cleared for agriculture, predominantly for monoculture banana plantations. Another issue related to agriculture and the environment is illustrated in a study by Bradshaw et al. (2010), which evaluated the relative environmental impact of countries and ranked

Dominica as one of the worst countries in proportional fertilizer use.

11.4.3 Other Contemporary Activities and Their Impact on Dominica's Landscape

The human-related impacts on Dominica's landscape and geology have also come from the actions of foreigners who have sought or have been given concessions to exploit Dominica's geological resources. In 1995, Broken Hill Proprietary (BHP), an Australian mining company came close to obtaining the rights to open a major copper mining operation from the government, potentially compromising 10% of Dominica's land surface. Activists worked to stop this from happening, resulting in BHP pulling out of Dominica (Atherton Martin 2015). A Canadian company, Dom-Can Timbers, using "best Canadian practices," including skidding logs to spar a tree, a practice acceptable in the temperate forests of Canada, destroyed areas of Dominica's tropical forests by taking down every tree and sapling in the affected area and causing gully erosion and soil compaction in the skid path. Despite these events, Dominica's harsh, rugged landscape is the main reason why the country does not face greater issues with deforestation, since most trees are located in mountainous regions that are difficult to reach.

While Dominica's water bodies are not navigable, many streams, waterfalls, and lakes are sources of hydroelectric power. The first form of hydropower on the island was derived from water wheels used for processing sugarcane. Electricity generation from hydropower sources started in 1951. There are currently three hydropower plants with a total capacity of 6.4 MW, providing 40% of the country's electricity. (UNIDO and ICSHP 2013). Modifications to the Freshwater Lake to accommodate the development of a giant man-made reservoir to provide for the hydroelectric stations caused the lake to be excavated, streams redirected, and the water level rose by over 6 m ("Dominica Export-Import Trade and Business Directory" 2013). The potential of geothermal energy is currently being explored through the drilling of test wells. Environmentalists have expressed apprehension over the impact of deep drilling associated with geothermal power on the water table and the release of noxious gases.

In the 1980s, non-extractive uses of the coral reefs, include SCUBA and snorkeling, emerged mainly in the southeast. However, Dominica's limited coral and reef structures have been impacted by both natural hazards and a growing population living predominantly along the shores and relying intensively on the marine resources (Steiner 2003). Fluvial sediment fallouts have influenced reef development, especially during the nineteenth century when agriculture-related deforestation was at its peak. Furthermore, pollutants from industry and household wastes often reach the coast because they are not treated and disposed of properly. Impacts of this pollution include suffocation of marine organisms such as corals and sponges, coral bleaching in Dominica's few coral growth areas in the Soufriere Pinnacle, and polluted beaches.

Fishing is a major local industry in Dominica, with fish protein comprising 13% of the Dominican diet, compared to 7% in the rest of the Caribbean and 6% in the rest of the world (Raymond, n.d.). The country's geology, including the rapid drop-off of the west coast (100 fathoms per half mile), allows for different types of fisheries, including fringing reef, shelf slope, and open sea. Unlike many other Caribbean islands, Dominica does not have sea grass bed and barrier reef fisheries. Reef fish are considered to be most intensively fished, to the point of being overexploited. While some Dominican fishermen have adopted modern fishing technologies, the vast majority of them harvest inshore using seine nets (Schwarzlose 2002). The north coast fringing reefs are the site of marine algae collection to make sea moss, a traditional beverage.

11.5 Heritage and Tourism

Tourism in Dominica is centered on its geomorphic landscapes. Whereas most other Caribbean islands have capitalized on the traditional "sun, sea, and sand" type of tourism, Dominica's mountainous terrain, rocky shores, and black sand beaches deterred its development in that direction. Instead, the Dominican government has focused, in policy and mostly in practice, on developing an ecotourism industry. Ecotourism involves visitors enjoying, learning about, and helping to sustain the natural environment and culture of a location. The varied geomorphic landforms of Dominica—hot springs, waterfalls, boiling fumaroles, mountain peaks, lake, rivers, wetlands, mangroves, dykes, and reefs, along with their associated vegetation and wildlife—fit well with this type of tourism. Concurrent with ecotourism, the government has also promoted cruise ship tourism, though this form of tourism comes with concerns over the impacts a large number of visitors at ecologically sensitive or fragile nature sites could have on the island's overall health.

In some respects, the Dominican government has implemented policies and practices to manage the island's heritage resources. These are reflected in land and marine parks that promote protection of Dominica's landforms, rainforest, and reefs. By establishing the Morne Trois Pitons National Park in 1975, the Morne Diablotin National Park in 2000, and the

Soufriere/Scott's Head Marine Research in 2001, one-fifth of the island has been allocated to national parks and protected areas (Patterson and Rodriguez 2003). Additionally, legislation, such as the Forestry and Wildlife Act, the Fisheries Act, and Beach Control Act, has been instituted to protect the island's natural environment. Research indicates that Dominicans are aware of the importance of their heritage resources to both the ecotourism industry and their livelihoods. This view has led to many personal conservation actions by individuals in the tourism industry that are considered to be beneficial for the island's landforms, including community and individual beach and river cleanups, placing boulders to protect against erosion, growing and using organic produce, using Green Globe recommended cleaning products (such as vinegar to clean furniture), educating locals and tourists on conservation, preventing tourists from taking coral, building good sewage systems due to proximity to the sea, using solar heating systems for energy, and composting (Slinger-Friedman 2009).

Still, government, corporations, and individuals have at times made decisions and taken actions related to the tourism industry that have adverse or, at best, unknown effects on the country's landforms. Some areas of concern involve the following:

- The lack of impact assessment at certain tourist sites that are receiving increasing numbers of tourists (Watty 2008).
- The creation of hydroelectric power developments at Trafalgar Falls, Titou Gorge, and Freshwater Lake that have increased noise pollution in these tourist areas and diminished water flow to Trafalgar Falls, a key tourist attraction (Evans and Williams 1997; Gayle 1997).
- Consideration of a cable car system to take large numbers of tourists to the Morne Trois Pitons National Park. This cable car project was stopped in part due to public outcry and to the threat by UNESCO to strip the park of its designation as a World Heritage Site (UNESCO 1998), and the plans of a previous government to build an international airport that would displace farming communities, destroy mountains, and cut down forest (Fontaine 2003; Watty 2008).
- Government sanctioned quarrying near the Emerald Pool Waterfall has contributed to increasing amounts of sediment to its waters.

Some authors have noted the Dominican government's ambivalence over promoting nature-based tourism versus mass tourism or some other types of development. Actions such as developing hydropower facilities in potentially sensitive areas in the Morne Trois Pitons Park and trying to attract an oil refinery to the north of the island support this concern (Weaver 2004; Klak 2007). Researchers in this area suggest that this wavering demonstrates the desperate actions of a fiscally impoverished government seeking economic development by any means possible (Weaver 2004; Klak 2007).

11.6 Hazards

Dominica is exposed to a wide range of natural hazards. The most common and historically most significant are tropical storms and hurricanes (Benson et al. 2001). Other potential but lesser hazards include droughts, storm surges, floods, bush fires, and tsunamis. The coastal location of most of its population and infrastructure reflects its rocky and mountainous physical topography and means that Dominica's population is especially vulnerable to strong winds and high seas, although the island has a high potential for mass wasting events, such as landslides (Fig. 11.13).

11.6.1 Hurricanes

Dominica experiences two seasons, a wet period between June and October and a dry period between February and May. Temperatures range from 85 °F in the northern winter months and 90 °F in the summer. The island lies on the hurricane path that affects this region most between September and November. While Dominica has fortunately not experienced many hurricanes, some of the ones that have landed on the island have caused extensive damage. This includes Category 4 Hurricane David in 1979, Hurricane Hugo in 1989, Hurricanes Luis and Marilyn in 1995, Hurricane Lenny in 1999, and Hurricane Dean in 2007. Hurricanes Luis and Marilyn caused $66 million in damage to infrastructure and agriculture (Gayle 1997) and Hurricane David left 80% of the island's population homeless. More recently in 2015, Tropical storm Erica with its associated flooding and landslides caused 20 deaths, and an additional 50 people went missing. The coastal town of Petite Savanne in the southeast had to be evacuated because of potential landslides.

Hurricane David left visible impacts on the geomorphology in the south. These included the narrowing of the 300-m-long isthmus joining Scotts Head Point to the mainland by 15 m (Cambers 1996), and the replacement of sand with stones on a beach on the Caribbean side of the isthmus. After a beach monitoring program was established in Dominica in 1987, more measurable impacts of the hurricanes were derived. Following Hurricanes Gabriella and Hugo in 1989, on average, all beaches narrowed by 4.4 m and the land edge retreated inland 1.7 m. While the beaches recovered 93% of their profile area and width values, they were an average of 3 m narrower than before the hurricanes (Cambers 1996).

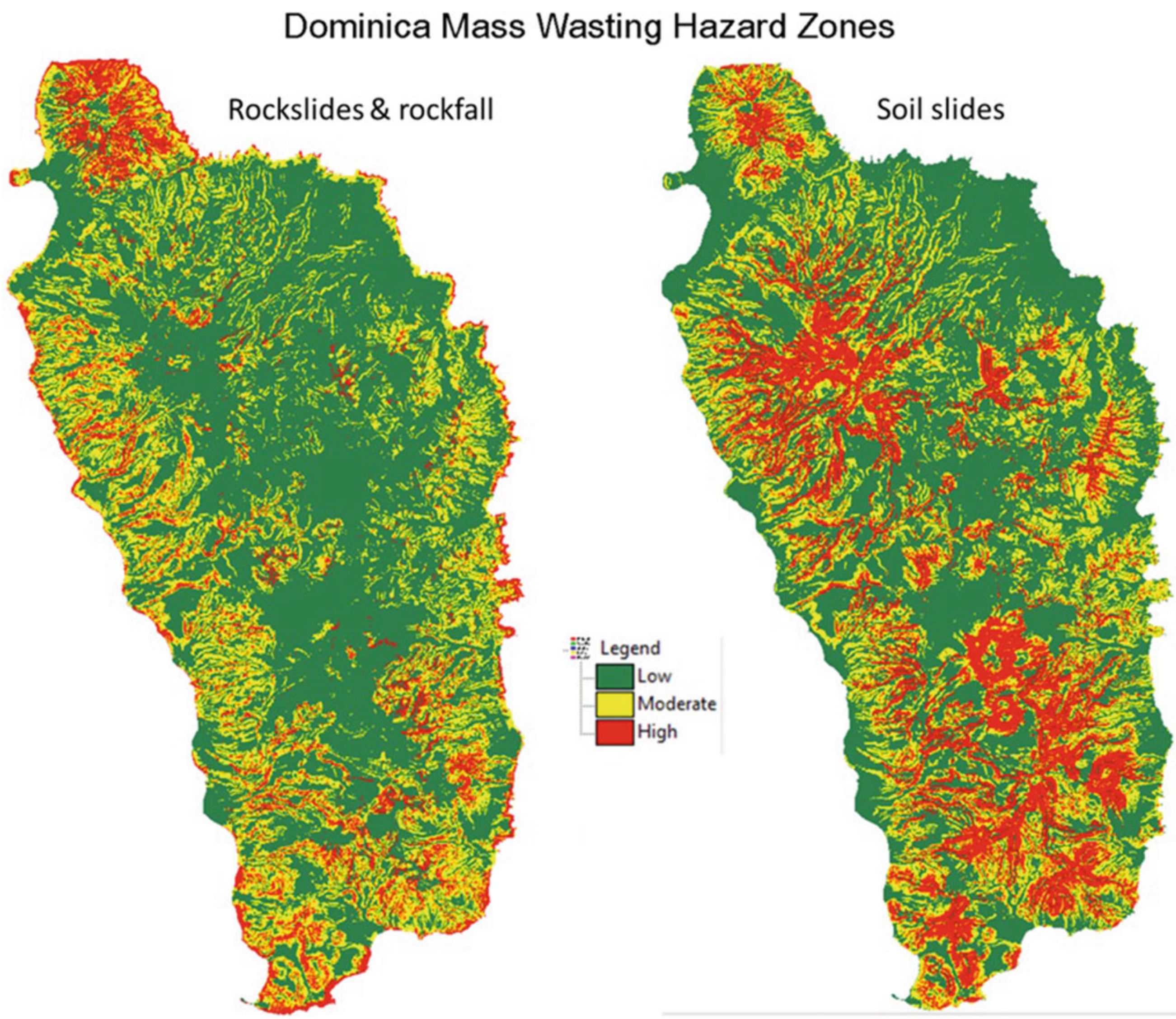

Fig. 11.13 Map of susceptible mass wasting regions in Dominica. Note that high rockslide and rock fall events tend to occur along Dominica's rugged, rocky coast, while landslides ("soil slides") areas remain confined to the island's steeper interior regions and along steep valleys. Map courtesy of Caribbean Handbook on Risk Information Management, available at http://www.charim.net/use/83, retrieved January 2017

11.6.2 Landslides

In Dominica, landslides are typically found to be debris flows, with volcanic bedrock, high rainfall, flooding often associated with hurricanes and tropical storms, and the steep slopes contributing to significant landslide activity (James and DeGraff 2012). The Good Hope landslide in 1987 is an example of a landslide induced from a prolonged period of rain during the wet season (DeGraff 1998). Deforestation of watersheds and construction on unstable soil aggravate the risk of landslides, particularly when it occurs on mountainous topography such as that found in Dominica. The Layou River Valley landslide in 1997 involved the formation and failure of two landslide dams. The first landslide dam was over 15 m high and it created a solid plug in the river before it was breached, sending 300 million gallons of water down the valley. The breach in the second landslide dam seven days later flooded the Layou River Valley with an estimated 350 million gallons of water. Significant deposition of sediments occurred along the river, reducing its carrying capacity and impacting its channel. In association with these two landslide dams, another landslide dam formed on the Matthieu River tributary of the Layou River. Water behind the dam built up into a lake—officially called Matthieu Lake, but dubbed "Miracle Lake" by locals (Fig. 11.14)—that attained a depth of over 43 m and persisted for almost

Fig. 11.14 “Miracle Lake,” as the locals called it, remained for 13 years, eight months, and three days before collapsing in 2011 sending huge amounts of water and sediment rushing down the steep-sided valley to the ocean, widening and perhaps replenishing beach sand (James 2014)

14 years before finally breaching in 2011 (James and DeGraff 2012). Geological impacts of this breach include the emptying of the Matthieu Lake, severe stream bank erosion downstream at the junction of the Layou and Matthieu rivers, and aggradation of the valley floor. Additionally, the large volumes of fresh pumice sand from the collapse of the Matthieu dam that were deposited into the Layou River estuary widened the Layou Beach, making it the widest sandy stretch on the island in 2012. It is believed, but not yet confirmed, that Mero Beach and Salisbury Beach have also been renourished with sand from the collapsed dam (James 2014).

11.6.3 Tectonic Activity

Dominica is volcanic in nature and geologically young. Sulfur springs have the potential to cause landslides, boiling pools, and phreatic (steam) eruptions. The last volcanic eruption in Dominica was roughly 500 years ago. Although there has been only one volcanic event in Dominica’s recorded history, there have been eight seismic crises in the past 50 years, and the island has been on a volcano alert since 1998, highlighting its susceptibility to future volcanic activity and the related risk of earthquakes. Earthquakes large enough to be recorded seismically occur once or twice a year. However, there have been locally felt swarms of small earthquakes from time to time over the past two hundred years (Abraham n.d.; Seismic Research Center 2015; Lindsay et al. 2005). Major earthquakes and aftershocks have occurred in 2004 (6.3 Richter scale) and in 2014 (6.7 Richter scale). The earthquake in 2004 caused landslides in areas such as Portsmouth that had already been affected by heavy rains. Phreatic explosions in the Valley of Desolation in 1880 and 1997, recent earthquakes, and the presence of one of the highest concentrations of potentially active volcanoes in the world indicate that future eruptions are highly likely and the potential for change in the island’s geomorphic future is strong.

11.7 Conclusion

Travel logs of several historic visitors to Dominica aptly describe the landforms and landscapes that they encountered. Trollope, a British traveler on an unnamed ship coming to the Caribbean to conduct, "affairs of the state," described Dominica as by far the most picturesque of all these islands and expressed the desire "to be off and rambling among those green mountains …" (Trollope 1867). An American traveler, De Forest Day (1899), echoed Trollope's sentiments about Dominica when she noted that all the elements of beauty which make the other islands such a feast to the eyes could be found a hundredfold in Dominica. Visitor's travel logs also recounted natural beauties in Dominica such as the Freshwater Lake, Boiling Lake, and forests, "the like of which we poor commonplace mortals had never before dreamed" (De Forest Day 1899).

These travelers' descriptions capture the variety and majesty of Dominica's landforms. They also depict a pure and untouched landscape, coastline, and waters. This is the vision that Dominica's Division of Tourism seeks to present and capitalize on as they promote Dominica as the "Nature Island of the Caribbean." This image is perhaps slightly removed from the reality due to the effects that nature and humans have had in modifying its pristine landscapes that early travelers encountered. Dominica's regular volcanic activity and frequent landslides often change its topography after each hazard event. While rainforest vegetation covers about 66% of Dominica's land surface, human-induced impacts on Dominica's physical landscape have occurred as people embedded their ecological footprint on the island—lightly at first, with the Caribs use of the landscapes to carve out a largely subsistence living, and then more heavily in the form of hydroelectric power plants, increased population pressure for tourism or habitation, timber extraction, and agriculture.

Despite these modifications, it has been suggested that Dominica would be one of the only islands that Columbus would recognize if he came back to the region today (Doyle 2005; Daniells et al. 2008). Its landscape has impeded Dominica from large-scale development in the form of traditional 3S tourism or any other major industry. Conversely, its outstanding natural features have allowed it to remain as intact as it is today, providing a unique backdrop for its nature-based ecotourism product. It is an island that engages its visitors to interact with its geological landscape rather than lay passively on pool decks. Perhaps the most strikingly unique feature of Dominica is the community of the Caribs who were protected to some extent by its rugged, tropical landscape and whose descendants still inhabit the island today.

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12 Martinique

E. Arnold Modlin Jr and Casey D. Allen

Abstract

Martinique is an island located at the northern end of the Windward Islands in the Lesser Antilles. One of the larger islands of the Lesser Antilles, Martinique, is unique because of its location near the convergence of two volcanic arcs on the eastern edge of the Caribbean Plate. The two volcanic arcs cross Martinique on close to parallel paths that run south to northwest. The arc associated with the Volcanic Caribbees is a few miles west of the arc connected to the Limestone Caribbees. Martinique's location has influenced not only its geologic past, but also its anthropological past and present. The shaping of the history of the island is a series of interactions between the geology of the island including specific geological events, its climate including specific weather events, and the social interactions of people native to the Americas, Europeans, Africans, South Asians, and East Asians. Approximately, 380,000 people call Martinique home. Still, the island is a tourism destination primarily for Europeans staying for a few days and cruise boat passengers staying for a few hours. However, tourism officials in Martinique are trying to diversify the origins of tourists vacationing in the islands. Located in a portion of the Caribbean susceptible to hurricanes, with a volcano that is still active, together with labor issues, Martinique faces challenges as it continues into the twenty-first century.

Keywords

Volcano • Mount pelée • Tsunami • Saint-Pierre • 1902 • Négritude • Tourism

12.1 Introduction

Martinique is located 33 km north of St. Lucia, 430 km north of the South American coast, and 42 km (26 miles) south of Dominica (Fig. 12.1). It has a land area of approximately 1128 km^2 with 350 km of coastline (Bocquené and Franco 2005). As an overseas department of France (also known as an overseas region since 2003), Martinique is part of the European Union and uses the Euro as currency, although it is not a part of the Schengen Area (US Department of State 2016). Citizens of Martinique are citizens of France, and the island's inhabitants are represented in the French national government by officials elected locally on the island. Approximately, 378,243 people lived on the island as of 2015 (INSEE 2016).

At its base, Martinique was formed by a series of volcanic activities. Due to land movement and a series of volcanic eruptions that stretch over at least the recent 8–10 million years, the island was created. The oldest southeast and east-central part of Martinique formed over 8–10 Ma. Mount Jacob, the largest volcano in the Lesser Antilles, was active from 5.2 to 1.5 Ma. Trois Îlets Peninsula area (southwest) was volcanically active from 1 to 3 Ma. *Pitons du Carbet* (north of Fort-de-France) were active between 800 and

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Fig. 12.1 General physiographic map of Martinique and surrounding islands displaying key features and points of interest highlighted in this chapter. Note the mountainous northern region with lower plains in the island's center. The majority of small, uninhabited islands are along the western coast. Cartography by K.M. Groom

300 Ka. Mount Pelée has been active for the last 10,000 years.

Though the Lesser Antilles are often thought of as a backwater to other places in the world, Martinique and Martiniquais have often taken a primary place in history—though not always in a good way. Archaeological evidence indicates that prehistoric people settled the island around 100 BCE, though Martinique might have been settled much earlier than that as it was part of the pathway of prehistoric people migrating north from South America. Although the Spanish "discovered" the islands in 1502, they considered it one of the *islas inútiles* (meaning "useless islands"). Over a century later, the French eventually settled it. In time, it was transformed into a sugar island based on the labor of enslaved Africans and their descendants. After emancipation of enslaved people, the planter class turned to imported indentured workers from Africa and Asia. Eventually, even this coercive labor system faded out. Yet, the unique experience of ones who were the descendants of those forcefully migrated to the island was expressed in a number of ways. *Négritudes* and *Créolité* are just two theoretical and activist stances enunciated and developed by Martiniquais in response to French colonialism of the island and its people.

Today, Martinique and Martiniquais face a number of challenges and hazards. High unemployment and low employment participation rates in Martinique exacerbate the effects of other hazardous events and processes. These other events include volcanic eruptions and seismic activity, tsunamis, tropical storm activity, overuse of natural resources, and the challenges of climate change and sea level rise.

12.1.1 Setting

Martinique's location created a dramatic setting for the island's geologic and anthropologic histories. Located due north of St. Lucia and southwest of Dominica, Martinique is oriented from southeast toward northwest. South of the islands midpoint on the west (Caribbean) side of the island is the present-day Department capital of Fort-de-France which lies on the north side of the Fort-de-France Bay (sometimes known as Flamands Bay[1]).

To the south of the bay is a peninsula created by volcanic activity. Located on the northern (bay) side of the peninsula is Les Trois Îlets, birthplace of Josephine, the daughter of a planter and the first wife of Napoleon Bonaparte. Most of the southern third of Martinique, including the peninsula, are in the sub-prefecture of Le Marin, home to a quarter of the population of Martinique. Continuing counterclockwise around the island, the next sub-prefecture is Le Trinité, which is oriented northeast toward the Atlantic Ocean. The Caravelle Peninsula stretches east into the Atlantic Ocean approximately 15 km. About a fifth of the total population of Martinique lives in the sub-prefecture of Le Trinité. The final sub-prefecture is in the northwestern corner of Martinique. It is the sub-prefecture of Saint-Pierre, which is further divided into cantons including Saint-Pierre, Le Morne-Rouge, and Le Prêcheur. Parts of the sub-prefecture, particularly Saint-Pierre and Le Morne-Rouge, were the sites of extensive damage and loss of life due to the eruption of Mount Pelée in 1902.

Historically, the 08 May 1902 eruption of Mount Pelèe (see Sect. 12.4.2 for a detailed account), which killed tens of thousands of people, served as a turning point for research on volcanos in the Caribbean and elsewhere, with scientists like the geographer Heilprin (1903) using Martinique as a research laboratory for studying geology, geochemistry, and geophysics of volcanos. Indeed, this focus on volcanism in northern Martinique has led to less focus on the southeastern part of the island that shares some characteristics in common with Grande-Terre (part of Guadeloupe), and other Limestone Caribbees.

12.2 Landforms

To say that Caribbean geology is complex is an understatement. This is true too with Martinique. The older, eastern arc nearer to the eastern edge of the Caribbean Plate is a curvature of islands known as the Limestone Caribbees. The recent (new) arc, to the west of the older arc, is a track of islands and portions of islands that are the result of recent volcanic activity and are known as the Volcanic Caribbees (Fig. 12.2; see Bouysse et al. 1990; Germa et al. 2010). Chronologically, and generally speaking, the oldest rocks on Martinique—a basal complex and series from the Late Oligocene—reside in the island's southern half, with rocks from the Mid- to Late Miocene comprising most of the southeastern and middle eastern sides of the island, and Pleistocene-age rocks making up most of the island's north half. The historical analysis of geology and geomorphology has, for Martinique, made huge advances over the last century in some ways, while still being focused on only certain questions such as volcanism in Martinique's northern and central areas, paying less attention to the southeastern section of the island. Even though Martinique is often classified on its whole as one of the Volcanic Caribbees, parts of the eastern and southern sections of the island share more in common with the Limestone Caribbees (Germa 2010). Since 1902, the geologic focus in Martinique has primarily been on the two-part question of what exactly is Martinique's geologic past as it relates to volcanism and how can the

[1]Not to be confused with the Anse des Flamands in St. Barthélemy.

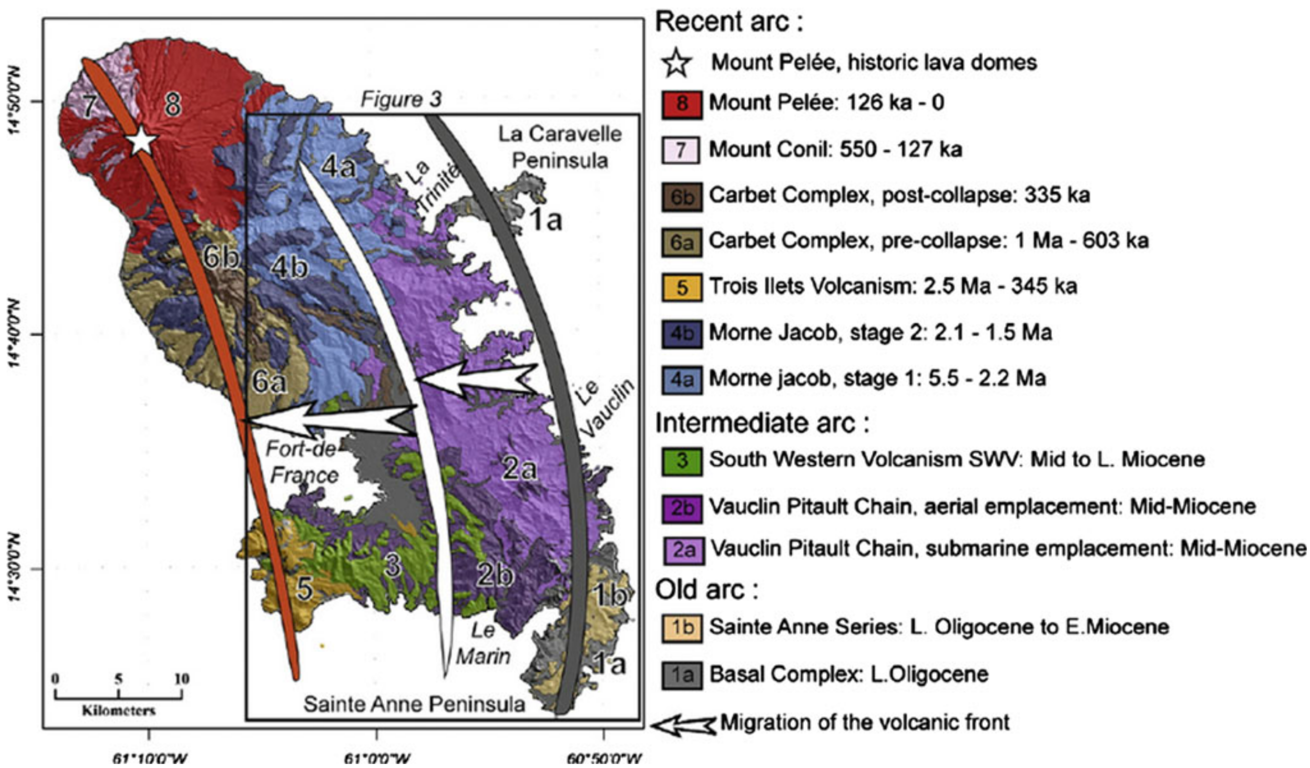


Fig. 12.2 Basic geologic map of Martinique displaying its distinct volcanic units, from Germa et al. (2011b: 124), who note "1: old arc (*1a* Basal Complex, *1b* Saint Anne Series); *2* Vauclin—Pitault Chain (*2a* submarine emplacement, *2b* aerial emplacement); *3* Southwestern volcanism; *4* Morne Jacob shield volcano (*4a* stage 1 tholeiitic, *4b* stage 2 calc-alkaline); *5* Trois Ilets Volcanism; *6* Carbet complex (*6a* pre-collapse stage, *6b* post-collapse stage); *7* Mount Conil; *8* Mount Pelée." *White arrows* show the westward displacement of the volcanic front. The *white star* indicates Mount Pelée volcano. *Gray*, *white,* and *orange parallel lines* (from east to west) indicate the location of the old, intermediate, and recent arcs, respectively. Ages for the recent arc complexes (4, 5, 6, 7 and 8) are from Germa et al. (2010, 2011a). Epochs of activity for old and intermediate arcs (Oligocene and Miocene) are from Westercamp et al. (1989). Available online at: https://www.researchgate.net/figure/235828104_fig2_Fig-2-Simpli-fi-ed-geological-map-of-Martinique-Island-and-its-eight-volcanic-units

human disaster that occurred in May 1902 be prevented from occurring again.

Out of this research, our understanding of Martinique has moved from anecdotal and superstitious to a better understanding of volcanic mechanisms and geochemistry on the island. For example, in 1902, National Geographic reprinted part of Lafcadio Hearn's book from (1890), *Two Years in the French West Indies* which made the statement,

> "No description could give the reader a just idea of what Martinique is, configuratively, so well as the simple statement that although less than fifty miles in extreme length, and less than twenty in average breadth, there are upward of *four hundred mountains* in this little island, or of what at least might be termed mountains elsewhere…Ninety-one only of the principal mountains have been named" (Hearn 1902 italics original).

The northern, central, and western parts of the island are mountainous, at times with steep inclines. However, four hundred mountains is an overestimation of the number of mountains on Martinique—although that number could include the many hill crests nowadays considered to be part of larger mountains (Fig. 12.3).

12.2.1 Volcanics

It is understandable why Martinique's volcanic geology and geomorphology get so much attention, as the island's genesis and growth are the result of the activity of dozens of volcanos. Mount Jacob, southeast of Mount Pelée, is the largest volcano in the Lesser Antilles covering an area of 350 km^2 (Germa 2010). Based on their research, Germa et al. (2010) note that the volcano was continuously active through most of the period of 5.2–1.5 Ma. *Pitons du Carbet,* a set of twelves volcanic domes in Martinique located south-southeast of Mount Pelée and southwest of Mount Jacob, were active from 770 to 331 Ka (Germa et al.

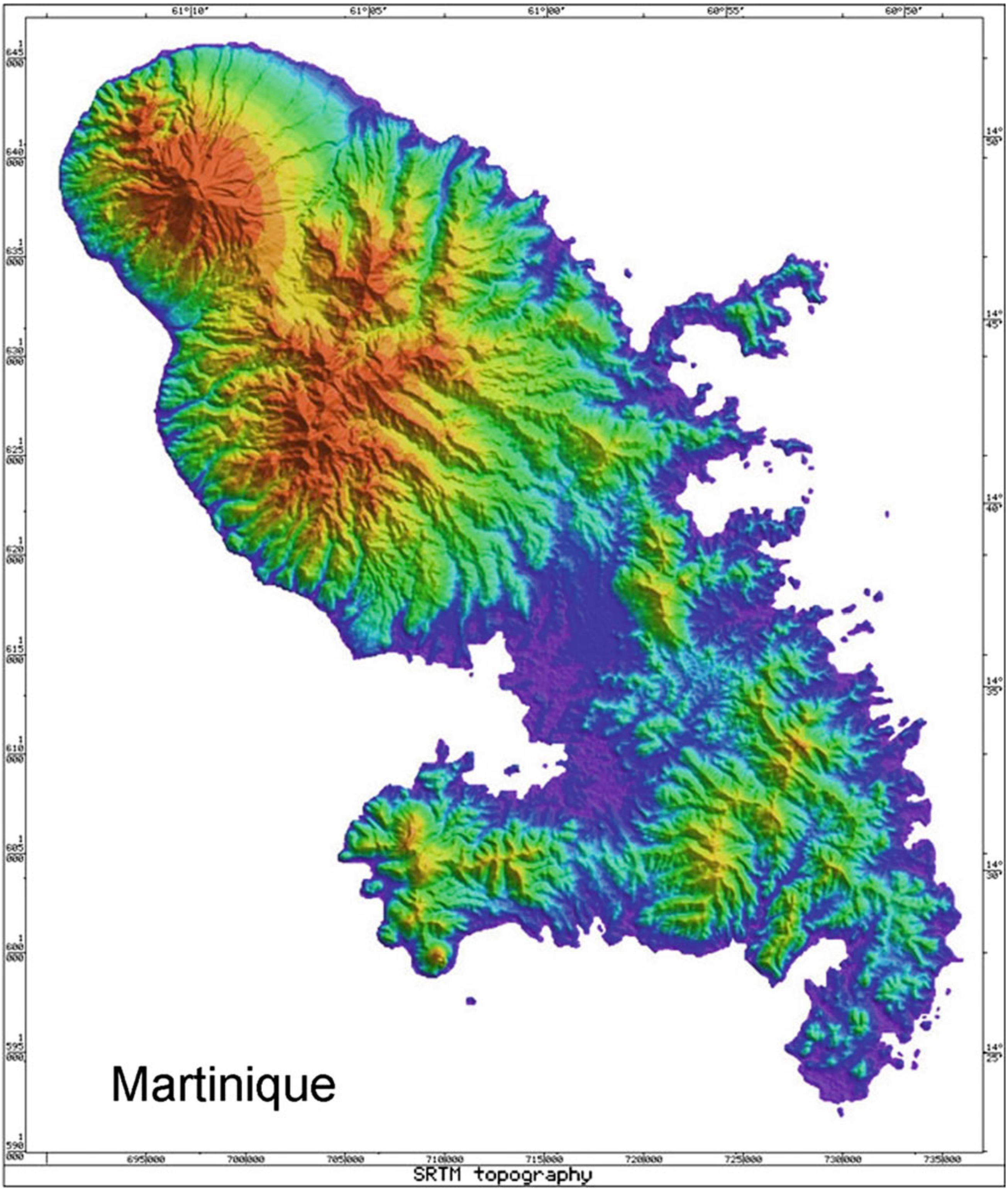


Fig. 12.3 Digital elevation model (DEM) of Martinique. *Red* denotes high elevation regions (in the island's northern half, where Mt. Pelèe is located), with the elevation decreasing according to color (i.e., *red*, *orange*, *yellow*, *green*, *teal* (light *bluish-green*), *blue*, and *purple*). Note the topographic variance between the north (recent geology) and south (older geology) portions of the island. *Image source* http://caribbeanvolcanoes.com/martinique-radar-map/

Fig. 12.4 Coastal capital city of Fort-de-France as seen from Trois Îlets Peninsula across Flamands Bay. Parts of the Pitons du Carbet are visible beyond the city. Photograph by E.A. Modlin

2011a). Mount Conil to the northwest of Mount Pelée is much older, since Pelée's activity covers much of it (Germa 2011a). The Trois Îlets Peninsula on Martinique's southwest coast (Fig. 12.4) contains a series of less-studied volcanos with the western tip of the peninsula aligned on the recent arc south of the Carbet Complex, Mount Pelée, and Mount Conil (Germa 2011a). Data on the Trois Îlets volcanism date from the late 1980s and early 1990s, with some dating being challenged by results from newer methods. Still, it is generally assumed the range of activity for this area is fairly recent at over 3–1 Ma ago (Germa 2011a; Germa 2010). Extreme southern, eastern, and southeastern portions of Martinique including the La Caravelle Peninsula and Saint-Anne Peninsula are associated with the old (Eastern) Arc. Geologically, that means they are connected to the Limestone Caribbees' volcanic activity in these areas. Some researchers put the last activity in south and central parts of Martinique at almost 8–10 Ma (Germa et al. 2010).

While much of northern Martinique[2] was created due to the effects of multiple prehistoric volcanos, many of which are now extinct, Mount Pelée continues to be active over the last 10,000 years (Global Volcanism Program 2013a, b). Research has indicated that shortly prior to the arrival of French colonists in 1635, there was an eruption.[3] Eruptions recorded after 1635 include the eruptions of 1792, 1851–1852, 1902–1905, and 1929–1932 (Global Volcanism Program 2013a, b).

12.2.2 Coastal Forms

Martinique remains situated between the Atlantic Ocean and Caribbean Sea as all islands in the West Indies are, resulting in rugged, wind-swept eastern coasts (windward side) and calmer, gentler western coasts (leeward side), resulting in similar coastal landforms to other West Indian islands: the development of various colored beaches, coastal reef development, and mangrove ecosystems. In 2008, Schleupner estimated that about 79 km of Martinique's coastline was lined with mangrove forest, which on the island as a whole covered approximately 1850 ha (4571.4 acres), or around 6% of the total island surface. Over half of these mangroves are found in the Fort-de-France Bay with smaller mangrove forests found on portions of most of the bays along the east-central, southeastern, and southern coast.

[2] The Limestone covered portion of the island also rests on even earlier volcanic work.

[3] "Pelée" in French can mean "peeled" or "bare" which could be an indication that Mount Pelée was cleared of vegetation on top because of the recent eruption when they French arrived in 1635.

These mangroves serve as nurseries for a variety of fish, are rich in mollusks and crabs, and are home to a variety of birds, reptiles, and mammals (Schleupner 2008).

Martinique claims around three dozen beaches, most of which are sandy. Generally speaking, young volcanics in the north result in varying sizes of black sand beaches—both long stretches and small, hidden coves. The island's rugged eastern shore, facing the Atlantic Ocean and constantly battered by the northeast trade winds, hosts several beaches, though only a few remain viable options for water activities. Surrounding the island's southern and southwestern (and quite older, geologically) portions are renowned white sand beaches with calmer waters of the Caribbean Sea and beautiful palm-lined stretches such as *Plage de Salines* (Fig. 12.5). Though southern beaches often attract many tourists, so-called deserted beaches can also be found around the island (Fig. 12.6).

Off coast, the coral reefs surrounding parts of Martinique are most extensive on the eastern and southern coasts. Heavily damaged coral reefs are also present in the Fort-de-France Bay, while no reefs are present on the north and west coasts of Martinique (Schleupner 2008). Where reefs are present, they tend to slow down erosion and protect the shoreline, although major meteorological events such as swells from tropical storms can still cause damage.

12.3 Landscapes

12.3.1 Historical Landscapes

For thousands of years, Martinique's landscapes have been shaped by not just geomorphic forces, but also human forces. Prehistorically, migrants from the South American

Fig. 12.5 Martinique's longest stretch of white sand beach, *Plage de Salines*. Nourished by the erosion of some of the island's oldest volcanics, this remains a favorite beach for tourists. Images courtesy of Nicolas Bouthors, available from https://commons.wikimedia.org/wiki/File:Martinique_Beach_(Salines).jpg

Fig. 12.6 Hidden beach on Guadeloupe's far northwestern coast, *Anse des Galets* contains a mixture of *black* and *white* sand deposits, giving it a *gray-ish-brown* color. Beaches like this are often created mixing currents that transport sediments from both older and younger volcanics. Image courtesy of Jean and Nathalie, available from https://commons.wikimedia.org/wiki/File:Martinique_-_Anse_des_Galets.jpg

regions around the Orinoco River started to move up the Lesser Antilles prior to 2000 BCE (Higman 2011). Much of these nomadic peoples' material culture seems to have been too fragile to show up in the archaeological evidence collected from sites in Martinique thus far. Still, at least 100 Amerindian sites have been identified on Martinique, and evidence suggests the first permanent inhabitants arrived around the first century BC, though their interaction with the landscape remains an ongoing study (Bérard et al. 2014).

Direct European contact with the island did not occur until June 1502, on Columbus' fourth voyage.[4] Largely, the Spanish ignored the island as a whole, with two exceptions. First, they were responsible for the possible introduction of some of the invasive species such as pigs and goats (Borroto-Páez and Woods 2012). Second, in 1512, Martinique was declared one of the *islas inútiles* which allowed for the Spanish to capture Amerindians from the islands and remove them elsewhere in the Spanish colonies to work the gold and silver mines. In 1635, under the aegis of the French stock company *Compagnie des Îles de l'Amérique*, Pierre Bélain, Sieur d'Esnambuc settled in Saint-Pierre with approximately 100 colonists and claimed the entire island for France and the King. Despite Bélain's death within a few months, the colony continued to grow. Initially, the colonists focused on raising tobacco, even bringing the tobacco plants with them when they first arrived (Singler 1996). In Martinique and elsewhere, tobacco did not tend to create the concentrated wealth that sugar later would (de Gurbert 2014), partly because tobacco exhausted soil quickly and

[4]Columbus was told that the island existed on his first voyage and that it was occupied only by women who wore gold or copper. This idea excited Columbus and rivaled European interests with the Seven Cities and El Dorado (Columbus 1987: 172, 174).

Fig. 12.7 Two-room cabin built in the style and with the materials often used by rural Black Martinicans both before and after emancipation. While this structure is not representative of all of the housing types occupied by formerly enslaved people, it does demonstrate a dominate house type found up on steep mountains. Because of the building's size, the yard around the home was seen as an extension to the family's living space. Photograph by E.A. Modlin

constantly required new sites after a few years to produce meaningful yields (Berlin and Morgan 1993). While tobacco was not new to the Caribbean, the way that Europeans chose to grow it changed the landscape, with each farmer needing to clear a few acres every three to four years, while letting recently used land lay fallow. Though less documented, cotton was also grown during this period (Zamor 2015), and both would be grown for profit, shaping the landscape by clearing fields appropriate for each crop's production.

Sugar and slavery served as significant factors of the history of Martinique during the late seventeenth to early nineteenth centuries. The transition from tobacco to sugar occurred later on Martinique than in the Portuguese and Anglophone colonies of the Western Hemisphere, but still transformed the landscape by consolidating land away from small landowners to larger plantations. While sugar dominated the landscape, some planters also experimented with coffee and cacao (chocolate), further altering the landscape (Ruf and Schroth 2004; Pendergrast 2010). Cacao and coffee were grown in areas where there was at least some tree coverage, but this usually involved cutting down some of the tall trees in the canopy so filtered sunlight could reach the forest floor. Additionally, cacao was produced in Martinique on unfertilized land, and once the soil would no longer support its production, the cultivator would shift to new land (Ruf and Schroth 2004).

In Martinique, slavery was finally abolished in 1848, but this did not necessarily mean that life significantly improved economically for most Black Martiniquais. The ideal agricultural land was controlled by European planters and their offspring, including some mixed-race descendants. Meanwhile, many Black Martiniquais moved to some of the steep mountain slopes and lived in small two-room homes—primarily for sleeping and storage—with much of life happening outside of the cabin, including subsistence farming[5] (Fig. 12.7).

[5]Much of this information comes from a tour of La Savane des Esclaves, a museum located near Trois Îlets in December 2015. The museum was built between 2000 and 2004 and opened by Gilbert Larose in December 2004 (For additional information see La Savane des Esclaves 2016)

Other landscape changing events and processes have shaped Martinique and landscapes on parts of the island. For example, the end of slavery did not mean the end of coercive labor in Martinique or the dramatic reshaping of the rural, agricultural landscape away from the dominance of sugar (see Sect. 12.5.1 for more specific details). The eruption of Mount Pelée on 08 and 20 May 1902, reshaped the physical appearance on part of the northwest section of the island (see Sect. 12.4.2 for specifics). Finally, tourism has influenced the landscapes of Martinique with the preservation of certain areas and the distribution of tourism southward away from Saint-Pierre to Fort-de-France and Trois Îlets.

12.3.2 Mount Pelée and Saint-Pierre

While Mount Pelée (Fig. 12.8) erupted twice after the arrival of the French colonists between 1635 and 1852, the 1902 eruptions of Mount Pelée stand out as the worst volcanic natural disaster of the twentieth century. Understanding the loss of life can be difficult from our temporal standing over a century later, but, quite simply, the natural disaster was made worse by decisions made by some individuals locally—particularly the island's governor. The 1851–1852 eruption event was evidently a steam or phreatic eruption or set of eruptions, which fifty years later would have been remembered by the older individuals who lived in the area as relatively minor.

Even as it became apparent that the eruption event occurring was different than the one fifty years earlier, an upcoming election in May 1902 influenced some elected officials to minimize the potential danger just a few days prior to the election. As Mount Pelée had started minor activity a few years earlier, the feeling among some was that a few days more was not that risky. This was despite the fact that ash had fallen for a few days before the 08 May 1902 eruption. Research since the eruption suggests that hot mud and possibly lava flowed from the opening on the southwest side of Mount Pelée during the earlier eruptions. Depending on location, ash deposits ranged from a few centimeters up to a meter—though this depth of deposits might have been the result of air movement from the volcanic eruption on 08

Fig. 12.8 Mount Pelée. This view, looking almost directly north from a beach near the town of Le Carbet on the western coast showcases the volcano's steep sides and enormous presence on the island. To demonstrate its size, the summit lies roughly 15 km from the point this image was taken. Image courtesy of anonymous, available at https://commons.wikimedia.org/wiki/File:La_Pel%C3%A9e_vue_du_Carbet.jpg

Fig. 12.9 Mount Pelée (cloud covered, to the *right* of center) with Saint-Pierre in the foreground. The volcanic eruption of 08 May 1902 came from this (southwest) side of the volcano, reaching this part of Saint-Pierre—approximately 8 km from the volcano's summit—in less than two minutes. The top of the volcano is usually covered by cloud due to moisture condensing as it rises over the mountain. Photograph by E.A. Modlin

May (Heilprin 1903). Finally, news that Soufrière, on Saint Vincent erupted on 06 May 1902, led some to believe that pressure under the surface of the region was relieved, lending additional weight to the false sense of security.

The delay in evacuation proved deadly. On May 08, 1902, two days before the election, the volcano erupted at approximately 7:50 am (Fig. 12.9). The pyroclastic surge killed 30,000 people in just a few minutes. Because of the unexpectedness of the explosion, the simultaneous death of the island's governor, who with his wife was in Saint-Pierre, and the extreme heat emanating from the ruins, days passed before rescuers and others could enter the city proper. That day in May (08 May) was not when the then-current eruption period ended. Less than two weeks later, it was followed by an eruption that killed more people participating in relief work, searching for survivors, and surveying the damage (Heilprin 1903).

The May 1902 event preceded an eruption on August 30, 1902, which killed about 800 people in the Morne-Rouge area and about 300 in neighboring communities (Scarth 2002). The 30 August 1902 event was followed by another geological oddity. The eruptions that occurred from September 1902–1904 resulted in another noticeable, if temporary, topographical change of the island: A tall viscous spine rose from the earth that eventually peaked at over 300 meters before collapsing (Fig. 12.10; Westercamp and Traineau 1983). The last eruption of Mount Pelée was in 1929 (Global Volcanism Program 2013a, b). Today, the volcano is monitored, so hopefully future volcanic events will not lead to human loss of life, though real estate property built in the area could still make future eruptions economically costly.

As one of the most impressive cities in the French Caribbean prior to 08 May 1902, Saint-Pierre doubtlessly had tourists visit the city, but its sudden destruction started a new era for tourism in the area. Over the next few years, tourists visited by ship and toured the ruins. Scarth (2002) notes that this type of tourism started in January 1903 (Fig. 12.11a). While some tourists were "lucky enough" to have their pictures taken at the site, others relied on the dozens of different postcards that were created—some showing supposed survivors of the eruption, others demonstrating the damage, and still others showing people touring the site. One postcard sender, using racist terms, revealed that some locals had developed different ways to be paid entertainers for visitors to the site (see Fig. 12.11b).

12.4 Heritage and Tourism

12.4.1 Heritage

Martinique might have seemed minor and useless to the Spanish, yet it provided the French who maintained control over the island for most of its European colonial history, a part of their foothold in the struggle to claim and colonize islands in the Caribbean. Martinique's transition to the sugar industry, although later than the Portuguese and British, was

Fig. 12.10 SAINT-PIERRE (Martinique)—Title: "Le Cône du Mont Pelé. S'élevant à 250 m. de hauteur á la suite des éruptions volcaniques." The spine or "Needle of Pelée," approximately 250 m in this image, reached as high at 300 m by some sources. Though not mailed, the format of this postcard is from "Divided Back Period" usually published between February 28, 1907 and December 31, 1915. This postcard is from E.A. Modlin's personal collection

no less profound for Black laborers and their descendants. Although the majority of its history since 1634 has been as a part of the French empire, the British controlled the island three times, most significantly during the period when the French temporarily abolished slavery in its colonies and then reinstituted it in 1802[6] (Bélénus 2015; Sainton 2015). Freedom in 1848 for Black Martiniquais left the planter class looking for other laborers. The planter class turned to indentured servants who came from Africa, India, China, Vietnam, and Portugal. While more attention has been given to such groups in the British Empire, those imported into the French islands worked as hard and in many ways continue to be another set of outcasts in French society today (Northrup 2000). Mortality among some of the indentured workers was high enough that upward of one-third did not live to complete their five-year contract (Northrup 2000).

The island's residents lived—and continue to live—in a highly stratified society racially. Racism and its responses—including race-based resistance—continued well into the twentieth century. Out of resistance to colonialism and racism, the poet, author and future mayor of Fort-de-France, Aimé Césaire collaborated with other individuals under French colonial rule and developed the concept of *Négritude*. The idea *Négritude* appropriated the racially derogatory word for black people and used it to develop a strong sense of self-worth, which opposed the idea of assimilation, while still being politically involved, even if it meant forceful resistance (Njami 2015). In response to *Négritude*, *Créolité* emerged with significant contributors to the emerging style of discourse including the Martiniquais Patrick Chamoiseau, Raphaël Confiant, and Jean Bernabé—among others. This literary and philosophical set of thoughts builds on Edouard Glissant's *Antillianité* concepts which stressed a full idea of what "Caribbean-ness" is, including input from those of African descent, but also those of indigenous, European, East Indian, and Chinese descent. This created a unique set of worldviews deeply influenced by the synthesis communities that they created over the generations in the Caribbean. A significant mark of *Créolité* is that their works usually are initially published in both French and Creole.

12.4.2 Tourism

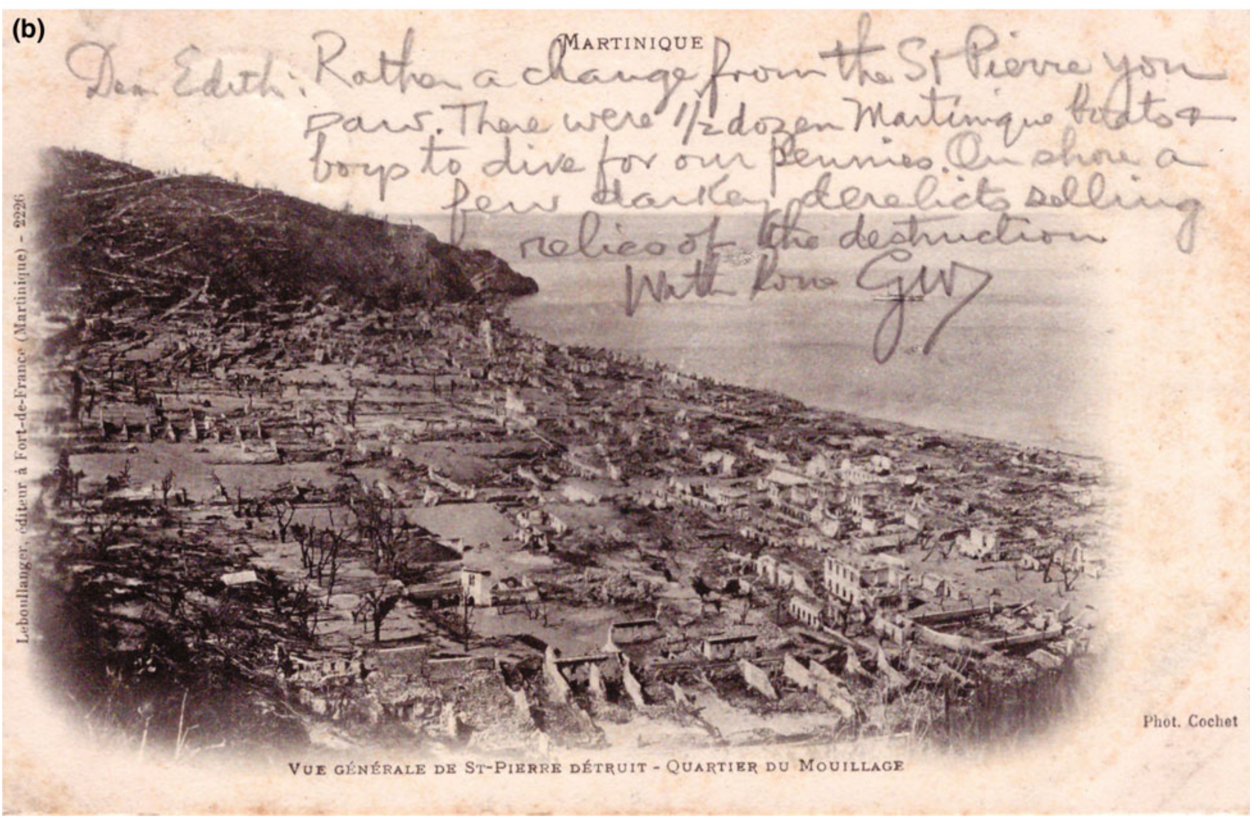
Heritage—the process of taking ownership of the past and making it your own—often ties tightly to tourism, particularly in places where the past is used to market a place as different. Martinique's tourism plans have not until recently seemed to heavily market heritage tourism. In many ways, the focus has been on "sun, sea, and sand" tourists. This focus served it well prior to 2000. According to the Caribbean Tourism Organization, from 2003 to 2014, tourist stopovers varied between 443,202 and 503,107, a difference of 12% (Table 12.1). Issues that affected these numbers are varied. First, there is the issue that Martinique competes with many other "sea, sun, and sand" destinations both in the Caribbean and elsewhere (Dehoorne and Augier 2011). Additionally, during the twenty-first century, North

[6]Thus, theoretically, Martiniquais did not go through the trauma of being freed and then re-enslaved as occurred in Guadeloupe, though René Bélénus (2015: 280) points out that in Guadeloupe this period could be seem as "false abolition" (see the chapter on Guadeloupe for more information on this). The main reason that local whites surrendered the island to Britain was over the issue of maintaining slavery, which Britain indicated it would do if it gained control of the island (Bélénus 2015).

(a)


MARTINIQUE
Leboullanger, éditeur à Fort-de-France (Martinique) - 2021
RUINES DE ST-PIERRE
Dear Jim, Passed near this to day & had a good view. 30/9/03
Terrible ruins. Best love, Father

(b)


MARTINIQUE
Leboullanger, éditeur à Fort-de-France (Martinique) - 2226
Phot. Cochet
VUE GÉNÉRALE DE ST-PIERRE DÉTRUIT - QUARTIER DU MOUILLAGE

◀ **Fig. 12.11** Examples of historic postcards highlighting the devastating effects of the 1900s eruption of Mount Pelée. **a** Title: "Ruins of St.-Pierre." A father wrote in part to his son in Toronto, "Passed near this to day & had a good view. Terrible ruins." The postcard is dated September 30, 1903. This postcard is from the "Undivided Back Period" published prior to February 28, 1907. For more information on the value of tourists' comment on postcards and general guidelines to dating postcards, please see Modlin (2014). **b** Title: "Vue Générale de St-Pierre Détruit—Quartier du Mouillage." Tourist's text says, in part, "Rather a change from the St. Pierre you saw. There were ½ dozen Martinique boats and boys to dive for our pennies. On shore a few darkey [sic] derelicts selling relics of the destruction." The card was canceled (mailed) on March 25, 1906. Despite the racist term, the author discusses some of the economic activities that are geared toward tourists visiting the site. This postcard is a very early example of a postcard from the "Divided Back Period" usually published between February 28, 1907 and December 31, 1915. Both postcards from E.A. Modlin's personal collection

Table 12.1 Number of all tourists who arrived by plane or cruise boat (Caribbean Tourism Organization 2015)

Year	Total overnight stopover tourists	Total cruise passenger arrivals
2003	445,424	268,542
2004	470,891	159,416
2005	484,127	93,064
2006	502,053	95,812
2007	503,107	71,683
2008	481,226	87,079
2009	443,202	69,749
2010	476,492	74,634
2011	496,538	41,142
2012	487,359	93,515
2013	489,706	103,770
2014	489,561	177,786

Cruise numbers were particularly volatile as Martinique competes against other Caribbean ports of call. Additionally, the very low numbers of arrivals by plane in 2009 and cruise ship in 2011 might be related to strikes on Martinique in 2009 (Chrisafis 2009; BBC 2009). Because of advanced planning and commitments, it usually takes a couple of years for Cruise companies to respond to such events. This pattern was noticeable in Curaçao in cruise tourists visit in 1971 after unrest in 1969 (see Chap. 18 in *Landscapes and Landforms of the Lesser Antilles*). While not reaching the high of 2007, stopover growth held steady around 487,000 to 490,000 from 2011 to 2014. Cruise passenger arrivals swung more dramatically in the years between 2003 and 2017. 2003, 2004, and 2005 saw dramatic drop-off of cruise tourists year-over-year, a trajectory that continued on average until the "bottom" was hit at the low of 2011, which was only about 15.3% of the number of such passengers in 2003 when 268,542 cruise passengers arrived in Martinique. Since 2011, the number of cruise passengers has risen to 177,786 in 2014

American tourist number declined, while French tourist numbers increased. For English-speaking tourists, there is also the issue that English is not as widely spoken as in some other parts of the Caribbean or even in Metropole France. Yet, the Martinique Tourism Authority (2015a) is trying to attract more English speakers by having English-speaking street guides for cruise passengers visiting the island.

The argument that by linking tourism and environmental concern, Martinique could draw a niche tourism clientele that looks for sustainable development—often meaning minimal development of some areas of the island—has been taken up most notably by Dehoorne and Augier (2011). They advocate for refocusing from mass tourism to ecotourism, where fewer tourists would participate in tourism activities and each tourist would have a smaller impact on the environment. While Dehoorne and Augier (2011) are quick to point out that Martinique has a great variety of flora and fauna, as well as geographic and geologic diversity, they do not clearly show how an increase in ecotourism will fill the financial gap of a drop in mass tourism. That said, those advocating for more socially and environmentally responsible touring like ecotourism recognize that in some ways Martinique's pursuit of more and more tourists is having an effect on the environment and will be ecologically unsustainable in the future.

As with other Caribbean islands, tourism remains a complex social topic. Hundreds of thousands of tourists visiting the island yearly can bring billions of dollars into the economy both directly and indirectly. Yet, this income is not evenly distributed to all Martiniquais. Ownership of the property and businesses that get much of this income are, in most cases, in the hands of a small population of descendants of the European colonial settlers (about 1% of the population). Meanwhile, the island struggles with high unemployment rates—19% as of late 2014, although that is down from 25% a few years earlier (Morisme and Greliche 2007; INSEE 2015).

12.5 Hazards

Martinique, like other Lesser Antillean islands, remains at risk of a number of hazards including hurricanes and tropical storms, flooding and landslides, earthquakes, volcanos, tsunamis, mosquito-borne illnesses, diseases contracted by contaminated water, and, in lower areas, even susceptibility to sea level rise.

12.5.1 Tropical Storms and Hurricanes

Hurricanes and tropical storms have struck or brushed the islands dozens of times since the first European settlement. Since 1864, 32 tropical storms or hurricanes have brushed or crossed part of the island (NOAA 2016), some causing significant damage and loss of life. The hurricanes of 1780 killed 9000 in Saint-Pierre due to storm surge and 4000 French sailors off of the coast, while a storm in 1891 killed 700 individuals (Pérez, n.d.). Other major storm-related events include Tropical Storm Dorothy in 1970 (killed 44 people), Hurricane David in 1979 (destroyed 500 homes, 80 boats, and injured at least 20 people), and Hurricane Dean in 2007 that heavily damaged Martinique's banana plantations and sugar farms affecting the employment of thousands of Martiniquais (Perrusset and Bouguen 1970; Reuters 2007).

12.5.2 Seismic and Tsunamic Activity

Heavy rainfall from named tropical storms can cause and has caused flooding and landslides in Martinique. Flooding can also occur for a number of other reasons, such as extreme meteorological events—like the 05 May 2009 rains that caused landslides and killed four people (Paravisini-Gebert 2009). In addition to meteorological events, the steep grades of the hills and mountains on the island are susceptible to landslides during seismic events from earthquakes and volcanic activity, even if the seismic event happens off-island.

Low-lying villages, towns, and cities that line the coast, including the capital city of Fort-de-French, are also vulnerable to tsunamis with 28 recorded tsunami events reaching Martinique between 1501 and 2004 (Fig. 12.5). Most of these events were local or regional (within the Caribbean area), although a few originated outside of the region, most significantly the 1755 Lisbon earthquake-initiated tsunami which traveled across the Atlantic Ocean and was observable in the Caribbean seven to nine hours after the earthquake (Accary and Roger 2010). Volcanic activity and the associated seismic activity near Mount Pelée caused a number of tsunamis that affected the island's northwest portion. Away from the areas immediately adjacent to Mount Pelèe, other parts of the islands, such as La Trinité on the Atlantic coast and Fort-de-France, have sustained major damage by one or more tsunamis over the years. For example, Fort Royal (renamed to Fort-de-France) experienced a tsunami in 1839 (11 January) that killed 400 people and destroyed 400 homes (Accary and Roger 2010).

12.5.3 Pollution and Sea Level Rise

Coral reef communities and mangroves in Martinique remain susceptible to development, pollution, and sea-adjacent development. Martinique lost about a third of the mangroves on the island between 1972 and 1992, primarily to development (Gabrie et al. 2004; as cited in Schleupner 2008). This is concerning and shows that while attitudes toward mangroves have largely shifted from viewing them as "unhealthy and inhospitable" (Avau et al. 2011), they are still not receiving the protection they should. Meanwhile, the coral reefs, particularly those in the Fort-de-France Bay, are also struggling to deal with chemical runoff and pollution that both harm coral and encourage an increase in algae at the cost of coral (Littler et al. 1993).

sea level rise (SLR) cannot be ignored on Martinique. Like other Caribbean islands, Martinique has a significant tourism industry that is, in part, based on its sea resources—seaside beaches, food, and hospitality venues. Scott et al. (2012) predict a SLR range of 18–59 cm between 1900 and 2100, noting SLR does not follow a global pattern, but that the Caribbean in general will experience it more dramatically (Compare Tamisiea and Mitrovica 2011). While trying to understand all of the processes associated with sea level rise and attempting to predict them, these numbers—as small as they seem—will affect mangroves and coral reefs causing damage in some areas that will remove or degrade some of the coastal protections. The damages of SLR can include saltwater intrusion, beach erosion, and even the endangerment of seaside buildings and infrastructure (Scott et al. 2012). Among, the possible effects of sea level rise are the destruction of coral reefs and the "disappearance or redistribution of wetlands and lowlands" (Schleupner 2008). While some mangroves have room to migrate landward in response to sea level rise, others on the island do not have such available space (Soares 2009; Compare Schleupner 2005)

12.6 Conclusion

By many measures, Martinique is a unique island. Geologically, it should be considered part Volcanic Caribbees *and* part Limestone Caribbees. The heavily populated southern part of the island is lower in elevation, but still hilly. The middle and northern portions of Martinique are mountainous, reflecting more recent volcanic activity of over a dozen volcanos. One of these volcanos—Mount Pelée—is still active and, currently, is the second tallest mountain in the Lesser Antilles.

As an island located in the hurricane belt with a population approaching 400,000, a number of hazards and challenges face the people of Martinique. Biological and environmental zones along the coasts—both below the surface and adjacent to it—are facing stress due to direct human activity such as development and climate change caused in part by human activity worldwide. Estimates place sea level rise in parts of the Caribbean at 20–50 cm by the middle of the century (Schleupner 2005). Coral and mangroves in certain areas might be able to keep up such sea level rise, but other places perhaps not.

Yet, not all challenges are environmentally centered. Socially, the past is very much with the citizens of Martinique, with slavery and indentured servitude leaving their legacy. Many of the descendants of freed slaves and completed-contract indentured servants still struggle to rise from the bottom, economically. With high unemployment rates and low labor participation rates, many young Martiniquais are looking to other locations for careers—places such as Metropole France and North American cities.

These potential negatives aside, however, there are some very positive things happening in Martinique. The government is investing in infrastructure, and over the last decade, employment has been on the rise. Some inclusive philosophical work is coming from Martiniquais writers and thinkers, such as *Créolité*. While not ignoring the troubling history of the Caribbean, this movement is attempting to open a dialogue about past heritage—acknowledging the variety of people who are part of Caribbean societies. Instead of being top-down focused, the use of Creole—as a language and as identity—attempts to refocus the conversation in a way that gives those often marginalized a voice in shaping their identity. Like most other Lesser Antillean nations, Martinique has room for improvement in various sectors, but it is working to take steps in a direction that will potentially mitigate those shortcomings.

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13 St. Lucia

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Abstract

Volcanic processes have crafted an undeniably beautiful geological landscape on the island of St. Lucia. The young island is rugged and mountainous with narrow valleys. St. Lucia's topology reflects its volcanic origin, including the Barre de I'Isle volcanic axial range, the dramatic twin Pitons, the Qualibou Caldera, and Sulphur Springs, one of the hottest and most active geothermal fields in the Lesser Antilles. Many of these outstanding geomorphic features are why the Pitons Management Area in the southwest of St. Lucia was inscribed as a UNESCO World Heritage Site. The second largest of the Windward Islands, St. Lucia, has been home to Amerindian populations, pirates, whalers, runaway slaves, and European colonists. Today, the island's geomorphic features continue to play an important role in providing the base for agriculture and for attracting tourists from around the world. Both of these activities, while important for the island's economy, are susceptible to the hazards of hurricanes, floods, and landslides experienced on St. Lucia; and in turn, both these activities and the natural hazards have impacts on the island's geological landscapes.

Keywords

St. Lucia • Volcanic • Agriculture • 3S tourism • Alternative tourism

13.1 Introduction

With its contrasting volcanic, mountainous peaks and its flat white sand beaches, and well-formed harbors, St. Lucia is a strikingly beautiful island. Perhaps its most prominent topographic features are the volcanic axial range, known as the Barre de l'Isle, extending down the length of the island and the famous steep-sided seaside Pitons. The mountains rise to the south peaking at Mount Gimie (950 m). The main attraction for most visitors to St. Lucia are the rainforest-clad twin mountain peaks of the Pitons, along with white sand beaches, natural harbors, coral reefs, and sulphur springs.

St. Lucia is composed of its mainland and the Maria Islands in the southeast (Fig. 13.1). The island was once inhabited by indigenous Arawaks (200–400 AD) and Caribs (800 AD) and vigorously fought over by English and French colonists during the seventeenth and eighteenth centuries. Over time, the island's geological landscapes played several roles, including the provider of a subsistence living for the Amerindian groups, a pirate hideout, a whaling station, a refuge for runaway slaves, the backdrop for extensive plantations, and the setting for a tourism haven. For each of these activities, the island has experienced a corresponding adjustments of its geomorphic landscape.

St. Lucia's mainstay agriculture and tourism industries are vulnerable to hazards such as hurricanes, floods, and landslides due to its location in the hurricane belt and its geological rugged landscape. Likewise, the geological

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Fig. 13.1 General physiographic map of St. Lucia and smaller surrounding islands, such as the Maria Islands off the southeast coast. Copious rivers and valleys radiate from the central mountains and the various peaks that dot the coast, such as Petit Piton and Gros Piton on the southwest coast. Cartography by K.M. Groom

landscape is impacted by the economic activities taking place on its surface. Over time, the focus of tourism has shifted to include the promotion of its natural geological landscapes in a form of alternative tourism. The concern is that this form of tourism might be just as destructive as the traditional mass tourism product that has been so popular in St. Lucia due to the ecologically sensitive settings of the most visited locations. Only time will tell whether environmental policies put into place by the government will reduce the potentially harmful impacts of its humans on its landscape.

13.2 Setting

13.2.1 St. Lucia's Interior

St. Lucia, part of the of the Windward Island chain of the Lesser Antilles, is 620 km^2 and has 158 km of coastline (Nations n.d.). Like the majority of the Windward Islands, St. Lucia is volcanic in origin, and most of the geology reflects that history (Fig. 13.2). St. Lucia lies on the eastern margin of the Caribbean tectonic plate, and the island was formed in a series of volcanic processes that took place between 20 thousand and 19 million years ago. It is believed that there were three primary periods of island building for St. Lucia (Island Profiles n.d.a). The first took place between 9 and 19 million years ago, and formed the area between present-day Castries and the northern tip of the island. The second took place 5–6 million years ago, and formed a distinct landmass that has become the southern portion of the island. Between 1 and 2 million years ago, there was a significant period of volcanic activity in the present-day Mount Gimie region, which connected the two prior island formations and built up the center of St. Lucia (The Island and Nature n.d.). The Pitons were formed in the most recent period of volcanic activity, which started sometime in the last 1 million years in the Soufriere Bay region of St. Lucia (Island Profiles n.d.b). In the south, the young rock makes it easier to identify the various basaltic andesite centers in this area, which include Mount Gomier, Morne Caillandre, Moule a Chique, Beauséjour, St. Urbain, Mt. Tourney, and Savannes (Island Profiles n.d.a).

There is alignment between Morne Caillandre, Beauséjour, and Mt. Tourney, indicating that they are part of the same structural distribution (Lindsay et al. 2002). A large depression begins north of Soufriere and runs south of Mt. Tabac to the east, almost reaching Mt. Gimie before it loops unevenly to the south, just below Gros Piton. Known as the Qualibou Depression (Fig. 13.3), this area contains basalt rocks dated from 5–6 million years ago, while the Gros and Petit Pitons within the depression are as young as 290 thousand years old and give a more precise date range for the age of the region (Lindsay et al. 2002). Originally, the depression was thought to be one large caldera, but Wohletz et al. (1986) determined that only a portion of the area was actually a caldera. The initial depression resulted from subsequent landslides or other forms of structural collapse (The Island and Nature n.d.; Lindsay et al. 2002). There are debris avalanche deposits off the coast of St. Lucia near Soufriere that are potentially related to the Qualibou Depression (About 2010). Based on the assessment of sediment layers on top of the debris, the collapse is estimated to have happened approximately 300 thousand years ago. Though volcanic flows near Mount Gimie cut off at the margins of the depression, indicating that volcanic activity was taking place in the region before the depression formed, the actual Qualibou Caldera developed after the depression (Lindsay et al. 2002). The only limestone on the island is in this area, north of Soufriere on the eastern coast (Earle 1924).

In what is referred to as the Central Series, the rocks have been dated within six age ranges running from 10.4 million years old (Miocene) in lava flows west of Dennery, to 2.8 million years old (Pliocene) in lava flows near Derriere Dos. This region of St. Lucia is heavily forested and has the most significant relief on the island, with the second and third highest peaks, the Gros and Petit Pitons, that rises to 770 and 743 m, respectively. The Piton Mitan Ridge, which is part of a 2909 hectare area designated as a UNESCO World Heritage Site and known as the Pitons Management Area, links these two volcanic spires (UNESCO n.d.).

North of the Rousseau Valley, the older volcanic features are significantly eroded, which limit the ability to identify specific volcanic centers (The Island and Nature n.d.). This volcanic region is known as the Northern Series, and is comprised of basalt and andesite lava flows and pyroclastic deposits (Government 2001). Based on comparison with similar rocks in Martinique, Newman (1965) suggested that these rocks are from the Eocene period, but nothing on St. Lucia has been definitively dated to that time period. The oldest basalt in this region of St. Lucia has been dated to 18 million years old, in the Miocene (Lindsay et al. 2002; Smith et al. 2013). The youngest centers in the Northern Series, dating from the Late Miocene to the Early Pliocene, are Mt. Pimard, Vigie, and Mt. Monier, which have an area of weak geothermal activity on its south flank in Ravine Raisinard (Smith et al. 2013).

13.2.2 St. Lucia's Coastal Setting

St. Lucia's coastal shelf has an area of 522 km^2, and is narrow along the western coast (0.1 km) and wider around the rest of the island, reaching a width of 5 km in places (Mohammed and Lindop 2015). Reefs are found along 44% of St. Lucia's coastline (Maps 2008), with the highest

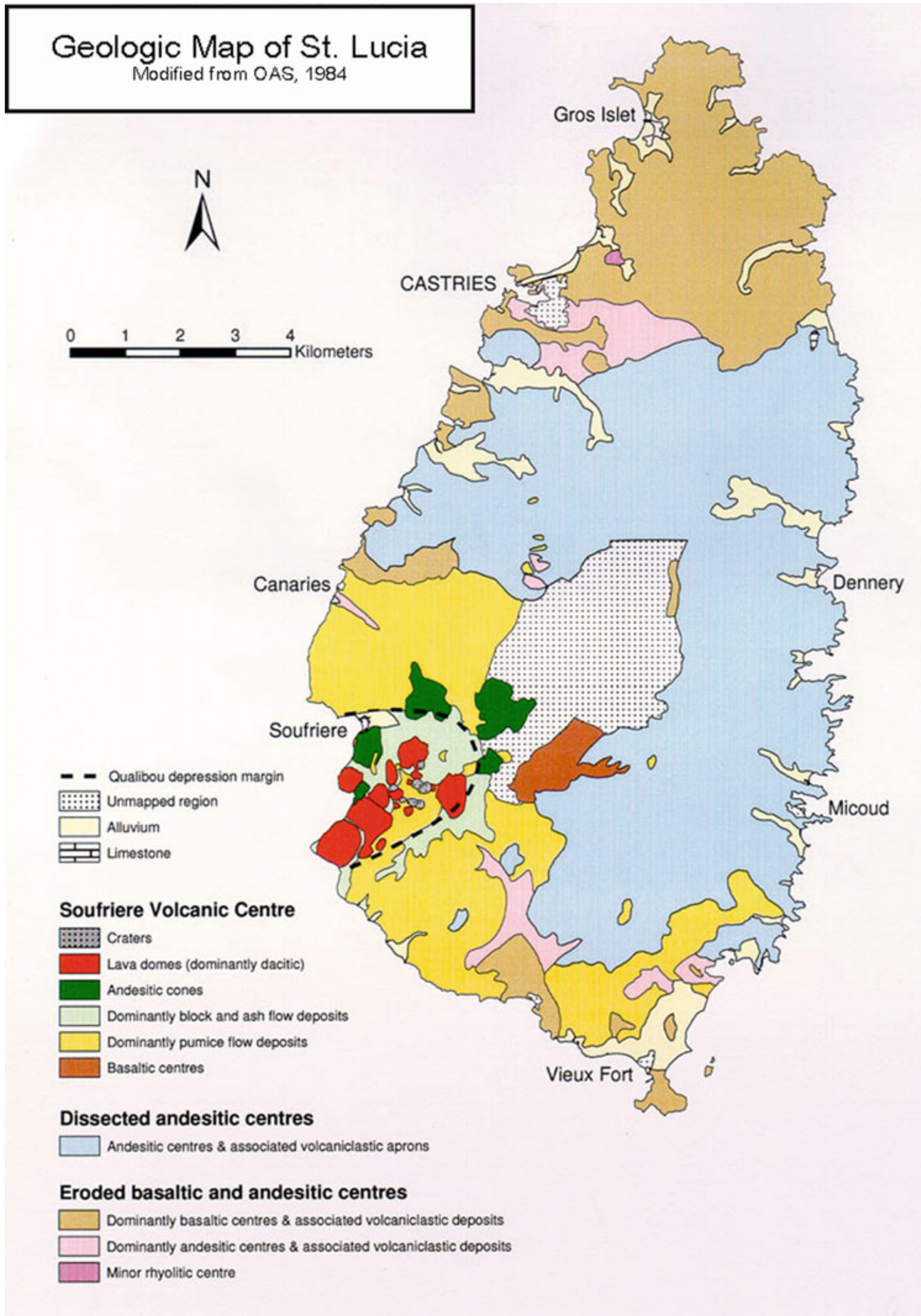

Fig. 13.2 Geologic map of St. Lucia displaying its varied volcanics. Generally, older rock lies to the north while younger rock can be found in the south. The region around Soufriere (especially the *red-colored* areas) represents perhaps the most recent volcanics on the island. Image courtesy of http://uwiseismic.com/General.aspx?id=72

concentration of reefs found on the east and south coasts. The reefs on the east coast are mostly patch reefs, isolated concentrations of coral growth, or fragmented fringe reef systems (St. Lucia n.d.). This relatively high degree of uneven reef distribution on the windward side of the island is likely due to the exposure to the forceful waters of the Atlantic. On the sheltered leeward side of the island, the narrow fringing reef grows on submerged volcanic rock, and it is the most vibrant and dynamic reef ecosystem on St. Lucia (Mohammed and Lindop 2015).

Fig. 13.3 The Qualibou Depression on the southern end of the island. The steep cliffs of the half-moon depression encompass the small volcanic peak of Petit Piton and the town of Soufrière. The formation and origin of this depression have been debated throughout recent history. Photograph by A. DeGraff Ollivierre

13.3 Landforms

13.3.1 Terrain Features

After Dominica, St. Lucia is the second largest of the Windward Islands. It is composed of the mainland and two smaller islands, the Maria Islands, off of its southeastern coast. Pigeon Island is located on the northwestern coast of St. Lucia, and in 1972, it was connected to the mainland by a human-made dirt causeway (Pigeon Island National Landmark). St. Lucia is a volcanically formed, mountainous island, with a north-south running backbone ridge called the *Barre de l'Isle* (Fig. 13.4). Heading south along this spine, the mountains generally increase in size, peaking at 950 m with Mount Gimie (St. Lucia 2008). Located on the western coast of the island southwest of Mount Gimie, the Gros Piton (770 m) and the Petit Piton (743 m) rise up dramatically from the sea and are visible from most parts of the island (Fig. 13.5). These mountains are so emblematic of St. Lucia that they are even featured on the country's flag, one triangle inside the other (Morales 2011). The two steep-sided spires are plugs, the resistant sections of an eroded volcanic dome, and are linked by the Piton Mitan Ridge. They sit along the edges of the Soufriere Volcanic Center, which encompasses the surrounding areas, including the town of Soufriere (Pitons Management Area Saint Lucia).

At the center of the Qualibou Caldera, a volcanic valley, and situated over a magma chamber two kilometers below the surface lies Sulphur Springs (Geology n.d.); it is marketed as the Caribbean's only "drive-in volcano" ("Sulphur Springs Park"). While not technically a volcano, it is one of the hottest and most active geothermal sites in the Lesser Antilles. The region is part of a UNESCO World Heritage Site, the Pitons Management Area (UNESCO n.d.), which also includes the Pitons. This area was inscribed as a World Heritage Site having met criteria (vii) and (viii):

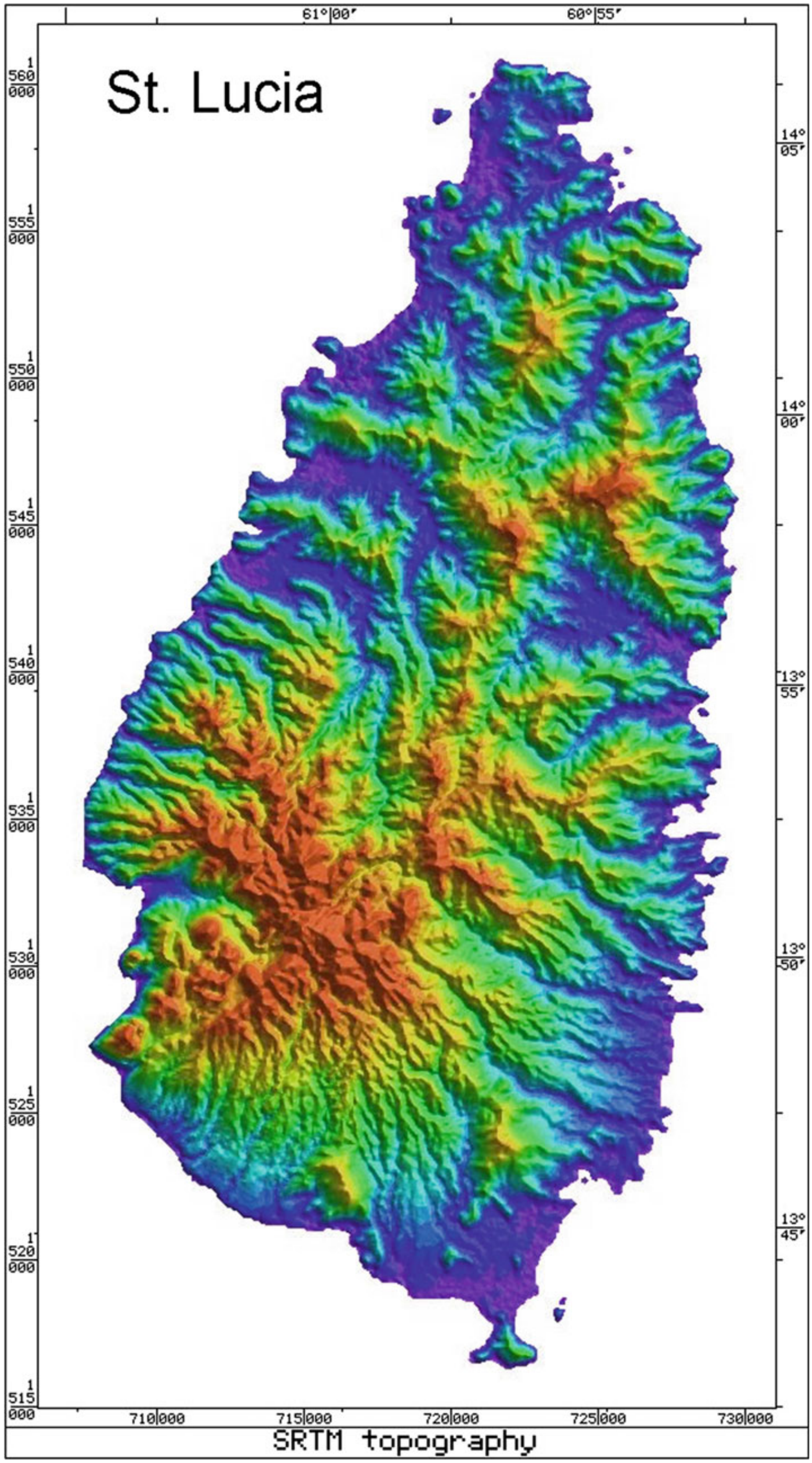

Fig. 13.4 Digital Elevation Model (DEM) showing St. Lucia's mountainous regions (*rust-colored* areas) and more gentle topography hugging the small coastal regions (*blue-colored* and *purple-colored* areas). The *Barre de l'Isle*, a generally north-south trending ridge, can be seen along the *center* of the image, with the highest elevations found along the ridge's southernmost points

Fig. 13.5 Perhaps the most iconic features on the island of St. Lucia are the volcanic mountainous peaks of Gros Piton and Petit Piton near the town of Soufrière. Both peaks are included in the 29 km^2 Pitons Management Area, which was declared an UNESCO World Heritage Site in 2004. Photograph by A. Potter

Criterion (*vii*): The Pitons Management Area derives its primary visual impact and aesthetic qualities from the Pitons, two adjacent forest-clad volcanic lava domes rising abruptly from the sea to heights greater than 700 m. The Pitons predominate over the St. Lucian landscape, being visible from virtually every part of the island and providing a distinctive landmark for seafarers. The combination of the Pitons against the backdrop of green tropical vegetation and a varying topography in the marine foreground gives the area its superlative beauty.

Criterion (*viii*): The Pitons Management Area contains the greater part of a collapsed stratovolcano contained within the volcanic system, known to geologists as the Soufriere Volcanic Center. Prominent within the volcanic landscape are two eroded remnants of lava domes, Gros Piton and Petit Piton. "The Pitons occur with a variety of other volcanic features including cumulo-domes, explosion craters, pyroclastic deposits (pumice and ash), and lava flows. Collectively, these fully illustrate the volcanic history of an andesitic composite volcano associated with crustal plate subduction" (http://whc.unesco.org/en/list/1161).

Morne Soufriere and Rabot Ridge border the Qualibou Caldera to the east and west, respectively. The slopes of these mountains that face Sulphur Springs are cut by numerous faults, which allow rainwater to penetrate deep into the earth, become heated with hot rocks, and return via pressure to the surface. As a result, the site includes a host of geothermal and volcanic landforms, such as hot springs, sulfur-spewing fumaroles reaching temperatures of 172 °C, pools of boiling water, and *soufrieres*, which are volcanic vents which emanate steam and chemicals, such as hydrogen sulfide (St. Lucia 1994). This area is also the location of two mineral pools attaining temperatures up to 90 °C (Hot Water n.d.). Other areas of geothermal activity exist outside of the Qualibou Caldera including the warm springs at Jalousie and Choiseul, underwater vents at Black Bay and offshore between Anse Mamin and Soufriere Bay, and areas of "cold Soufrière" (cold fumarolic activity which are acidic, roughly 28 °C, and associated with areas of highly altered rock) near Bois Demanje and in De Mailly Village (Lindsay et al. 2002) (Fig. 13.6).

13.3.2 Hydrological Features

St. Lucia has a tropical climate with two distinct seasons: a wet season from June to September and a dry season from February to May. The northern and southern coasts average 1500–1750 mm of rain a year, while the interior of the island nearly triples that number at about 3990 mm a year. There are nine major rivers on St. Lucia, including Cul de Sac, Cannelles, Dennery, Fond, Piaye, Doree, Canaries, Marquis, and Roseau. The Roseau River, on the western side south of Castries, is the longest river on the island (Nations n.d.). All of the rivers on the island run from the central highlands out to the coast and are evenly distributed around the island. The mountainous landscape combined with the high yearly rainfall makes St. Lucia an ideal environment for waterfalls. The Enbas Saut Waterfall Trail leads hikers through the thickly forested slopes of Mount Gimie, ending at a waterfall that is slowly eroding away the volcanic rock (Hastings 2015). With a drop of a little over 9 m, the Piton Waterfalls is in the south of the island and located near the Petit Pitons. On the northeast of the island is the Latille Waterfall, with a drop of about 7 m. Sault Falls (also known as Dennery Falls or Errand Falls), on the eastern side of the island, has a longer drop of roughly 17 m ("Top 5 Waterfalls in Saint Lucia"). Diamond Waterfalls, in the south, is set within Diamond Botanical Gardens. At 17 m high, the falls are notable not only for their height, but also for the spectacular coloration of the surrounding rock. The water comes

Fig. 13.6 An example of geothermal activity on St. Lucia, expansive Sulphur Springs Park near Soufrière volcano is prided as being the Caribbean's only drive-in volcano. The viewing platform with visitor in the *upper left* of the image provides scale. Photograph by A. DeGraff Ollivierre

down from the sulphur springs, and mixes with rainwater, carrying sulfur, copper sulfate, magnesium, iron, manganese, and calcium to the brink, where it colors the rock underneath (Fig. 13.7). The multicolored rock makes the water appear to change color from moment to moment (Caribbean n.d). The heated water from the springs blends with rainwater to create warm pools below ("Top 5 Waterfalls in Saint Lucia" n.d.).

13.3.3 Coastal and Marine Features

The influence of volcanic processes extends down to St. Lucia's coasts where black sand beaches can be found alongside the white sand beaches. Along the coast are natural harbors with white sand beaches. These include Marigot Bay, Rodney Bay with Reduit Beach, and Pigeon Island Park with Pigeon Point Beach (Porter and Prince 2007). There are 90 km^2 of coral reefs in total around St. Lucia. The most extensive reefs are located on eastern and southern coasts, but the west coast boasts outstanding reefs that grow out of the sides of volcanic rock ("Reefs in St. Lucia"). At the base of the Pitons are the Piton Wall and Superman's Flight, the latter having been used in the movie Superman III ("Diving" 2015). Both provide habitat for corals, fish, and other ocean life. Anse La Raye Wall is a steep underwater feature with fire coral in the shallow areas and a large variety of sponges and soft coral in deeper waters ("St. Lucia Dive Sites" n.d.). Finally, St. Lucia's southeast tidal shores support Mankòtè Mangrove, which cover 40 ha (99 acres).

13.4 Landscape

Prior to European discovery of St. Lucia in the sixteenth century, the island was inhabited by the Arawak people as far back as 200–400 CE (Things to do n.d.). The Arawak

Fig. 13.7 Diamond Waterfalls, a geothermal feature in the Diamond Botanical Gardens, displays discoloration and mineral deposits from both rainwater and naturally occurring chemicals in the underlying rock. The unique features of the waterfall and the pleasant setting make it a popular tourist destination. Photograph by A. Potter

were farmers and fishermen, and both utilized the natural resources of St. Lucia and maintained a spiritual connection with the land (St. Lucia n.d.). Gros Piton, called Yokahu, was worshipped as the god of fire, thunder, and rain. Petit Piton, Atabeyra, was the god of fertility and food. The Arawak also believed that the spirit of their gods was housed in the boiling water of the Sulphur Springs (The Soufriere Foundation—History of Soufriere 2010a, b, c, d). By contrast, the warlike Caribs, who came after them in 800 CE (All 2014), believed the Sulphur Springs was a god, and threw human sacrifices into the water during periods of increased hydrothermal activity. This practice gave name to the depression in which Sulphur Springs is located, as Qualibou means "at the place of death" (The Soufriere Foundation—History of Soufriere 2010a, b, c, d). The original Carib name for St. Lucia was Iouanalao, meaning, "land of iguana." This name took various forms over time, before settling on Hewanorra, now the name of St. Lucia's airport.

Credit for discovering St. Lucia goes to Juan de Cosa, who first labeled St. Lucia as El Falcon on a map dated to 1499. By 1502, the island was marked on a globe and labeled as Santa Lucia (All n.d.). The first documented European to actually set foot on the island was the French pirate François le Clerc, known at the time as Jambe de Bois, meaning "wooden leg" (Past and Present n.d.). He lived on Pigeon Island off the northwest coast of St. Lucia and attacked Spanish ships as they passed (Things, n.d.). Pigeon Island also played an important role during the French and British tug-of-war over territories in the West Indies, during which time St. Lucia became known as the "Helen of the West" (About n.d.). The British built a naval base on Pigeon Island in 1778, a move that was crucial to their success in subsequent battles with the French. Along with its history with piracy and its role as a strategic piece in British military control of St. Lucia, Pigeon Island served as a whaling station from 1909 to 1952, when legislation controlling whaling was enacted. Pigeon Island National Park was founded in 1992 as the culmination of an ongoing preservation project, both for cultural and natural heritage values (Sites n.d.). Where mainland St. Lucia meets the artificial bridge connecting to Pigeon Island is the town of Gros Islet. Once a small fishing village, Gros Islet has become one of the more popular places on the island today (Fig. 13.8).

Fig. 13.8 Aerial view of Pigeon Island, which has played an integral role as a naval base and whaling station. The now-ruined Fort Rodney atop the outcrop in the *lower left* of the image was an important British military outpost in the late 1700s, as the view from the *top* apparently included the French Navel Base on neighboring Martinique. Photograph by A. DeGraff Ollivierre

The colonial period saw many of the most dramatic changes to St. Lucia's landscape. Two Frenchmen built the first plantation on the island in 1765, and by the time the British finally took control in 1814, there were 50 operational plantations (All n.d.). Throughout this time, slaves were brought to the island from Africa. Although Britain outlawed slavery in 1807, this legislation did not reach St. Lucia until 1834, and slavery was not truly abolished until 1838. Emancipation did not correspond to a shift in power, however, and white landowners still held control over the island's resources (All, n.d.). This meant that the livelihood for many of the inhabitants consisted of intensive fishing, woodcutting, or charcoal making (Heritage n.d.). Leading up to World War II, charcoal was one of St. Lucia's top exports, but in the 1980s, concerns about rapid deforestation led to a significant reduction in this industry. Deforestation for fuel wood is still an issue today due to spotty enforcement of regulations (UNESCO 2010).

During the Second World War, St. Lucia became home to a US Air Force base on 1200 acres, which had been allocated by the British Empire. With its construction, several natural land features needed to be altered or removed, including streams and mangroves, in order to make way for the infrastructure (Burns and Novelli 2011). This meant that the installation had a significant impact on the environment, but after the base was dismantled and the land handed back, St. Lucia was left with roads, sewage lines, electricity, an airport, and a harbor. Despite the intrusion from the USA, this infrastructure enabled the future development of the agriculture and tourism industries.

Bananas became St. Lucia's primary agricultural export after large-scale sugarcane production diminished with the dissolution of slavery. Today, bananas are still St. Lucia's leading export (Exports 2013), though only 5% of national GDP comes from agriculture, while 80% comes from tourism and services (Lashley 2013; United 2009). Even though St. Lucia has been transitioning from an agriculturally based economy to a tourism and services-based economy since the early 1990s, agriculture is still a prominent feature on the island, and the significantly reduced agricultural industry is still actively shaping the landscape. The Roseau River feeds the banana plantations in the Roseau Valley, and it is a significant source of drinking water for the island (All n.d.). The Roseau Valley plantations are the most extensive agricultural area on the island, and the success of hillside agriculture in Roseau inspired similar work in Cul de Sac Valley and Mabouya Valley (Department 1986). In eastern St. Lucia, Mabouya Valley has been used heavily for agriculture, despite steep sides susceptible to landslides and a previously swampy valley floor that needed to be drained before it could be used. Modern erosion control techniques have led to hillside agricultural developments, including bananas, coconuts, and mangoes. Mabouya Valley is home to a nature and heritage park called Fond D'Or, where a colonial sugar mill was built over a former Amerindian settlement. This park provides an interesting cross section of the way landscape has been used through time (Heritage Sites n.d.).

Mangrove use on St. Lucia for fuel by French and British colonial powers began at Mankòtè Mangrove in 1760. Currently, there are only 18 mangrove sites remaining in St. Lucia, all of them are now Marine Reserves due to government recognition of their ecosystem value. The mangroves serve as the main source of nutrients for the island's natural fish nursery. However, enforcement of these reserves is highly variable, and the general public opinion still undervalues the mangroves (Wilkie 2005).

Other than for existing tourism purposes, the geothermal features on St. Lucia have not been tapped for use. While long explored through surveys and the drilling of shallow wells, the contemporary development of the geothermal potential of Sulphur Springs has been limited by lack of finances and the high cost of geothermal exploration (Geothermal energy in St Lucia 1989). These are examples of the ways that the striking landscapes in St. Lucia have been shaped by centuries of human impact, agricultural production, and the gradual increase of tourism. These examples serve to illustrate the ways that mixed development now informs the island's overall appearance, with some landscapes secluded and protected by the government, and others under endless fields of agricultural production or impacted by tourist pressure.

13.5 Heritage and Tourism

With the emergence of mass tourism in the Caribbean region in the mid-1960s, St. Lucia became a popular destination and progressed along the lines of large area foreign-owned development (Fig. 13.9). This type of tourism has been characterized by the standard 3S (sun, sea, and sand) tourism product and cruise ship tourism (Fig. 13.10). As the island has transitioned from agriculture to tourism, with a noticeable increase in visitors and rapid hotel growth, there has been a concurrent rise of resource use conflicts and planning challenges as land, labor, and capital are competed over (Fig. 13.11; McElroy 2003). Tourism and its related infrastructure have also brought threats to the environment in St. Lucia. Inadequate sewage treatment facilities have historically led to degraded shore marine water quality and coral reef death. Government action to establish sewage and wastewater treatment plants in the most heavily populated tourist areas like Rodney Bay area has attempted to reduce these impacts. Other tourism-related impacts include coral damage from divers and boat anchors, and sand compaction from heavily trafficked beaches (Nagle n.d.).

The construction of coastal tourism facilities and roads in ecologically sensitive areas has caused stress in marine environments. The building of tourism infrastructure has resulted in the destruction of mangroves and beaches. In addition, sand mining, dredging, and sewage dumpling caused the environmental degredation of a lagoon. Wetland areas function to create the ideal conditions for coral reef development; hence, their removal impacts the formation and health of coral reefs and the flora and fauna that inhabit them. A mangrove was destroyed in order to build the Rodney Bay Marina. The construction of the Pigeon Island causeway, which involved sand mining for construction and coastal erosion from coastal engineering works, altered the coastal water flows, caused siltation of coral reefs, and brought about the virtual wiping out of the nearshore fishing industry in Gros Islet (Nagle n.d.).

Since the 1990s, there has been a growing awareness in St. Lucia of the potential and need for promoting an alternative tourism based on its nature and culture. As a result, several localized ecotourism opportunities have been developed in St. Lucia and these have been instrumental in the island being labeled as a "Nature Heritage Tourism" destination (Weaver 2001). The tourism industry in St. Lucia is fueled by the island's beautiful natural landscapes, dominated by tropical rainforest. The island's government recognizes the tourist appeal of these areas, and 13% of the island is reserved forest (Arce 2009). St. Lucia's National Rainforest, covering 7690 hectares, is in a protected area in the southeast of the island, which also encompasses the Pitons (Natural Attractions n.d.). While the mountainous twin Pitons provided a safe haven and base for plotting rebellion for runaway slaves in the eighteenth century, today, tourists hike the Gros and Petit Pitons. Petit Piton involves a technical climb to reach the summit, and safety equipment must be brought in (Trend 2015). There is no hiking allowed in any protected rainforest without paying an entrance fee to

Fig. 13.9 Aerial view of Gros Islet, the town at the connection between Pigeon Island and the mainland, which is a popular tourism destination in and of itself with beach resorts, inland port, and coral reefs. Pigeon Island is to the *left* of the image. Photograph by A. DeGraff Ollivierre

the St. Lucia Forestry Department, and trails are typically guided (Ministry of Agriculture, Food Production, Fisheries, Cooperatives & Rural Development n.d.).

The Pitons Management Area (PMA) is a multiple use protected area of 2909 hectares. Located near the town of Soufriere, the PMA consists of both marine and terrestrial environments, encompassing the Pitons and the Sulphur Springs. This site was given World Heritage Status in 2004 and is St. Lucia's most visited attraction with 200,000 visitors annually (Nicholas et al. 2009). Reefs protect 44% of St. Lucia's coastline (Maps and Data 2008), and there are 20 marine protected areas (MPAs) in the country, many of which have significant coral reef content (St. Lucia n.d.). The MPA contained in the Piton Management Area has up to 60% coral reef coverage (UNESCO n.d.). Many of the other MPAs have experienced highly variable management practices, with differing success in protection and maintenance. The most well maintained of St. Lucia's MPAs is the Soufriere Marine Management Area (SMMA), an 11-km stretch along the southwestern coast of St. Lucia (Renard 2001).

The Soufriere Marine Management Area (SMMA) protects Soufriere Bay as well as the surrounding waters. The SMMA is divided into five different zones dependent on the activity allowed ("Pitons Management Area Saint Lucia"). Unfortunately, this type of care toward its natural landscapes has not always been apparent, as seen in 1969 when the wetlands surrounding the town of Gros Islet, once a small fishing village, were drained to reduce the available breeding ground for sand flies, which were irritating to the tourists. The land was thus reclaimed but with unforeseen consequences, such as stronger currents that began to erode some of the nearby beaches (Nagle 1999).

The northern city of Gros Islet and nearby Rodney Bay have become major scenic backdrops for the island's tourism marketing efforts. In 1970, a development plan was executed

Fig. 13.10 An example of tourism impacts and activity on St. Lucia, with cruise ships docked at Castries. The majority of tourists that visit the island do so as part of Caribbean cruises and spend most of their time in Castries, although various tours are offered to other parts of the island. Photograph by A. Potter

by the Caribbean Development Corporation to make use of the well-situated area (McGregor 1998). To the south of Gros Islet is Rodney Bay, named after an English admiral ("Pigeon Island National Landmark"). Shortly, after draining the wetlands near Gros Islet, an artificial lagoon was installed in Rodney Bay. This bay, with expansive Reduit Beach, was utilized heavily by pirates in the 1700s and 1800s, and its notoriety has added to its tourist appeal (Things to do n.d.). Rodney Bay's popularity has limited development in Marigot Bay to the south. Surrounded on three sides by steep, heavily forested hills, Marigot Bay is a secluded inlet. This bay, considered one of the most picturesque in the Caribbean, was featured in the 1967 "Dr. Doolittle" film. Long popular with yachters, it has been built out in recent years to accommodate increased tourist demand (Visions of St. Lucia Tourist Guide n.d.). This increased use of coastal resources is one of the most common landscape conflicts in St. Lucia today. Traditional fishing practices are slowly being edged out by increasing use of coastal regions by yachts, tourists diving to coral reefs, and coastal development that leads to erosion, and pollution of the water (Morales 2011).

13.6 Hazards

St. Lucia is exposed to a number of natural hazards, such as tropical storms, hurricanes, heavy rainfall, winds, occasional droughts, landslides, earthquakes, and eruptions. Weather-related hazards, like hurricanes, are the most severe climatic disturbance in St. Lucia. In 1980, Hurricane Allen destroyed the agricultural sector and killed nine people (Meditz and Hanratty 1987). The hurricane seasons of the 1970s and 1980s were relatively tame in comparison with the 1990s, when seven devastating hurricanes or storms hit the Caribbean. The inhabited and more developed coastal areas between Gros Islet and Castries, where 60% of the population is living, were greatly impacted. This part of St. Lucia is particularly vulnerable because it is composed of low-lying, flood-prone land. Loose regulations and outright

Fig. 13.11 Local man collecting mineral-rich volcanic mud by bucket to ensure an ample supply at the Sulphur Springs Volcano Mud Baths near Soufrière for tourists. While the therapeutic mud accumulates naturally in the springs, increased tourist demand has made it necessary to manually retrieve the substance from areas upstream. Photograph by A. Potter

illegal development along the coast have worsened these problems. Between 1970 and 1999, St. Lucia suffered economic losses equally 272% of the country's GDP due to hurricane and hurricane-related damage, such as flooding or storm surges. In terms of geological impacts, Hurricane Lenny, an unusual west to east traveling hurricane occurring in 1999, washed away beaches from the white-sanded western coast (Mycoo 2011).

Flood and coastal erosion threats in St. Lucia come mainly from storm surge and coastal wave action. Low-lying coastal areas, such as Dennery and the area of Anse La Raye, are especially susceptible (The World Bank and GFDRR 2010). Coral reef habitat has also been shown to suffer from the effects of storms and sedimentation (Hawkins et al. 2006). St. Lucia, along with five other Caribbean nations, was listed as one of the world's top 40 climate hot spots. Models that attempt to predict the effects of climate change on St. Lucia estimate drier seasons, more heat waves and droughts, increased rainfall when it does occur, and rising seas levels, which could particularly affect St. Lucia's predominant coastal development. In addition, climate change can also cause the sea temperature to change, leading to more intense storms (The World Bank and GFDRR 2010).

With its steep slopes and patterns of heavy rainfall, St. Lucia is particularly prone to landslides. Tropical storm Debbie was responsible for extensive landslides in 1994. A recent initiative in collaboration with the World Bank has been hailed as a success story in the Caribbean. When Hurricane Tomas hit the island in 2010, hillside communities in St. Lucia that had implemented the initiative were not affected by landslides. St. Lucia's vulnerability to adverse natural events has been reduced, through improvements such as rehabilitation bridges, coastal protection works, and small mitigation works in various communities across the island. They have significantly increased the percentage of population with access to improved infrastructure, from 30% to an estimated 80% (The World Bank 2013).

St. Lucia's location on the eastern margin of the Caribbean Plate means that it is commonly subjected to lowest magnitude, low-risk earthquakes (The World Bank and GFDRR 2010). The Qualibou Caldera, with its Soufrière Volcanic Center, is considered to be the only volcanically active center on the island. The last recorded eruption was in 1766, and the most recent activity was a swarm of minor volcanic earthquakes in 2000. Some of these earthquakes were located beneath older basaltic centers previously considered to be "dead," such as Mount Gomier (Lindsay et al. 2002). The phreatic (steam) eruption in 1766 deposited a thin layer of fine ash-like material of mud, old altered rock, and mineral fragments over the area. Within the Soufrière Volcanic Center, St. Lucia's Sulphur Springs is an active geothermal area with numerous hot springs, bubbling mud pools, and fumaroles. Underground acidic water below Sulphur Springs causes rock alteration, resulting in soft and unstable soil that is prone to landslides, especially triggered by earthquakes. An example of such a landslide was reported on the Terre Blanche flank of Sulphur Springs in 1990. Over time, any migration of geothermal activity at Sulphur Springs will potentially increase the chances for landslides in areas with steep slopes (Lindsay et al. 2002). Landslides in geothermal areas in St. Lucia, in turn, can affect the internal material of a system, causing a hydrothermal eruption.

Many mountains in southern St. Lucia are thought to be the work of one volcano with many vents. This volcano, Soufrière Volcanic Centre (SVC), is the only volcano on the island and it is unknown when it may erupt again. Many of the other Lesser Antilles islands have a single, potentially active volcano with a history of activity. However, St. Lucia does not have one clear volcanic vent from which future eruptions are expected, making it challenging to predict when and where the next magma eruption will take place (Lindsay et al. 2002). Prior eruption history for the island suggests that the Soufriere Volcanic Center is the best potential location for future eruption on St. Lucia. The most likely scenario for future activity is a short-lived (a few hours or days) phreatic or hydrothermal eruption (not containing any magma) from the Sulphur Springs area with effects contained to the surrounding area (University of the West Indies 2009–2011).

13.7 Conclusion

St. Lucia's dramatic landscapes have provided for its inhabitants over the island's history. Today, this landscape provides all the ingredients for a successful tourism industry. Tourism in St. Lucia is evolving from the traditional sun, sea, and sand to include alternative tourism attractions such as land- and sea-based nature tourism and cultural heritage tourism. While this brings in more tourists and a greater potential stream of capital for development, it also means that formerly relatively untouched geological landscapes are being exposed to environmental degradation. A concern would be that if the natural landscape and ecological systems suffer from too much degradation, this could negatively impact the island's tourist capacity, and thus reduce the desired development impact from tourism. Directed government policies and actions can and do play a role in reducing the harmful effects of agriculture and tourism on the environment. There has been a significant decrease in environmental impacts despite the rise in human footprint because of the revenue generated from tourism and the St. Lucian government being proactive (Sharmon 2005). Will it be enough, however, as St. Lucia tries to develop its economy using a strategy that promotes tourism to its most ecologically sensitive geological sites?

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Barbados

14

Mick Day and Patti Day

Abstract

Barbados is unique in the Lesser Antilles, in that it is an exposed portion of an accretionary prism, with no volcanic basis. Pleistocene carbonates cover some 85% of the island, and terraced karst terrain, with dry valleys and dolines/sinkholes dominates the landscape. The Scotland District is composed of siliclastics, which have been disturbed by fluvial erosion and mass movements. Distinct wet and dry seasons result in paradoxical flooding and drought, both accentuated by human interference, particularly colonial agricultural clearance and twentieth-century mass tourism, and risks are likely to increase because of projected anthropogenic climate change. Maintaining adequate water supplies is a perennial problem, and occasional flooding represents another major hazard. Mass movements afflict the Scotland District, and there are under-appreciated karst collapse and tsunami risks. Conservation-based land use management and planning is poorly developed, yet vital to residents and a sustainable tourism-based economy.

Keywords

Accretionary sediments • Limestones • Reefs • Karst • Drought • Water supply • Floods • Human impacts

14.1 Introduction

Barbados, the most easterly of the Caribbean islands, has a land area of about 432 km^2 and a coastline some 92 km in length (Carter and Singh 2010; Government of Barbados 2010; Fig. 14.1). Barbados is unique within the Lesser Antilles in that it has no volcanic basis, being composed entirely of sedimentary rocks, with the exception of minor volcanic ash beds (Humphrey 1997; Speed 2012). Geologically, the island is dominated by carbonate rocks (primarily limestones) of Pleistocene age (2.6 Ma–11.7 ka), which were formed predominantly as fringing coral reefs and have now been uplifted tectonically as a series of terraces that occupy about 85% of the island (Day 1983; Humphrey 1997; Donovan 2005; Government of Barbados 2010; Speed 2012; Kambesis and Machel 2013). Separated from the overlying limestones by a thin sheet of Miocene chalks and marls, the remainder of the land area is underlain by older sandstones, siltstones, and clays of the Tertiary Scotland Series (Patel 1995; Humphrey 1997; Government of Barbados 2009, 2010; Speed 2012).

Elevations range from sea level to 340 m at Mount Hillaby (Donovan 2005). Numerous terraces have been documented at elevations ranging from 3 m to 192 m (Humphrey 1997), with particularly conspicuous examples at about 30 m (First High Cliff, 125 ka) and 170 m (Second High Cliff, 460 ka) serving as litho- and chronostratigraphic markers separating the Coral Rock Formation into Lower, Middle, and Upper members (Fig. 14.2; Humphrey 1997). On and within the limestones has developed a karst landscape, produced essentially by carbonate dissolution, containing numerous dolines (sinkholes), extensive dry valley

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Fig. 14.1 General physiographic map of Barbados. Low-lying plains dominate the southern region with single perennial river, Constitution River, flowing from the central highlands. Cartography by K.M. Groom

Fig. 14.2 The Second High Cliff of Barbados. Note the limestone outcrops on the cliff and the small doline (*light-colored area*) at the vegetation break in the middle distance, just *left of center*. Photo by M. Day

systems, springs, and cave systems (Kambesis and Machel 2013). The poorly consolidated sedimentary rocks of the Scotland District are extensively eroded by gullying and slope failures (Patel 1995; Government of Barbados 2010; Speed 2012).

The climate is dry sub-humid with temperatures between 20 and 30 C. Mean annual rainfall ranges with elevation between 1254 and 1650 mm, with evapotranspiration generally exceeding precipitation, and with a distinct dry season from January through May and an August–December wet season (Government of Barbados 2009, 2010; Carter and Singh 2010). Soils on the limestones are mostly mollisols and vertisols, with complex components including detrital carbonates, Antillean volcanic ash, and Saharan dust (Muhs 2001). Soils in the Scotland District are immature and strongly controlled by parent materials, being dominated by sands and clays (Patel 1995).

Barbados represents perhaps "…the wealthiest and most developed country in the Eastern Caribbean," with a resident population nearing 300,000 (CIA 2015). The population density at about 638/km^2 is the highest in the Caribbean and among the densest 20 in the World (CIA 2015). Annual population increase has been effectively limited to about 0.3% (Government of Barbados 2010; CIA 2015) but visitor numbers have increased steadily to about 500,000 annually (Caribbean Tourism Association 2011), effectively doubling the population impact. The resident population, of which about 40% is urban, remains concentrated along the west, south, and southeast coasts particularly around Bridgetown in St. Michael parish and also in St. Philip, Christ Church, St. James, and St. Peter (Government of Barbados 2010).

Human impact on the landscape has been long term and profound, resulting in wholesale environmental changes. Drought and water supply are fundamental problems, as well as accelerated erosion and, paradoxically, occasional flooding. Environmental issues are intensified by the combination of limited land area, the predominance of karst landscape, (ironically) relative economic wealth, and mass tourism.

14.2 Setting

Barbados is the only emergent portion of the Barbados Ridge Accretionary Prism, "…an elongate, arcuate accretionary complex…east of the Lesser Antilles magmatic island arc and the Tobago Trough forearc basin," formed by subduction of the South American Plate under the Caribbean Plate (Humphrey 1997: 382; Donovan 2005). An Eocene marine mixed sedimentary basement is overlain by Miocene chalks, marls, and radiolarites, which in turn are capped by up to about 100 m of Pleistocene limestones (Fig. 14.3; Speed 2012; Limonta et al. 2014).

The island is dominated areally by Pleistocene limestones of the Coral Rock Formation, or "Coral Cap," most of which originated over the past 600 ka during eustatic high sea level stands as a series of discontinuous coral reefs fringing the Tertiary island core (Bender et al. 1979; Poole and Barker 1983). Subsequent and ongoing tectonic movements during eustatic lowstands have elevated the reefs, forming a series of terraces. Each of these essentially represents a separate reef complex (Mesolella et al. 1969), with terrace risers consisting of rear-zone, reef-crest, and fore-reef lithologies,

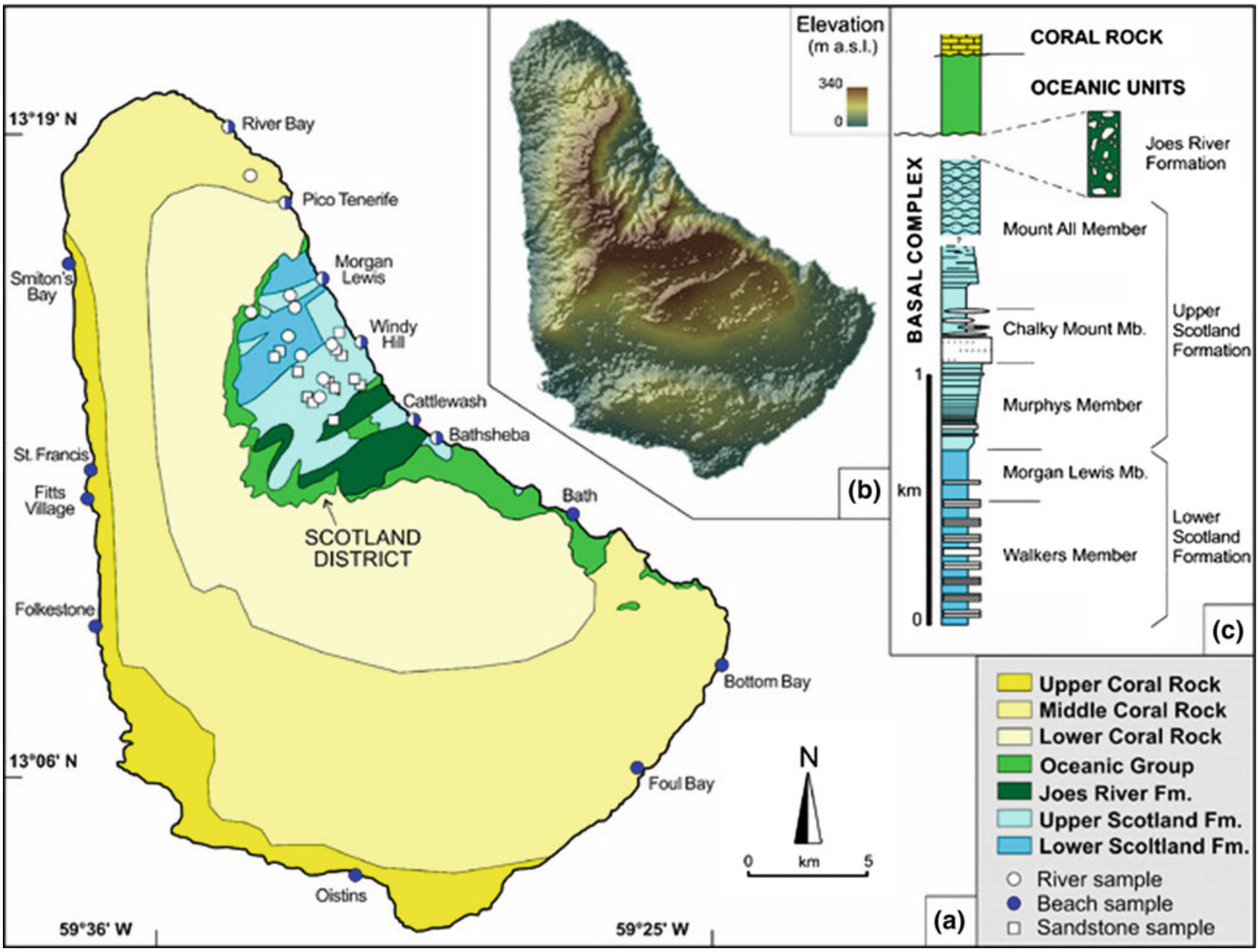

Fig. 14.3 Geologic map of Barbados (**a**) by (Limonta et al. 2014), with accompanying topographic relief image (**b**), and stratigraphic column (**c**), with sample points denoted by small circles. Available from https://www.researchgate.net/profile/Eduardo_Garzanti/publication/268528051/figure/fig1/AS:272681375367224@1442023714925/Figure-3-Geological-sketch-map-a-topography-b-and-stratigraphy-c-of-Barbados.png

and landings composed of backreef deposits (Humphrey 1997), although at least locally the situation is more complex (Schellmann and Radtke 2004a, b; Speed and Cheng 2004). Highstand reef deposition probably occurred over periods of 10–15 ky^{-1} (Humphrey 1997) and uplift rates have been estimated at between 0.12–0.22 m ky^{-1} (Jones 2009) and 0.3–0.4 m ky^{-1} (Speed 1994).

The older and higher limestones in the center of the island are relatively well-lithified biomicrites, but most of the later Pleistocene carbonates are poorly consolidated, although interactions with meteoric and mixing-zone waters have resulted in a wide range of diagenetic modification (Humphrey 1997). The Coral Rock Formation, although variable, averages about 70 m in thickness and overlies Oligocene–Miocene chalks and marls that act as a regional aquiclude (Humphrey 1997).

The sedimentary basement beneath the limestones consists of four major units of structurally complex allochthonous tertiary marine rocks exposed only in the Scotland District (northeast of the island), where the overlying limestone has been eroded (Speed 1994, 2012; Donovan 2005). The Scotland Formation, an Eocene complex of terrigenous turbidites and hemipelagic/pelagic radiolarites, is overlain by Miocene prism-cover rocks deposited in the Woodbourne Trough, and in thrust contact with these are nappes of calcareous (hemi) pelagic rocks interbedded with volcanogenic ashes, constituting the Oceanic Formation. Intruding into these three units are "…tectonic diapirs consisting of a mélange of organic mud matrix" (Humphrey 1997: 383).

14.3 Landforms

Speed (2012) recognized four geomorphic zones reflecting the geological structure and topography: the Central Highlands, the Terraced Flank and the Windward Slope on the limestones, and the Scotland District. On and within the limestones, carbonate dissolution and associated processes have developed a karst landscape dominated by dolines (sinkholes), dry valleys, caves, and springs (Fermor 1972; Day 1983, 2009; Kambesis and Machel 2013). Surface water is rare here, except during particularly intense rains, when sinkholes might fill with localized ephemeral runoff, and normally dry valleys may channel dangerous floodwaters. Except during these events, drainage is predominantly subterranean, via rapid infiltration into and percolation through the thin soils, then transmission at various rates via pores, fissures, and conduits through the limestones to the groundwater aquifer and/or to terrestrial and coastal springs.

The most conspicuous karst landforms are the extensive dry valley systems (Fig. 14.4), which in many aspects represent the Caribbean type-example (Fermor 1972; Day 2002). Ranging from shallow to steep-sided, with or without distinct stream channels, and wooded or farmed, these valley systems are significant geomorphologically, because they represent earlier phases in the karst development when secondary permeability was not sufficiently developed to permit total subterranean drainage, and runoff occurred via "normal" fluvial valleys (Smith 1975). As secondary permeability has increased through carbonate dissolution, drainage has increasingly been diverted underground, and the valleys have been essentially abandoned, only to be activated during intense rainfall, when the capacities of the karst plumbing system and its overlying soils are exceeded (Smith 1975; Day 2002). As such, in a sense, they represent ephemeral drainage systems, and their persistence indicates that karstification has not yet progressed to the extent that surface drainage has been completely abandoned and the valleys obliterated by doline development, as appears to be the case in older karst landscapes elsewhere in the Caribbean (Day 2002).

The precise development of the Barbados dry valleys remains contentious among researchers, with both surface drainage and speleogenesis implicated (Kambesis and Machel 2013). Many valleys are clearly surface erosional features, but others resemble collapsed caves. Still others appear to have polygenetic origins (Speed 2012), with Kambesis and Machel (2013: 10) advocating a complex scenario involving five stages: (1) initial surface erosion, (2) flooding during sea-level rise, and the development of flank margin caves in the valley walls, (3) renewed surface erosion and vadose speleothem formation in the valley flank caves following sea-level fall, (4) partial marine erosion associated with further sea-level rise, and (5) "…final exposure…through tectonic uplift, resulting in wide gullies with opened flank margin caves that are lined with speleothems."

Dolines are often regarded as diagnostic of karst landscape (Ford and Williams 2007), and more than 2800 occur in Barbados (Kambesis and Machel 2013), with initiation still occurring through small collapses, both within and beyond existing depressions (Day 1983; Fig. 14.5). Dolines are generally shallow and near-circular, with a tendency

Fig. 14.4 Coastal dry valley in Christ Church parish with a dry channel in the valley axis. Most of rivers depicted radiating from the highlands on maps of Barbados are actually dry valleys and ephemeral streams such as this one. Photo by M. Day

Fig. 14.5 Localized collapse within a doline/sinkhole in St. Thomas parish with exposed limestone and gullying on the doline flanks. Photo by M. Day

toward clustering, and sampling has suggested systematic variations in their density, with increasing densities up to about 150 m elevations, and lower densities at higher elevations (Day 1993). Rainfall often collects in larger interfluvial dolines, while smaller shafts within the valleys transmit water rapidly into the karst aquifer (Jones and Banner 2003).

The relationship between dry valleys and dolines is not entirely clear, although it is probable that formation of the former precedes that of the latter (Smith 1975; Day 2002). Fermor (1972) suggested that the features were competitive, in the sense that each developed preferentially under different hydrological conditions. It has also been suggested that dolines typify flatter areas, whereas valleys occur on more steeply sloping surfaces, although the nature of this relationship is not explicit, and there may be distinct doline subpopulations in valley and interfluve locations (Day 1983; Jones et al. 2000, 2003).

There are over 100 known caves in Barbados (Kambesis and Machel 2013). Harrison's Cave, in the Highlands, is the best-known on the island (Hobbs 1994) and is developed for tourism, as is Animal Flower Cave, on the north coast. Kambesis and Machel (2013) recognize five types of caves: (1) *epigene*, formed by freshwater dissolution in the upland interior, (2) *flank margins*, formed by mixing-zone dissolution along modern and older coastlines, (3) *littoral*, formed by contemporary marine corrasion, (4) *mechanical*, formed by bedrock mass movement, and (5) *hybrid* (polygenetic), which constitute the majority on Barbados, often involving modification of flank margin caves.

Depending on interpretation, Barbados exemplifies either the composite or the carbonate-cover type of the carbonate island karst model (Mylroie and Vacher 1999; Mylroie and Carew 2000; Mylroie 2004). The geologically young carbonate rocks have not been buried beyond the range of meteoric diagenesis, and they interact both with fresh and saline groundwater that is affected by glacio-eustatic and tectonic changes in sea level, forming immature (essentially Neogene) eogenetic karst (Mylroie 2004). Significantly, however, the geological configuration is such that the older non-carbonate rocks of the Scotland District do not contribute significant allogenic discharge to the karst landscape, precluding development of a composite speleogenetic situation, and resulting in cave development taking place above and at the carbonate–non-carbonate contact. Kambesis and Machel (2013) ascribe Barbados to the composite category, suggesting that the epigene karst receives both autogenic and allogenic recharge, as well as hypogene karst being decoupled from the surficial hydrology.

The most prominent landform in the Scotland District is an unstable east-facing escarpment, below which detached limestone blocks are evident (Fig. 14.6). Below the escarpment are steep gullies, landslides, debris flows, slumps, and other mass movement features, generally correlated with geology and slope angle (Patel 1995; Hearn et al. 2001; Hodgson et al. 2002). There is evidence of slab or toppling failure from the escarpment, and headward gully erosion close to the escarpment has captured headwater drainage from limestone valleys, "…forming preferred locations of infiltration" locally (Hodgson et al. 2002: 282). Much of the accelerated erosion is human-induced, caused by removal of the pre-European forest cover and subsequent land use practices (Carson and Tam 1977; Patel 1995). Beaches are siliclastic, locally sandy or pebbly, and highly dynamic, with

Fig. 14.6 Large detached limestone block forming a coastal stack in St Joseph parish with a person for scale. The block has developed a wave undercut notch. Photo by M. Day

localized coastal sand dunes (Patel 1995). Coastal carbonate landforms illustrate the multifaceted interaction between terrestrial and marine geomorphic processes, with abrasional terraces, restricted tidal platforms (Fig. 14.7), littoral karren, cliffs with wave-cut notches, littoral caves indicative of saline-freshwater mixing, sea stacks, sea arches, carbonate clastic beaches, and localized sand dunes (Fig. 14.8; Lundberg 2004; Speed 2012).

The coastline of the Scotland District is particularly dynamic, featuring rapid delivery of sediments through fluvial erosion and slope processes, and effective removal by long-fetch Atlantic wave action. Cliffed erosional shorelines are characteristic of the windward northern and eastern coasts, contrasting with the sandy low-energy coasts to the leeward. Fringing reefs, particularly off the leeward coast represent contemporary analogues of the older features now exposed on the island itself, although the species composition differs (James et al. 1977).

14.4 Landscape

As with most other Caribbean islands, human impact on the landscape of Barbados has been long-term and severe (Watts 1987, 1988; Day 1993, 2010a, 2010b). Although Amerindians could have perhaps arrived as early as 2600 BCE (Fitzpatrick 2011), later dates of 350–650 BCE are more commonly accepted (Drewett 1993). The native population abandoned the island in the 1500s, following Spanish slave-raiding, when it was named by Portuguese. Barbados was claimed subsequently by the British in 1625 and gained independence in 1966 (Beckles 2006).

The physical landscape was devastated during the early colonial period by almost complete clearing of natural vegetation and the institution of sugar cane monoculture (Randall 1970; Watts 1987, 1988; Richardson 1997). A few steeper-sided gullies were spared, and these represent important ecological remnants, although invasive species are highly competitive (Waugh 2009). Destruction of the natural vegetation undoubtedly changed the hydrologic regime and may have contributed significantly to historical aridification (Watts 1987, 1988).

The nature of maronnage (resistance by escaped slaves) during the early colonial period was constrained by the limited area of the island and the subdued topography, which provided scant permanent isolation and little defensibility, but escaped slaves used caves and more remote wooded valleys as hiding places (Kambesis and Machel 2013) and took advantage of both the physical and the built landscape to create at least temporary refuge (Handler 1997).

Environmental issues that have been assessed as being of national priority include the inadequacy and unreliability of freshwater supplies, the degradation of coastal ecosystems, waste management challenges, the limited land area and inefficiency of land use, and natural hazards, including the challenges posed by climate change (Carter and Singh 2010). The overall environmental situation in Barbados mirrors that throughout the Caribbean, but it is magnified by the combination of limited land area, the predominance of karst landscape, (ironically) relative economic wealth, and mass tourism.

14.4.1 Hydrologic Implications

Water supply difficulties are largely a function of the contemporary and historical rainfall regime and the island's predominantly karst landscape. Surface drainage is usually of short duration, and water runs off quickly, particularly from impervious surfaces in urban areas, causing flooding

Fig. 14.7 A view overlooking the Atlantic Ocean from Barbados' northern coast, near Animal Flower Cave. Barbados is resplendent with such coastal karstscapes, such as these abrasional terraces and restricted tidal platforms. Photo by T. Zabarauskas

Fig. 14.8 Looking east along Barbados' northern coast, near Animal Flower Cave. Note the wave-cut platforms and notches, sea caves, and small sea arch (just *right of center*). A small platform/sea stump can also be seen just offshore (and to the *left*) of the far background, just below the horizon. Other coastal karstscapes exhibit similar features. Photo by T. Zabarauskas

and non-point pollution, and being effectively lost to human use. Land use in Barbados has changed considerably since the 1960s, with urban land increasing from 21.2 to 37.6%, and arable land declining from 57.7 to 46.2% (UNDSEC 2000; UNFAO 2004a).

In non-urban limestone areas, water usually drains underground rapidly, either diffusely via pores and fissures or discretely via sinkholes, drainage ("suck") wells and valley bases, to replenish a shallow and volumetrically restricted lenticular or wedge-shaped karst groundwater aquifer that varies in thickness seasonally from less than 5 m to nearly 20 m (Humphrey 1997; Jones et al. 2000). This overlies deeper saline water, separated by a mixing zone of similarly variable thickness (Humphrey 1997). Above the elevation of the groundwater aquifer, upper surface (about 20 m) water movement is vadose and occurs via a spectrum of voids in the limestones ranging from individual pores, through dissolutionally enlarged fissures to large conduits (caves). The contact with the underlying relatively impermeable Tertiary rocks acts as an aquiclude (Humphrey 1997). Freshwater aquifer recharge occurs almost entirely in the wet season and represents 15–30% of precipitation (Jones et al. 2000, 2003). This represents the major source of potable water, which is extracted via 21 municipal wells (with horizontal basal adits designed to reduce drawdown), and the Three-Houses and Porey's springs. There are also in excess of 100 private agricultural irrigation wells, and abstractions currently approach potential ground water yield estimates of 59.0 million m^3 per year in an average year and approximately 45 million m^3 per year in a 1 in 15 year drought (United Nations 1998; Government of Barbados 2010). Further restrictions result from limitations of the water distribution system, and available supply is below the 1000 m^3 per capita threshold at which a country is classified as "water scarce" (UNFAO 2004b), although three seawater desalination plants now supplement groundwater supplies, a wastewater recycling plan is now in operation (Johnson and Mwansa 2007), and there is an increasing awareness of the need for integrated water resources management (Farrell et al. 2007).

Through land use ordinances dating to 1963, so-called water protection zones were designed to provide partial safeguards against potential groundwater loss and bacterial contamination, and overall groundwater quality is good (Carter and Singh 2010). "Development" is most restricted in zone 1, but is unrestricted in zone 5. This zoning provides no effective protection against chemical pollution, and increasing nitrate and pesticide levels resulting from agriculture activities are of concern, as are incidents of accidental and negligent industrial and domestic pollution (Chilton et al. 1990; Carter and Singh 2010). Seawater intrusion into the shallow coastal aquifer is also an ongoing threat (Humphrey 1997).

14.4.2 Resource Conservation Efforts

Several agencies share responsibility for land use and resource management on Barbados, including soil conservation, environmental protection, sustainable agriculture, and planning, broadly under the auspices of the Natural Heritage Department (NHD), which was established in 2005. Rapid soil erosion is widely recognized as a problem within the Scotland District, but affects the karstscape as well. About 140,000 m^3 of limestone is quarried annually, mostly for road construction and maintenance (Government of Barbados 2009), and quarry expansion is a complex and contentious issue (Dey and Ramcharan 2008).

Solid waste management and disposal represent long-term and increasing problems, driven particularly by rising volumes of residential and tourist consumer waste. The capacity of the main sanitary landfill at Mangrove Pond, St. Thomas is limited, and illegal dumping is particularly problematic in dolines, valleys, and quarries, where it poses a serious potential for groundwater contamination and human health impacts. Hazardous waste represents a special problem, and recycling efforts seek to divert recoverable materials (Carter and Singh 2010).

Government agencies, international and national NGOs, and other groups have developed multiple and overlapping policies and programs to address environmental issues. Relevant government policies addressing water supplies, sustainable resource development, waste management, increasing land use efficiency, and improving disaster management include the National Physical Development Plan (1998), National Strategic Plan 2006–2025, Barbados Sustainable Development Policy (2004), and the Barbados Medium Term Strategy 2010–2014. Government retains its stronghold over physical development planning, effectively restricting the participation of the public and NGOs (Pugh and Potter 2002), and there remains a need for better coordination and effective implementation of plans and policies to achieve environmental protection and sustainable development (Mycoo 2006; Carter and Singh 2010).

All these environmental conditions notwithstanding, Barbados maintained its strong agricultural basis until the end of the twentieth century, following the ascension of tourism and the conversion of agricultural land to other uses (UNDSEC 2000; UNFAO 2004a). With annual tourist arrivals totaling some 500,000 (Caribbean Tourism Association 2011), the Barbados karstscape is among the most intensely visited globally (Day and Hall 2012), and this large, but temporary population influx places major demands on the water-supply system and the coastal environment (Burke 2002; Charara et al. 2011; Cashman et al. 2012).

14.5 Heritage and Tourism

The preponderance of Barbados tourism is focused on beaches, coastal hotels, relaxation, and hedonism (Dharmaratne and Brathwaite 1998), with only a minor component involving ecotourism and attention to local heritage (Mycoo 2006). Sustainability is highly questionable, both from environmental and economic perspectives, and projected climate change poses exacerbated challenges (Mycoo 2006, 2014; Cashman et al. 2012). The "…transformation of rural areas into up-scale leisure amenity landscapes…" (Bunce 2008: 969) creates conflicts between offshore elites and local interests and constrains implementation of sustainable environmental and development agendas (Fig. 14.9; Bunce 2008).

Barbados has only four IUCN-category protected areas, the Folkestone Marine Reserve (II), Harrison's Cave (III), Welchman Hall Gully (IV), and Turner's Hall Wood Nature Reserve (Ia). Other areas, such as Carlisle Bay, Jack-in-the-Box Gully, the Farley Hill Barbados Wildlife Reserve, and the Graeme Hall (Swamp) Nature Sanctuary (a threatened Ramsar wetland), are also accorded variable levels of informal protection, and 13 protected areas, including the 7000+ ha Barbados National Park are recognized within a prospective national protected areas system (Government of Barbados 2010).

Within the karstscape, Harrison's Cave has been a significant tourist destination since its commercial opening in 1981 (Hobbs 1994) and is touted as Barbados' "number one attraction," offering a variety of tours including those by electric tram and "eco-adventure" tours (Harrison's Cave 2015). Nearby Welchman Hall Gully has been developed as a

Fig. 14.9 One of several real estate lots for sale, looking south over the Atlantic Ocean from Inch Marlow near the island's most southern point. Notice the relatively flat relief, creating naturally (mostly) flat building plots. Photo by T. Zabarauskas

botanical garden by the Barbados National Trust, with a focus on restoration of native flora, and Farley Hill National Park features the ruins of a colonial mansion. By comparison, Barbados lags behind other Caribbean countries in protection of its karst landscape (Kueny and Day 1998; Day 2011).

Despite its relative inaccessibility from the airport and major tourism areas of the south and west coasts, the Scotland District has considerable ecotourism potential (Hearn et al. 2001). Despite the overall sensitivity of the steep slopes and poorly consolidated bedrock, the area has attractive and unspoiled high-energy beaches, with considerable potential for watersports, camping and hiking, and other nature-based activities (Patel 1995).

Degradation of coastal ecosystems is particularly acute in the highly populated southwest urban corridor and in tourism areas along the west coast, where infrastructure is infringing upon beaches, wetlands are being degraded and infilled, coastal water quality is decreasing, and coral reefs are in decline (Leitch and Harbor 1999; Lewis 2002). Such environmental impacts adversely affect residents and tourism alike (Carter and Singh 2010; Cashman et al. 2012). A Coastal Zone Management Unit was established in 1996, and a proposed Marine Management Authority potentially augurs well for improved integrated coastal zone management and this will also most likely affect the tourism industry.

14.6 Hazards and Environmental Issues

Drought and hurricanes (with associated floods) are the major natural hazards affecting Barbados, and projected anthropogenic climate change increases these threats, as elsewhere throughout the Caribbean karst (Day and Chenoweth 2009). Increased hurricane and drought frequencies have been experienced in recent years, with consequences including increased flooding, erosion, sedimentation, and decline in agricultural productivity (Carter and Singh 2010). Institutional, legislative, and societal shortcomings as well as questionable economic and development priorities exacerbate these problems (Pugh and Potter 2002; Bunce 2008; Carter and Singh 2010). Projected climate change has major implications both for the natural environment and human activities such as tourism (Cashman et al. 2012), with considerable differences of opinion about appropriate responses (Belle and Bramwell 2005).

Drought represents a perennial problem in Barbados, and human activities have only exacerbated it (Watts 1987; Richardson 1997). Seasonal water deficiencies, particularly for agricultural needs, are to be anticipated and can be prepared for, but longer-term rainfall insufficiencies are less predictable and, in tandem with inadequate storage and transmission capacities and unrestrained usage, pose serious societal problems (Peters 2015). Extended drought cycles with periodicities of about 50 years have been recognized (Burton 1995), and rainfall variability has been attributed to both the El Nino Southern Oscillation (ENSO) (Laing 2004) and the North Atlantic Oscillation (NAO) (Charlery et al. 2006). Barbados has experienced numerous periods of more-than-seasonal drought, most recently in 2009–2010 (Peters 2015), with subsequent environmental and human impacts.

The majority of Caribbean hurricanes pass north of Barbados (Mah and Stearn 1986), so their impact is generally limited to moderate winds and heavy rainfall, which may still be damaging. Still, eleven hurricanes, three of which caused severe damage, were recorded between 1651 and 1850 on Barbados, with the 1780 hurricane killing over 4000 people. Subsequent "hits" were recorded in 1895, 1955 (Hurricane

Fig. 14.10 Comparison of coastal landforms between windward and leeward coasts. A high-energy coast in St Lucy parish displays steep, eroded cliffs and limited tidal platforms (**a**), while a low-energy beach in St James parish, beckons the visitor to relax (**b**). The boat in (**b**) sits on a low beach berm, and the breaking waves indicate an offshore reef. Photos by M. Day

Janet), 1979 (Hurricane David), and 1980 (Hurricane Allen) (Mah and Stearn 1986). The most recent to hit the island, Hurricane Thomas in 2010, caused only minor damage.

Flooding in the karstscape is a particular danger, since dolines and dry valleys contain water only occasionally, and the potential risk of flooding is often underestimated. Extensive networks of check dams and drainage ("suck") wells were installed to ameliorate flooding and aid groundwater replenishment during the colonial period, but these have now largely fallen into disrepair. The damaging flood potential in the karstscape, particularly where urbanization has occurred, is demonstrated by the 1995 flooding in the vicinity of Holetown and Weston, in St James parish (Leitch and Harbor 1999).

Surface collapse over karst cavities is generally a minor and localized hazard, although it may be accentuated by increasing groundwater withdrawal (Humphrey 1997). The most frequent result is agricultural inconvenience, but structural damage occurs occasionally, and a surface collapse over a cave in the Brittons Hill area of Bridgetown in 2007 resulted in five deaths (Government of Barbados 2009; Kambesis and Machel 2013). Welchman Hall Gully is also reported to be a collapsed feature (Donovan 2005).

In the Scotland District, hazards include accelerated soil erosion, gullying, landslides, and other mass movements, many of which are human-induced (Carson and Tam 1977) and some of which have caused structural damage and abandonment (Hearn et al. 2001; Hodgson et al. 2002). The Boscobel Landslip of October 1901 displaced some 10 million cubic meters of material, and mass movements of similar magnitude continue to represent a potentially significant hazard (Cruden et al. 2014).

Although tectonism and volcanism do not pose immediate local threats to Barbados, there is a risk of tsunami impact, resulting from earthquake activity elsewhere in the Caribbean (Scheffers and Kelletat 2006). Recognizing that earthquake and tsunami risk in the Caribbean has long been underrated, the Caribbean Tsunami Information Center was established in Barbados in 2013 and remains the only tsunami-warning mechanism for many Lesser Antillean islands.

14.7 Conclusion

Barbados is unique geologically within the Lesser Antilles, but its karst landscape—dolines, dry valleys, and caves—serves as a model for karst elsewhere in the limestone Caribbees. The raised reef terraces are Caribbean type examples, with considerable paleoenvironmental significance and parallels with contemporary reefs and coastlines. Landforms in the Scotland District provide a marked contrast, exemplifying considerable dynamism in the form of extensive slope instability and a readily erodible coastal fabric.

Visitors often regard Barbados as a Caribbean paradise, with warm weather, fine beaches, and interesting coastlines (Fig. 14.10), a verdant landscape, a vibrant, thriving population, and a sound economy, but the reality is somewhat different. The climate poses extreme risks of drought and flood, and the geology compounds these through the prevalence of karst landscape, with its inherent hydrological complexities, and the presence of poorly consolidated rocks in the Scotland District that are easily eroded and subject to rapid mass movements. Coupled with a history of landscape devastation, poorly developed conservation practices, unsustainable mass tourism, and projected climate change, Barbados faces a difficult future, in which rational land use planning needs to give full weight to the underlying geological and geomorphological frameworks.

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Saint Vincent and the Grenadines

15

Russell Fielding and Alison DeGraff Ollivierre

Abstract

Saint Vincent and the Grenadines is a southern Caribbean archipelago consisting of one major island, seven smaller, inhabited islands in the Grenadines, and numerous other uninhabited islets and cays. Geologically and culturally, St. Vincent differs from the Grenadines. St. Vincent is a large island, forested and mountainous, heavily dependent upon agriculture, and entirely the product of volcanic activity. St. Vincent's stratovolcano, La Soufrière (1178 m), has erupted several times since European settlement, most recently in 1979. The Grenadines consist of small, tourism- and fishery-dependent islands, which are more arid, and geologically much older and more complex. The entire archipelago is subject to a suite of natural hazards, owing to its geography, with St. Vincent particularly susceptible to volcanic hazards.

Keywords

Saint Vincent • Grenadines • Volcanic • Coralline • Archipelago

15.1 Introduction

15.1.1 Orientation

St. Vincent—lushly forested on the flanks of its volcanic peak, La Soufrière—together with the Grenadines, is billed in some tourism literature as "the Caribbean you're looking for" (SVG Tourism Authority 2009). The main island's interior landscape is steep, rugged, and largely undeveloped. The coastline is urbanized in places—most notably the area surrounding the capital of Kingstown—but far from completely developed. In fact, St. Vincent's coastal road does not even travel the entire island's circumference, such is the lack of development in the hinterlands.

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St. Vincent is a relatively large island (344 km^2) situated between 13° 23′ and 13° 07′ North latitude (Fig. 15.1), while the Grenadines are a chain of smaller islands (the inhabited of which range from 0.4 to 16 km^2), islets, rocks, and reefs dotting the shallow sea between the larger islands of St. Vincent in the north and Grenada in the south (Fig. 15.2). The international boundary between St. Vincent and the Grenadines and Grenada passes through the archipelago between the (relatively) larger inhabited Grenadine Islands of Union Island and Carriacou. According to local knowledge, the northernmost tip of Carriacou, at Gun Point, is also technically part of St. Vincent and the Grenadines, due to the political boundary originally being drawn along a line of latitude. Apart from this artifact land border, the border falls between the two small islands Petit St. Vincent (PSV) and Petite Martinique (PM), which lie less than a kilometer apart. This chapter will limit its discussion of the Grenadines to only those islands politically linked with St. Vincent, as Chap. 16 will cover Grenada and its Grenadines.

At the northern end of the archipelago, the island of St. Vincent serves as the economic, cultural, and political hub of the nation. Physically and culturally, the Grenadine islands

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Fig. 15.1 General physiographic map of St. Vincent depicting radiating rivers and central mountain range, as well as St. Vincent's location just north of the Grenadines (see inset map). Cartography by K.M. Groom and A. Ollivierre

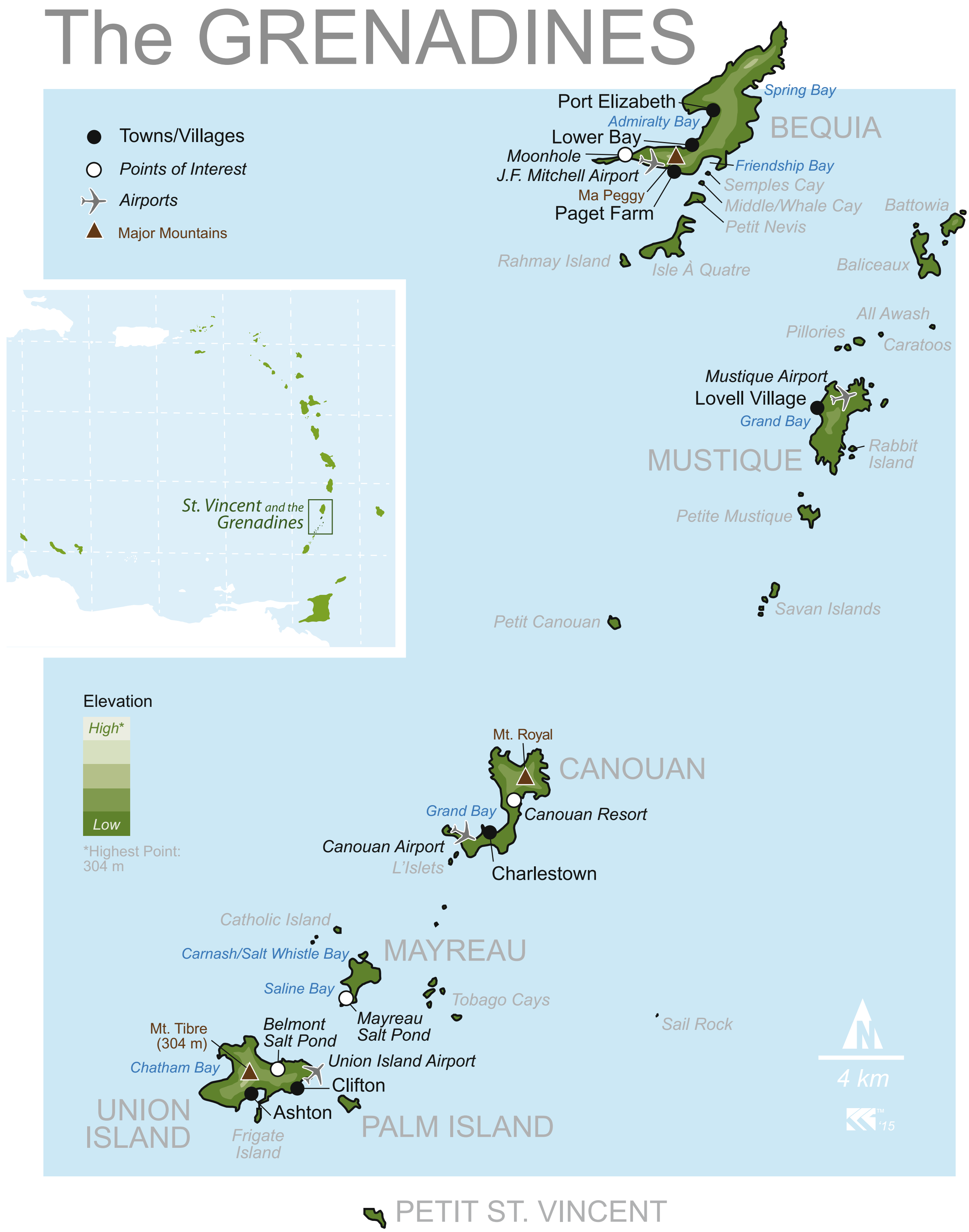

Fig. 15.2 General physiographic map of the Grenadines. In order to maintain accurate size and distance between islands, topographic representation is not as detailed as other maps in this volume. Please note: The names of the inhabited islands are shown in all caps whereas names of uninhabited islands and cays are lowercase. Cartography by K.M. Groom and A. Ollivierre

differ starkly from St. Vincent. In terms of landscape, the Grenadines represent more of the stereotypical Caribbean island scenery, white sand beaches, crystalline blue water, and bright coral reefs, while St. Vincent's shoreline rises steeper and rockier from the ocean, with many of the beaches marked by dark-colored, volcanic sand. Culturally, the Grenadines also differ from St. Vincent in that they support less urbanization, with economies based primarily on fishing and tourism, rather than agriculture.

15.1.2 Previous Work

Much of the early geological interest in St. Vincent related to eruptions of its iconic stratovolcano, La Soufrière. Scientists (e.g., Anderson 1903; Flett 1908; Aspinall et al. 1973; Barr and Heffter 1982; Fiske and Sigurdsson 1982) have recorded and described all three of the twentieth-century eruptions—1902, 1971–1972, and 1979—however, earlier eruptions, while occasionally documented, lack rigorous scientific data.

The Grenadines, being much older than St. Vincent and with no volcanic activity since the time of human settlement, attracted a different type of early scientific interest. As in other locations, the first scientists to explore the Grenadines geologically—paleontologists—sought fossils. Donovan (2003) cites Earle's and Trenchmann's collections (taken in 1924 and 1934, respectively) as the first from the region, though these fossils originated on Carriacou, in Grenada's Grenadines. More recently, archaeologists (e.g., Fitzpatrick and Kappers 2013) have analyzed pre-Columbian sites in St. Vincent's Grenadines, such asUnion Island and Mustique.

Anthropologists and historians (both amateur and professional) visited St. Vincent and several of the Grenadines, searching for rock engravings, petroglyphs, and other signs of past cultures during the late nineteenth century. Ober (1880) and Brinton (1889) conducted early, notable research. Occasionally, these and other early researchers would remark on the landscapes and landforms of the islands as a way to create a backdrop for their specific subjects of study.

15.2 Setting

15.2.1 St. Vincent

Like most islands of the inner arc of the Lesser Antilles, St. Vincent is volcanic in origin. Its volcano, La Soufrière, remains one of the most active in the region, having erupted both frequently and recently. The last major eruption occurred in 1979, the latest of three during the past century. Magma produced by the subduction of the South American Plate under the Caribbean Plate reaches the subsea surface at many points along the island arc, forming seamounts; islands occur when these seamounts extend above sea level. The majority of the island's structure, therefore, is basaltic and pyroclastic in composition. Relatively geologically young, at only approximately three million years, St. Vincent consists of a chain of stratovolcanic centers. Geologists conceptualize the island in four major regions: the Southeast Volcanics, the Grand Bonhomme Volcanic Center, the Morne Garu Volcanic Center, and the Soufrière Volcano (Robertson 2003b). Older sedimentary rocks exist, such as the Miocene specimens discussed by Robertson (2009), but have been brought to the surface as a result of uplifting and are rare on the surface of St. Vincent. Ample rainfall nourishes the forest in St. Vincent's mountains, giving the island a "rugged beauty," while rivers erode the soft volcanic rock and deposit dark sediment on the coasts, providing St. Vincent with its many characteristic black sand beaches (Robertson 2003a).

15.2.2 The Grenadines

With white beaches, shallow waters, and fringing reefs, the Grenadines have long been favored destinations of sailors, divers, and other tourists. The Grenadines represent the high points of the Grenada Bank, "a partially submerged ridge [that exists as] an extension of the South American Continent" (Bland 1871, p. 60), making the geologic history of the archipelago more complex than that of St. Vincent. Having been formed by volcanoes during the late Oligocene, the Grenadines are considerably older than St. Vincent. Since their early formation, the Grenadines eroded during the Pliocene and completely submerged under high sea levels during the Pleistocene (CCA 1991). Regional uplifting brought the islands above sea level, along with the coralline limestones and other sedimentary rocks that—in many places—top the older igneous rocks. While ample evidence of past volcanic activity still presents itself on the surface in the Grenadines (Fig. 15.3a), the complex geology and presence of coralline rocks and sediments indicate that these islands share a history quite distinct from that of St. Vincent, where the oldest rocks are sedimentary from the Middle Eocene to Middle Miocene (Robertson 2009).

15.2.3 Climate

The islands of St. Vincent and the Grenadines experience warm, humid conditions throughout the year. Rainfall and temperature vary seasonally, but the variation in the former is significantly more pronounced. During the dry season (December–May), the islands receive 76–90 mm of precipitation per month. The wet season (June–November) brings 190–215 mm of rain per month. These ranges represent the

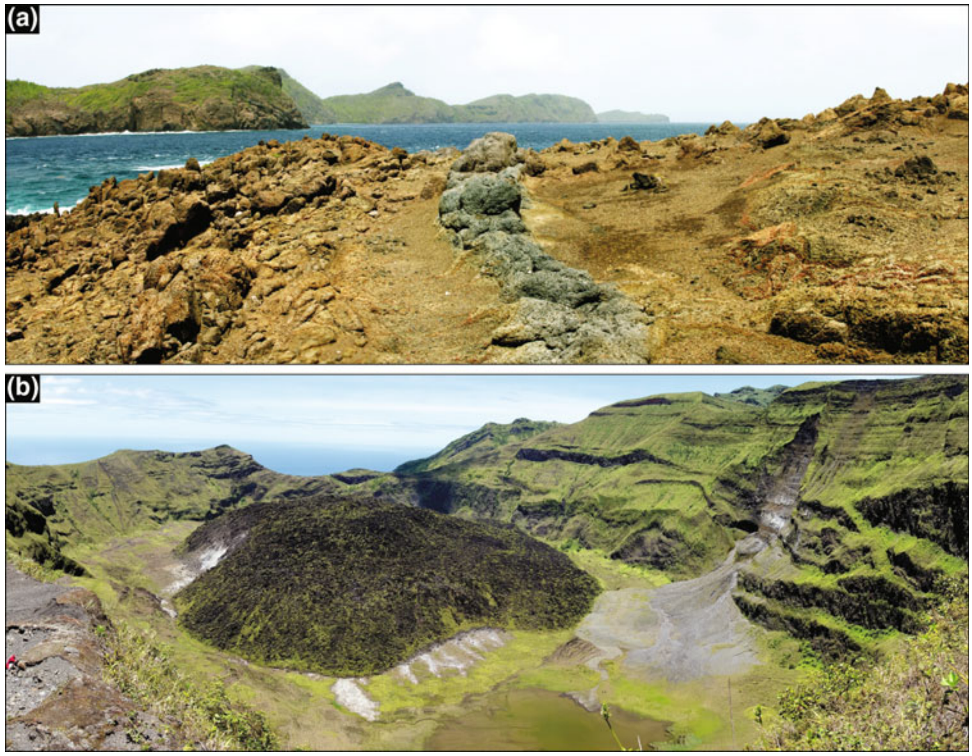

Fig. 15.3 Examples of volcanic landforms in St. Vincent and the Grenadines. **a** An exposed dike on Petit Nevis (foreground), a Grenadine island just south of Bequia. Photograph by A. Ollivierre. **b** A view inside the volcanic crater atop La Soufrière on St. Vincent. Visible in the center is the magma dome; to the right is evidence of a recent landslide. Photograph by P. Cole

means of observed measurements taken between 1970 and 1999 (McSweeney et al. 2010a).

These figures represent countrywide averages, so significant variation exists, both among and within the islands. Those with higher elevations see more rainfall, which is concentrated specifically in those high-elevation mountains. The peak of La Soufrière and surrounding mountainous areas, the wettest parts of the country, receive up to 580 mm of rain per month, while the low valleys and windward coastal plains can be quite dry, experiencing much lower monthly rainfall totals (CCA 1991). Across the archipelago, precipitation generally decreases from north to south, owing to the climatological influence of La Soufrière (and the other high mountains on St. Vincent) and the relatively low elevations and small islands further south in the Grenadines. Climatological models predict a decrease in overall annual precipitation, based on observed trends since 1960 (McSweeney et al. 2010a, b).

With regard to temperature, elevation again drives variation—in this case outweighing both seasonality and diurnal fluctuation (CCA 1991). Between 1970 and 1999, observed mean temperatures for the entire archipelago ranged from 25.6 to 27.3 °C. Climatologists have observed a trend of increasing temperatures since 1960 and predict an annual increase in the average temperature between 0.6 and 2.3 °C by 2060 (McSweeney et al. 2010a, b). Models predict that both warming and decreasing precipitation will be more pronounced and more rapid in the Grenadines than in St. Vincent.

15.3 Landscapes and Landforms

With numerous inhabited and uninhabited islands to the south of the main island, St. Vincent and the Grenadines, as an archipelago, spans a north–south range of nearly 100 km. To accommodate its vastness, this section begins in the north at the island of St. Vincent and moves southward through each major Grenadine island and several minor islets, cays, and rocks. This section ends at the small island called Petit St. Vincent (PSV)—the southernmost in the country—after expounding on the main landscape feature(s) associated with each island or islet.

15.3.1 Leeward and Windward Sides of St. Vincent Island

The dichotomy of a windward (eastern) and leeward (western) side common to many islands in the Lesser Antilles is present on St. Vincent, but seems less pronounced here than on other islands. Barbados sits 159 km to the east of St. Vincent, making St. Vincent the only Lesser Antillean Island with a similarly sized, equilatitudinal island on its windward side—the direction from which the dominant winds blow. This means that, even though Barbados has minimal relief, its orographic processes still affect St. Vincent's eastern coast (Watts 1987). While St. Vincent's windward side is dry compared to the island's lusher leeward

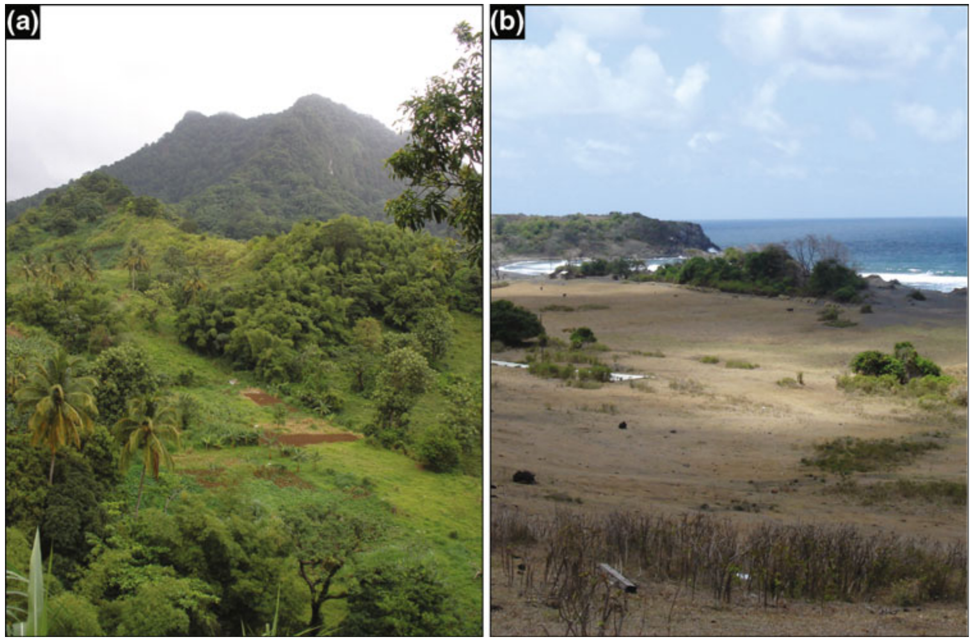

Fig. 15.4 Comparison of vegetation and landscapes between the leeward and windward coasts of St. Vincent. **a** A forested landscape on St. Vincent's leeward side near Vermont. **b** An arid landscape on the windward side of St. Vincent near Brighton. Photographs by R. Fielding

side, its climate is perhaps not as dry as it would be without the presence of Barbados (Fig. 15.4).

Coastal morphology also differs from one side of St. Vincent to the other. The windward side features rocky coasts—many with steep cliffs—and a few coastal plains, with the steepest finding their origin in the ridges leading down from the island's major mountain peaks. The leeward coast undulates between rocky headlands and sandy beaches. The beaches are composed of volcanic sediment transported by rivers and longshore currents, which leaves them dark in color. The one white sand beach on the leeward side can be found at a luxury resort in Buccament Bay. The developers nourished the beach artificially with imported sand. Lighter sand—more gray than white—is found on St. Vincent's southeastern side, near Indian Bay and Villa Beach. Here, currents nourish the beach from offshore, rather than sediments from terrestrial rocks of volcanic origin, eroded and carried coastward by fluvial transport.

15.3.2 La Soufrière

The highest point, and most recognizable landform, on St. Vincent is the summit of La Soufrière (1178 m).[1] Viewed from its base, the mountain appears steep, dark, lush, and impenetrable, with clouds often obscuring the summit. On the rare clear day, La Soufrière reveals a spectacular steep-walled crater with a pyroclastic volcanic dome, dark and smoldering, rising from within (Fig. 15.3b).

The entire northern quarter of St. Vincent, exclusive of some immediately coastal areas, consists of pyroclastic deposits and lava flows from the Soufrière volcano. Upon approaching the crater along the foot paths that rise from either coast (meeting in the middle at the peak), the vegetation shifts from rain forest to cloud forest as the terrain gets steeper, higher, and more geologically fractured. Scarps and rifts appear—some of which carry ephemeral streams—as indicators of this mountain's dynamic nature. Researchers have recently discovered debris avalanche deposits from scarp collapses on La Soufrière offshore during high-resolution bathymetry data-collection cruises. This has led to a new understanding of the evolution of the volcano—and subsequently the entire island—and the magnitude of the eruptions during its formation (Le Friant et al. 2009).

15.3.3 Other Mountains on St. Vincent

The massive presence of La Soufrière dominates St. Vincent's topography. Local residents often refer to it simply as "the volcano." Geographically though, "the volcano" and its flanks only cover the northern quarter of the island's area.

[1] Maps and written records ascribe a range of elevations to La Soufrière. We rely upon the work of Robertson (2005), whom we consider authoritative, for our figure, but acknowledge that the easily remembered measurement of 1234 m appears most often on maps and in print. A recent amateur expedition (Gilbertson and Gilbertson, Personal communication) took GPS readings from various promontories around the crater rim and settled on a maximum of 1236 m. Part of the discrepancy may result from imprecise survey methods or from measurements being taken from various locations around the crater rim and not necessarily the highest point. Actual change in the height of the mountain, owing to volcanic or tectonic activity, cannot be thoroughly dismissed.

Two major rivers, the Wallibou (not to be confused with the Wallilabou) and the Rabacca, flowing west and east, respectively, have their sources on the southern slopes of La Soufrière, separated by a high, narrow, north–south running ridge. These rivers and the gorges they carve serve to separate La Soufrière from the rest of the island. The southern region comprises a complex of mountains and hills, all volcanic in origin, but none as recent nor as starkly impressive as La Soufrière. Moving south from La Soufrière, the first peaks encountered are the Morne Garu mountains, dominated by Richmond Peak (1077 m) and Brisbane Peak (932 m). Further south, the Cumberland and Colonarie rivers again nearly bisect the island as they flow down from the northern flanks of the Bonhomme Peaks: Grand Bonhomme (970 m) and Petit Bonhomme (756 m). This mountainous area also serves as the source for the Yambou River, which carves the Mesopotamia Valley, one of St. Vincent's deepest, lushest, and most verdant regions. South of "Mespo" (as locals call it), Mt. St. Andrew (735 m) provides a steep backdrop to the capital city, Kingstown, located in front of a natural harbor on the island's southwest coast.

The major mountain peaks of St. Vincent stand in a roughly north-south alignment, but the landscape obscures this neat arrangement. Numerous smaller peaks, sharp ridgelines, and deep valleys—all the result of erosion and dissection of the southern, pre-Soufrière volcanic centers—radiate outward from the mountains, lending St. Vincent a sense of topographic randomness with sharp rises, steep descents, dark valleys, and a few coastal plains. St. Vincent is an island for mountain people—a place where choosing between volcanic topography and coastal morphology is unnecessary.

15.3.4 Geothermal Areas

Found only in the area inside the crater of La Soufrière and on the southern flanks of the volcano, geothermal activity includes fumaroles at the base of the dome within the crater and warm springs (37 °C) along the upper Wallibou River (Robertson 2005). Owing to the risk of future eruptions, experts see these sites' potential for geothermal energy development as unlikely (CCA 1991).

15.3.5 Airport Development

At the time of writing, the largest and most landscape-altering development project in St. Vincent and the Grenadines was the construction of the Argyle International Airport on St. Vincent's windward side. The new airport has finally reached the completion of its politically charged, oft-delayed, decade-long planning and construction process. Replacing the current E.T. Joshua Airport, Argyle, will handle larger jets, potentially opening St. Vincent to more international tourism. The airport development provoked controversy among several groups in St. Vincent and the Grenadines, with concerns ranging from safety (e.g., strong crosswinds common on the windward side of the island) to opposition to the major landscape changes that the airport construction required. For example, one tourism official stated that "to build this airport, engineers had to move three mountains, fill two valleys, create embankments, and span a river" (Myers 2015). Additionally, the construction of the runway uncovered significant archaeological findings, including the postholes from at least eleven structures, stone tools, pottery, and the buried remains of several humans. A hastily organized, yet remarkably effective rescue excavation determined that the site had been a Carib settlement from the late sixteenth to early seventeenth century (Hofman and Hoogland 2012). The most important finding from the site involved the commingling of native and colonial artifacts, suggesting a degree of cultural interactions not previously documented.

15.3.6 Salt Ponds: Recreational and Productive

St. Vincent features at least two so-called salt ponds, formed by lava flows that reached the sea and created small pools, sealed off from the ocean during low tide, but capable of being replenished at high tide. Both are on the windward side—a small one at Brighton and a larger one at Owia—and are popular as swimming areas for locals and visitors alike (Fig. 15.5a). By contrast, water bodies called salt ponds in the Grenadines rarely get used recreationally. Instead, locals (primarily on Union Island and Mayreau) harvest salt, a culturally important heritage that dates back to the 1700s when colonial settlers produced salt for domestic use and export (Fig. 15.5b). These salt ponds and lagoons additionally provide essential habitat for resident and migratory birds, with many being recognized as BirdLife International important bird areas (IBAs) (Culzac-Wilson 2008).

15.3.7 The Grenadines

The largest of St. Vincent's Grenadines is Bequia (16 km^2), an S-shaped island surrounded by a number of smaller offshore cays. The Bequia Channel—8.3 km at its narrowest point—separates this northernmost Grenadine island from St. Vincent. Bequia is an island of steep, rolling hills,

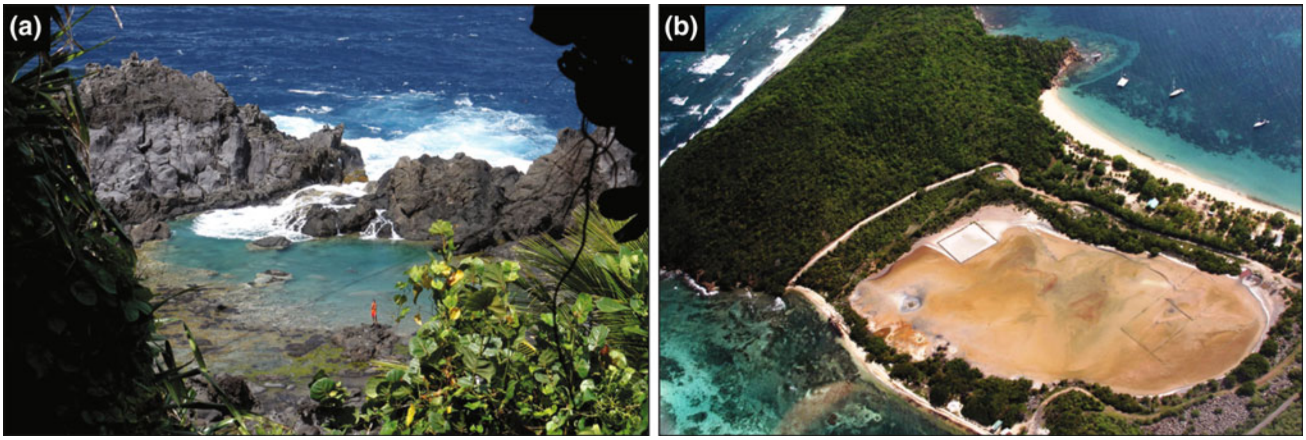

Fig. 15.5 Comparison of salt ponds on St. Vincent versus those found in the Grenadines. **a** The Owia Salt Pond, on St. Vincent's northeastern coast, with a swimmer for scale. The relative clarity of the water and picturesque setting make it a popular natural attraction. Photograph by R. Fielding. **b** An aerial view of the salt pond on the southern peninsula of Mayreau in the Grenadines. The murky water and small salt mining retaining pond visible in the center of the image discourages swimmers. Photograph by A. Ollivierre

Fig. 15.6 Conglomerate beach rock with basaltic clasts on Bequia, located on a headland between Lower Bay and Princess Margaret Beach. Photograph by R. Fielding

vegetated coves, and small, sandy coastal plains. Volcanic in origin, as are all of the Grenadines, Bequia has a complex geologic history. The beach sand ranges from white to golden, evidence of the island's surficial coralline nature, although basaltic clasts occur in some of the beach rock, underscoring its volcanic origin (Fig. 15.6).

Perhaps Bequia's most renowned natural feature is Admiralty Bay, a large, deep bay on the island's protected leeward side. At the northern end of this bay sits Port Elizabeth, Bequia's principal settlement, while other notable features on the island include Spring Bay on the windward side and Friendship Bay on the south coast. An interesting housing development called Moonhole is found at the southwestern-most extent of the island. Developed around a natural arch by the same name at the tip of Bequia, it was first developed in the 1960s using local materials including olivine-rich basaltic stone and whalebone to create unique holiday homes. While the structure inside the arch itself has

Fig. 15.7 Aerial view of the J.F. Mitchell Airport on the southern coast of Bequia. Photograph by A. Ollivierre

fallen into disrepair and is considered unsafe to visit (following a rockfall that preceded its abandonment), the rest of the site remains an eclectic part of the island's history and current settlement pattern.

Built on reclaimed land along the south coast near the community of Paget Farm, the creation of Bequia's airport (Fig. 15.7) resulted in the destruction of a beach, a barrier reef, and shallow lagoon habitats. This subsequently created further problems for the community due to an inadequate and malfunctioning drainage system that has resulted in severe problems with stagnant waters and the accumulation of marine debris (Jaja 2013).

Several islets off the south coast of Bequia also warrant attention. The first is Semples Cay, an islet at the mouth of Friendship Bay. To some, Bequia earns a certain amount of fame—notoriety to others—as the only Caribbean community with an aboriginal subsistence whaling quota from the International Whaling Commission (Adams 1971; Ward 1995). Based around Friendship Bay, on the island's south coast, Bequia whalers pursue humpback whales (*Megaptera novaeangliae*) in an area extending approximately 19 km off the windward side of Bequia and encompassing the unprotected waters around the island of Mustique's marine conservation buffer, along with several smaller cays (see chart in Adams 1971, pp. 64–65). Captured whales are brought to Semples Cay for processing. This is the only remaining whale processing station out of at least seven that once stood on Bequia and the nearby islets. East of Bequia lie the uninhabited islets of Battowia and Baliceaux. These arid islets lack natural freshwater sources and find use primarily as grazing land for livestock. The history of Baliceaux, however, belies its pastoral present. During the early colonial era, the British used this islet as a natural prison—a holding place for native Caribs exiled from St. Vincent and later deported to Central America (see *Heritage*).

Continuing south, the next inhabited island is Mustique. This private island is owned by the Mustique Company and has been developed almost exclusively as an island of holiday homes and rental villas, although a small community of local Mustiquans remains in the town of Lovell Village. What once was a derelict sugar island has been transformed into an impeccably manicured resort, the island's eponymous mosquitoes (the name evolved as a corruption of *moustique*, the French word for *mosquito*) controlled through the draining of some of the wetlands in which they formerly bred.

The channel between Mustique and the next inhabited island to the south, Canouan, is dotted with several small cays and islets important for seabird nesting and roosting, but otherwise represents the longest stretch of open water within the Grenadines archipelago. Another luxury resort company owns two-thirds of Canouan. This resort achieved local infamy for its golf club whose runoff of herbicides and fungicides led to the degradation of Canouan's extensive coral reef (Scott and Horrocks 1993). Despite this, the main industry on the island remains tourism—particularly

Fig. 15.8 Aerial view, facing south, of the Carnash tombolo on Mayreau. Photograph by A. Ollivierre

associated with the resort—while traditional fisheries, though weakened along with the health of the reef, maintain a smaller contribution to the local economy.

South of Canouan is the small island of Mayreau, home to not more than 300 people. Mayreau's landforms include a classic tombolo (Fig. 15.8) at its northern end where Mt. Carbuit is joined to the main island by a narrow strand, the western side of which forms the back beach of Carnash (or Salt Whistle) Bay, a favorite anchorage for yachts. The northern point of the island features an example of coral pavement (Fig. 15.9), exposed during low tide. At Mayreau's south end, a wide isthmus featuring a large salt pond in its center connects Lande-Ici Hill to the rest of the island. To the west of this isthmus, on the leeward side of the island, is Saline Bay, home to Mayreau's main port—by which this island maintains its sole connection (as it has no airport) to the rest of the archipelago.

Due east of Mayreau stand the uninhabited, but noteworthy, Tobago Cays. This tightly clustered group of four islets, Petit Rameau, Petit Bateau, Jamesby, and Baradal, plus a fifth outlier—Petit Tabac—rise above the shallow sand, grass, and coral-covered seafloor just meters below the surface. Narrow channels of only 100–200 m separate the four main cays, while Petit Tabac lies west of the reef from which the other cays sit, about a kilometer from the rest of the group. The Grenadines contain the most extensive coral reef system in the Eastern Caribbean, with each island supporting fringing, patch, or barrier reefs, and a variety of ecologically important seagrass and mangrove habitats. The Tobago Cays Marine Park (TCMP) (originally established in 1997, but ineffective until its relaunching by the government in 2006) protects the two largest of these reefs, Horseshoe Reef and World's End Reef (Fig. 15.10a), that surround the Tobago Cays in the southern Grenadines (Mahon et al. 2004; DeGraff and Baldwin 2013). The decision to include the entire neighboring, fisheries-dependent island of Mayreau in this protected area, however, continues to provoke controversy in the community (Hoggarth 2007).

South of Mayreau sits Union Island, home to the highest point in the Grenadine archipelago, Mount Tibre[2] (304 m), and the largest mangrove forest in the country (25 ha). One of the most controversial development projects in the Grenadines is the failed Ashton Marina project (Price and Price 1998), which had intended to build a 300-berth marina and replace the existing lagoon and its surrounding reefs with condominiums and a golf course. When the Italian development firm abandoned construction due to bankruptcy in 1995, the marina berths remained, causing a stagnation and eutrophication of the water in the lagoon, which critically reduced the marine habitats and marine life (Sorenson 2007).

One somewhat unique geologic feature within the Caribbean, an outcrop of columnar basalt, may be found on Frigate Island, just south of—and artificially connected to—Union Island (Fig. 15.10b). This feature was exposed during mining operations to produce rocks and fill for a marina

[2]This mountain has several similar alternate names. *Taboi* is seen most often on official maps. *Tibre* is the most commonly used local name. Other maps and charts label the peak as *Toboi* or *Tabor*. The confusion is perhaps a result of variations in pronunciation or a cartographic transcription error propagated to subsequent maps.

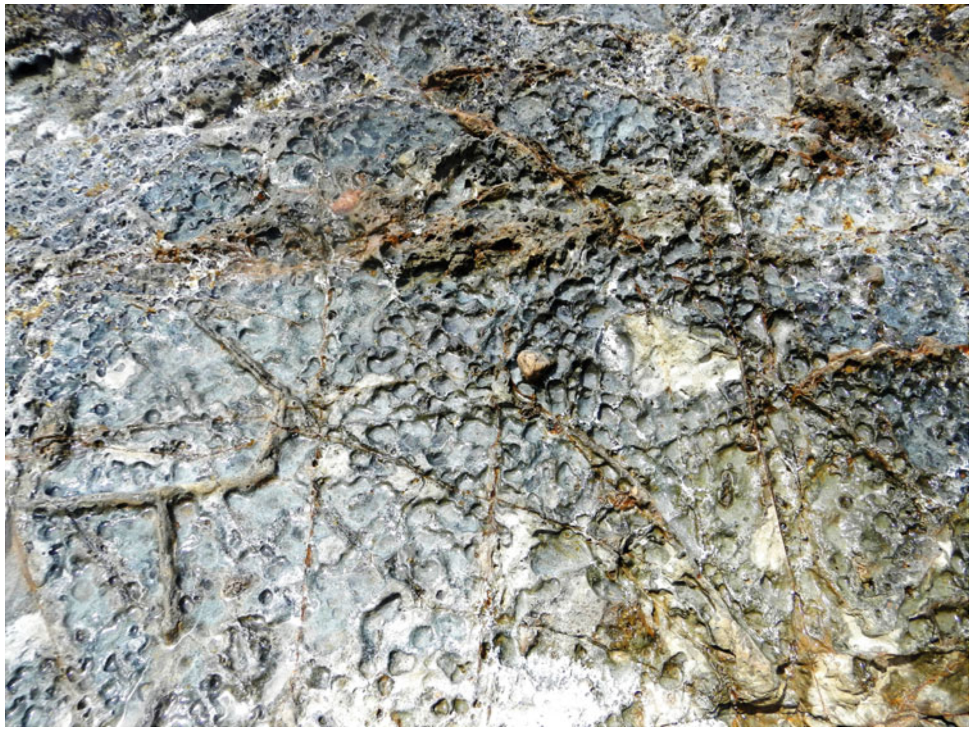

Fig. 15.9 Coral pavement, exposed and eroded on the north coast of Mayreau. Photograph by A. Ollivierre

Fig. 15.10 Examples of unique landforms in the Grenadines, both terrestrial and aquatic. **a** Horseshoe Reef (*foreground*) and World's End Reef (*background*) with Petit Tabac, one of the Tobago Cays, in the center. **b** Columnar basalt on Frigate Island, a small cay off of Ashton Bay, Union Island, that was artificially joined with Union in 1994–95 in a failed attempt to build a marina in Ashton Lagoon (Price and Price 1998). Photographs by A. Ollivierre

project (Price and Price 1998). When lava cools, it contracts, both vertically and horizontally. Horizontal contractions can lead to jointing—or cracking—of the hardening rock. In basalts, these joints often result in a hexagonal shape, although irregular cooling can sometimes produce columns with less regular shapes and varying numbers of sides. Another example of columnar basalt exists in the Cumberland valley on St. Vincent. Early visitors to the island (e.g., Davy 1854; Sharp 1890) described and photographed the geology of this site, indicating that its exposure likely resulted from natural surface movement processes.

East and southeast of Union Island stand the small private resort islands of Palm Island and Petit St. Vincent. Both have received numerous international tourism awards and recognitions and are known for their luxury accommodations. Palm Island, known as Prune Island before its sale to resort developers, served as a leper colony for stricken inhabitants of Union Island from the late 1700s into the early 1800s.

15.4 Heritage and Tourism

15.4.1 Heritage

Evidence of human occupation in St. Vincent and the Grenadines exists from as early as 2000 BCE. Hairouna (the indigenous name for St. Vincent) remained a stronghold for native inhabitants well into the colonial era. While other islands were being depopulated through disease, genocide, and forced relocations, the native population on Hairouna continued to thrive. Only on Dominica was the maintenance of Carib culture and population greater. Although Columbus sighted the island in 1498—on January 22, the feast day of Saint Vincent—Europeans did not begin to settle on St. Vincent until the late seventeenth century (Young 1993). The French came first, basing their operation at Barrouallie and establishing farms, primarily on the leeward side. Today, the names of many villages and geographic features, especially on the island's west coast, retain their French roots.

In 1635, the arrival of Africans on Bequia, survivors of the wreck of a slave ship [or possibly two shipwrecks (Matthei and Smith 2008)], augmented the Carib population in St. Vincent and the Grenadines. As depicted in an art installation (Fig. 15.11a) at the museum in Fort Charlotte (located on a hill above Kingstown), the survivors eventually came to St. Vincent, where the local Caribs welcomed them. Over time, the Africans assimilated into the Carib culture, and their descendants became known as "Black Caribs." This mixed-ancestry population gained a reputation for their strong defense of their land against colonizers (Kirby and Martin 1972). Despite having declared St. Vincent, along with Dominica, a refuge for the native Carib people (also called "Yellow Caribs") displaced by colonization on other islands, the British became interested in settling on St. Vincent in 1763. Soon thereafter, a three-way contest for control of the island began with the British, French, and Carib peoples in near-continuous conflict.

In 1796, the British defeated the Caribs. The victors captured over 4000 native prisoners and placed them temporarily on Baliceaux, a previously uninhabited Grenadine islet between Bequia and Mustique. Over half of those

Fig. 15.11 Remnants of St. Vincent and the Grenadines' native heritage. **a** A 1972 painting by William Linzee Prescott, on display at Fort Charlotte, St. Vincent. The caption (*not pictured*) reads, "A few Black Caribs who had escaped Abercrombie's dragnet were eventually settled at Greiggs, shown here. Their descendants still display that fierce independence that so characterized the BLACK CARIBS." Photograph by R. Fielding. **b** Work stone in Spring Bay, Bequia. Such stones would have been used to grind flour or pastes from seeds, meat, plants, etc. Photograph by A. Ollivierre

captured died during their three-month interment on Baliceaux; the rest were deported to Roatán, an island off the Caribbean coast of Honduras. From Roatán, the deportees—the Garifuna as they came to be known—crossed to the Honduran mainland and spread along the Caribbean coast of Central America where their descendants live today (Taylor 2012). St. Vincent and the Grenadines maintains a strong connection to its Carib heritage despite only a small percentage (2–4%) of the population claiming direct Carib ancestry. In March each year, Carib descendants from St. Vincent, Dominica, and throughout Central America make a pilgrimage to Baliceaux, the site where their ancestors were held and where many died. Pilgrims are often overcome by emotion as they experience first hand the dry, shadeless, inhospitable landscape to which their ancestors were banished.

15.4.2 Petroglyphs and Stone Artifacts

According to one early Caribbean anthropologist, "throughout the West Indian archipelago there is nothing of greater archaeological importance than the St. Vincent petroglyphs" (Huckerby 1914, p. 239). Researchers have found and recorded twelve separate petroglyph panels—each with numerous motifs—in St. Vincent, all of which are either found along the coast or the island's river valleys (with the exception of the area around La Soufrière). For many years, a petroglyph also survived on the northern side of Canouan in the Grenadines; however, this artifact disappeared during the construction of the resort. Petroglyphs in St. Vincent and the Grenadines share a similar motif style with engravings in Grenada, leading researchers to hypothesize that inhabitants of both main islands maintained contact, or perhaps familial relations, with one another (Haviser and Strecker 2006).

Work stones, also known as *polissoirs* (polishers, grinders) or cupules, once served as mortars for sharpening tools and for grinding dried or fibrous food sources and may still be found in the river valleys and beaches of St. Vincent and on Bequia (Martin 2006; Bradford 2001). Haviser and Strecker (2006, p. 79), perhaps somewhat hyperbolically, claim that work stones have been found on "practically every beach" on St. Vincent. Despite this apparent exaggeration, Kirby (1969), a Vincentian prehistorian, cataloged over fifty work stones in St. Vincent alone, with the vast majority found on the island's beaches (Fig. 15.11b).

15.4.3 Early to Modern Agro-Processing

During the plantation era, sugarcane was a major crop, both for local consumption and international export as raw or processed sugar, molasses, and rum. Many signs of this economy remain visible on the landscape. Remnants of cotton mills and lime kilns for producing cement also dot the landscape, though many have been left to ruin and overgrow with weeds and "cashi" (cacti). Overcultivation of the Grenadines' hilly landscapes with cotton, sugarcane, and subsistence crops such as cassava, pigeon peas, and corn led to erosion and gullying, as well as soil nutrient loss—a problem further propagated in the sharecropping land tenancy system after emancipation. As cash agriculture declined in the seasonally dry Grenadines, hardy livestock such as goats, sheep, and fowl became the leading exports, alongside the ever-persistent fisheries industry (Adams 1978). In St. Vincent, sugarcane cultivation dominated much of the coast, though the crop did not fare as well in the foothills of the wet forested mountains. The cotton industry followed sugar and led to similar, if not more severe, erosion problems. Experimentation with other crops—especially arrowroot—ensued, with varying degrees of success until, finally, bananas emerged as the largest export for the island, booming in the 1980s as a result of preferential pricing arrangements in Europe, and then declining as prices dropped amidst foreign market shifts to Latin American bananas (Grossman 1998). Today, bananas still comprise the majority of St. Vincent's official agricultural production, with illicit marijuana cultivation supplementing legal agriculture to an unquantified, but large, degree (INCSR 2006).

15.4.4 Tourism

Many, perhaps most, tourists entering the country are destined for the Grenadines. Sailors, divers, snorkelers, and those who simply want to lie on a pristine beach are drawn to this archipelago of small islands with white sand beaches and extensive reef systems in brilliant turquoise waters. The Grenadines also host a number of exclusive resorts and private villas, the latter primarily on Mustique, though the number of villas on Bequia is growing. St. Vincent continues to work hard at attracting adventure tourists, and recently established its first all-inclusive luxury resort. Despite these developments, agriculture in St. Vincent still competes with tourism as a major part of the country's GDP—the two industries contributing 7.5 and 12.6%, respectively—a rare economic situation in this region (World Bank 2013).

The tourism industry in St. Vincent boasts a long history of environmental protection for recreational purposes. For example, the St. Vincent Botanical Gardens are, by some count, the oldest extant botanical gardens in the Western Hemisphere, dating to 1765 (Anonymous 1922; Howard 1954). The gardens feature endemic species from around the Caribbean, as well as other tropical locations. One of the most famous plants in the gardens is an individual breadfruit tree (*Artocarpus altilis*), said to have been brought to St. Vincent from Tahiti personally by Captain Bligh on his first voyage after the infamous *Bounty* mutiny (Howard 1954). Breadfruit has a long and complicated history in the Caribbean, being a beloved, yet humble, local delicacy as well as a botanical link to the region's history of slavery and the perceived need, on the part of the planters, for local, abundant, high-caloric food to fuel the workforce. Another long-standing example of environmental protection in St. Vincent is the Kings Hill Forest Reserve, with protection of its 55 acres of dry forest commencing in 1791 (CCA [Caribbean Conservation Association] 1991).

15.5 Hazards

As with the rest of the Eastern Caribbean, the islands of St. Vincent and the Grenadines remain particularly vulnerable to natural hazards (Anderson et al. 2011). That heightened vulnerability stays strongly tied to the demographic, economic, and geopolitical situation in the Lesser Antilles which favors relatively high population densities on islands or island groups of small geographic size with relatively low GDP (Anderson et al. 2011). The result is that a single hazardous event can have a disproportionate effect on a small island's population, infrastructure, and GDP. Indeed, in the case of tropical cyclones, the storm systems themselves are usually many times larger than the individual islands over which they track.

Researchers have catalogued St. Vincent's hazards numerous times (e.g., Boruff and Cutter 2007; Robertson 2009). Among these, Boruff and Cutter (2007) compiled records for natural hazards in St. Vincent, considering historical sources spanning the entire twentieth century. From these data, we see that fire occurs most frequently, although the mix of qualitative and quantitative data in the tally makes for difficult direct comparison among specific hazards. Perhaps the most striking lesson from Boruff and Cutter's (2007) list is the sheer variety of hazards that have occurred and are likely to continue, if not intensify, as a result of global climate change. As hazards intimately connect to geomorphology and landscape anywhere, especially in St. Vincent and the Grenadines, our discussion of past, current, and potential hazards here will necessarily be among the most in-depth of this chapter.

15.5.1 Fire

A scholar considering Lesser Antillean natural hazard vulnerabilities would likely not think of fire first. Caribbean fires do not make headlines in North America or Europe as readily as volcanic eruptions or major hurricanes. This lack of newsworthiness may originate from the fact that most fires in the Caribbean are human-caused—intentionally or unintentionally—though, as Richardson (2004, p. 196) concludes in his study of fire in the Caribbean, they are "never under complete control." In St. Vincent and the Grenadines, the process of making charcoal has had disastrous ecological effects—both from over-zealous, yet controlled, burning, and from fires spreading out of control and burning unintendedly large swaths of forest. The colonial government passed the first regulations on the production of charcoal in St. Vincent in 1839 and amended the laws several times throughout the nineteenth century (Richardson 2004). The procedure to legally produce charcoal was so complicated, expensive, and laden with bureaucracy, however, that many would-be law-abiding charcoal makers opted to practice their craft illicitly. This often took place in the hinterlands, away from the watchful eyes of colonial administrators based in Kingstown, an early analogue to today's illicit, yet normally uncontested, remote marijuana farms. The essentially unregulated production of charcoal through felling and burning trees in situ resulted in such dramatic deforestation that the once-forested slopes of Mt. St. Andrew had become, in the words of one late nineteenth-century writer, reduced to "complete barrenness" (Hooper 1886, pp. 9–10 [cited in Richardson 2004, p. 89]).

Even the smaller islands of the Grenadines were susceptible to the hazards wrought by human-caused fires. Richardson (2004, p. 90) notes that, despite their remoteness with respect to the seat of colonial administration, the Grenadines "supplied slooploads of charcoal to the Bridgetown [Barbados] market, to the detriment of their own insular habitats." Considering the small land area of the Grenadines, the general lack of precipitation and surface water, and the resultant meager forest cover, the disproportionate impact of even a single "sloopload" to the ecological health of a Grenadine forest community becomes apparent. Today, there is virtually no first growth forest remaining.

15.5.2 Volcanic Eruptions

While most hazards to which St. Vincent is vulnerable occur more frequently than volcanic eruptions, the ever-present sight of La Soufrière, combined with the high number of casualties and large economic losses due to its regular—yet infrequent—eruptions, may serve to make perceptions of volcanic risk more widespread than that of other hazards (Robertson 1995; Scarlett 2014). For example, according to Boruff and Cutter (2007), between 1955 and 2004, over 1500 human lives on St. Vincent were lost due to the gases, debris flows, and ejecta associated with the eruptions. La

Soufrière's eruptions have claimed a death toll greater by an order of magnitude than the second leading cause of natural hazards death: windstorms (presumably as part of tropical cyclones). The subtitle to a contemporary account of the 1902 eruption, reading boldly, "DEATH! DEATH! EVERYWHERE!" does not seem as sensationalistic when the sheer number of victims is considered (Garesché 1902, p. 5, capitalization in original). Still, volcanic eruptions are among the least frequent of all natural hazards experienced on St. Vincent and do not occur at all in the Grenadines. So, while the volcano looms over everyday Vincentian life and wreaks enormous havoc when it erupts, volcanic hazards occur perhaps once in a generation, not nearly as frequent as other, less disastrous hazards.

Eruptions have not only caused human deaths and injuries, but have reshaped the island landscape as well. The changes to the physical landscape are straightforward: nearly all the surface rock on St. Vincent is basaltic or pyroclastic in origin. In terms of human geography and the built landscape, Richardson (2004, p. 17) presciently states that

> The rapid transformation of St. Vincent from a sugarcane island in the 1880s and 1890s to an island of smallholders in the earth twentieth century probably was brought about by an 1898 hurricane followed by a volcanic eruption in 1902, twin disasters that drove away most of the island's planter class.

Twenty-five volcanic eruptions occurred in the Eastern Caribbean between 1780 and 2006 (Lara 2006), the deadliest being Mt. Pelée on Martinique in 1902, which killed over 28,000 people. During that event, La Soufrière also erupted, though the casualties were considerably fewer, owing to the sparse population in the north of the island. These simultaneous eruptions of neighboring volcanoes demonstrate the long-known fact that "there are sub-marine communications between the burning mountains or volcanoes in each of [the islands]" (Anderson 1785, p. 30). La Soufrière last erupted in 1979, claiming no lives but forcing the evacuation of over 15,000 people, due to the increased populations on the north of the island by then. The typical "St. Vincent style" eruption (Robertson 2005, p. 247) is highly explosive, preceded by frequent, strong earthquakes, and involves the emission of toxic gases, lahars, and the ejection of large volumes of new material (Boruff and Cutter 2007).

Robertson (2005), the preeminent geologist studying La Soufrière, expects the volcano to continue to erupt at least once per century. The next eruption could be explosive, like the 1902 eruption, or effusive, like that of 1979. In the event of an eruption, the northern quarter of the island faces the greatest risk from pyroclastic flows, volcanic projectiles, and lahars. This would include the settlement of Georgetown, the largest on the windward side. Ashfall could affect more than half the island, reaching as far south as Barrouallie on the leeward side and the Bonhomme Peaks in the island's center. Even the so-called Safe Zone—essentially the southern third of the island—would not escape the effects of a major eruption, as evacuees from the northern area would increase the burden on housing and services in southern communities such as Layou, Mesopotamia, and, most predominantly, Kingstown.

15.5.3 Earthquakes and Tsunamis

St. Vincent and the Grenadines' location near the Caribbean and the North and South American tectonic plate boundaries and the presence of an active volcano on St. Vincent (and several others in the region) leads to common tectonic and volcanic earthquakes. Although earthquakes occur often, they are not usually strong or destructive—a trend that Robertson (2009) attributes to the relatively slow plate convergence at the subduction zone ($\sim$2 mm/year). The Seismic Research Centre at the University of the West Indies (UWI) maintains five seismic stations and eight GPS stations, and monitors changes in ground angle at several dry tilt sites on St. Vincent (UWI 2011).

Tomblin (1981) points out the added vulnerability of reclaimed or filled land in waterfront development—a common construction strategy in St. Vincent and other Caribbean islands—to liquefaction events during earthquakes. The inherently low elevation of reclaimed land also increases its vulnerability to storm surge, sea-level rise, and tsunamis. For example, Tomblin (1981) cites the infamous 1692 earthquake and subsequent tsunami that partially and permanently submerged the settlement of Port Royal, Jamaica. Port Royal had not been built upon reclaimed land, but on similarly soft, accreted sediment on a coastal spit. This historical event, well known throughout the Caribbean and beyond, should serve as a warning to nearshore developers around the region.

Despite the occurrence of earthquakes in St. Vincent, the zone between Grenada and St. Lucia—where St. Vincent and the Grenadines comprise the majority of the area—is the least seismically active in all the Lesser Antilles. By way of explanation, Robertson (2009, p. 32) mentions two competing hypotheses, attributing the less-than-average number of earthquakes either to the smooth descent of the subducting slab, in which case the scarcity of earthquakes may be seen as a reliable, ongoing trend, or, more ominously, "to the accumulation of strain energy, which is yet to reach its limit," a scenario that would indicate the future occurrence of a major, possibly catastrophic earthquake, resulting in the release of long accumulated energy.

Earthquakes and volcanoes in the region are rarely, but powerfully, tsunamigenic. One notable tsunami-like event involved a "tidal" run-up on the coastal plain near

Georgetown on St. Vincent's windward side, associated with the 1902 eruption of La Soufrière, which researchers have retrospectively estimated at just over three kilometers (Lander et al. 2002). Despite the multitude of potential causal events, such as earthquakes, terrestrial volcanic eruptions, submarine volcanic eruptions, and landslides, both in the region and further afield (earthquakes as far away as the Iberian Peninsula have resulted in destructive tsunamis to Caribbean shores), tsunamis in the Caribbean are uncommon. One team of researchers analyzed data related to 91 extreme wave events that occurred throughout the Caribbean region between 1498 and 2000 and determined that only about one-third represented true tsunamis (Lander et al. 2002).

In 1867, a strong earthquake centered in the Virgin Islands caused shaking as far away as Guadeloupe, generating a tsunami that affected many Caribbean islands farther from its epicenter. Owing to the large area affected, this earthquake and its associated tsunami represents one of the best-documented natural hazard events from the nineteenth century, even if some of the descriptions of local effects and observations are likely to have been exaggerated. While no record exists indicating that the earthquake was felt in St. Vincent and the Grenadines, effects of the tsunami were recorded for both St. Vincent and Bequia, the latter experiencing three large, yet smooth waves of about two meters' height (Zahibo and Pelinovsky 2001).

Another set of scholars (Le Friant et al. 2009) found evidence suggesting at least one major flank-collapse on La Soufrière during the past 50,000 years. The team also located a debris avalanche associated with this event, which deposited 9–10 km^3 of material offshore. If a similar collapse were to happen in the future, the combined results of the volcanic eruption, mass wasting, and the tsunami that would likely result would be catastrophic, posing a hazard to all islands in the region.

15.5.4 Flooding and Mass Wasting

Floods and landslides also threaten St. Vincent. The most recent natural hazard to have occurred on a national scale is the flood of December 24–25, 2013, when numerous rivers swollen by heavy rains overflowed their banks. According to a government report on the disaster (Locke et al. 2014), during one three-hour period on the evening of December 24, 278 mm of rain fell in the northeastern portion of the island—a hundred-year event. The government declared over a dozen specific disaster areas where the most intense flooding and erosion had occurred. The transport sector suffered largest economic losses with many bridges and sections of road washed out. Nine people were confirmed dead. At the time of writing, recovery—assisted by the World Bank and other international organizations—has made good progress but is still ongoing with some of the planned long-term actions expected to take up to 5 years to complete. While the flooding of December 2013 was a highly unusual event, damaging floods do occur, on average, about four times per century (Boruff and Cutter 2007).

Landslides and other examples of mass wasting occur more frequently. DeGraff et al. (1989) found debris flows to be the most common form of mass wasting in a three-island study area comprised of St. Vincent, St. Lucia, and Dominica. A common scenario for mass wasting in St. Vincent is a slope of greater than 35° failing at a depth of less than two meters as a result of heavy precipitation, often produced by a tropical cyclone (DeGraff et al. 1989). Considering that half the island's surface area is sloped at least 30°, and only 20% of the island has slopes less than 20°, the frequency of mass wasting events in St. Vincent is certainly not surprising (CCA 1991). Road-cutting and other forms of anthropogenic alteration of the landscape, including unplanned housing on steep, unreinforced slopes, exacerbate the landslide risk (Anderson et al. 2011). The alternating layers of ash, basaltic rock, and cemented pyroclastic material underlying the island's steep slopes allow for differential decay rates that often weaken lower layers and destabilize entire areas. Rock falls also occur on St. Vincent, usually where bedrock scarps occur on mountain slopes or where sea cliffs and rocks show well-defined jointing, or as a result of undercutting by wave action (DeGraff et al. 1989). Still, the most common trigger of mass wasting in St. Vincent is precipitation, although tectonic and volcanic activities also cause mass wasting, particularly in the form of mudflows, or lahars, associated with eruptions of La Soufrière (DeGraff et al. 1989; Robertson 2005).

Landslides and flooding are rarely experienced in the Grenadines. Very little surface water exists on most islands except for salt ponds, ephemeral pools and streams following periodic rain events, and built ponds used to water livestock. The slopes and elevations also remain generally lower in the Grenadines than on St. Vincent, so while minimal flooding in low-lying coastal areas may occur, it does not cause the same devastating effects as floods do on St. Vincent.

15.5.5 Hurricanes

Located at the Hurricane Belt's edge, strong hurricanes usually pass slightly to the north of St. Vincent and the Grenadines. Notable exceptions to this trend occur regularly, however, and many hurricanes and lesser cyclones have caused death, injury, or major damage on these islands including, most recently, Hurricanes Matthew in 2016, Tomas in 2010, Ivan in 2004, and Lenny in 1999.

15.5.6 Sand Mining

The removal of sand from beaches and mixing with concrete for construction purposes is a common, albeit illegal, practice throughout the country. Sand mining has a negative impact on coastal zones, minimizing the beach's effectiveness as a form of coastal protection, and affecting beach recreation activities—an essential draw for tourism in St. Vincent and the Grenadines (Christie et al. 2015). The Caribbean Conservation Association (CCA 1991, *xxi*) describes how "virtually all the beaches… accessible by road have been mined to some extent, but those closest to Kingstown and other population centers have been the most affected." Sand mining can result in erosion along the coast and require placement of seawalls, gabions, or groins to protect coastal properties and developments. Port Elizabeth, in Bequia, serves as a salient example of these attempts at mitigation. In addition, vehicles used to access the sand destroy fragile beach vegetation.

15.6 Conclusion

The archipelagic nation of St. Vincent and the Grenadines typifies Eastern Caribbean landscapes, but also stands out in several key ways. With examples of both large (by Lesser Antilles standards) and small islands; wet and dry environments; volcanic and sedimentary geology; and French, British, and Carib cultural heritage, this island nation presents something of a microcosm of the wider region. The typical Lesser Antillean landscapes that are lacking in St. Vincent—coralline beaches, offshore reefs—are abundant in the Grenadines, and the volcanic landforms either lacking or obscured by more recent geological activity in the Grenadines are found in abundance on the surface of St. Vincent. Still, there remain important ways in which this island nation is unique within the region. Foremost among these is the risk presented by the active volcano, La Soufrière, one of the most active in the Lesser Antilles. The economic focus on agriculture also stands out among the islands of the region and increases the vulnerability of St. Vincent and the Grenadines to certain hazards, especially climate-driven changes in precipitation patterns, which would affect agricultural islands more drastically than those exclusively focused on tourism.

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Grenada: the Spice Isle

16

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Abstract

Located on the southern end of the Lesser Antilles' Windward Island chain, the tri-island nation of Grenada is comprised of primarily volcanic islands. Grenada proper retains a mountainous landscape with a variety of volcanic features and fertile soil that supports the island's agricultural economy and helps to promote tourism. The nation's other two islands, Carriacou and Petite Martinique, both have mountainous interiors as well (at least for their size), though significantly less population. Grenada's strategic position made it a desirable territory for both French and English colonial powers, but its landscape gave the Amerindian people an edge in resisting colonization. Though there is little Amerindian cultural presence on the island now, their legacy can be seen around the island in petroglyphs, a few archaeological sites, and with place names like *Morne de Sateur's* (Leaper's Cliff). Today, the landscape supports both the primary industry, agriculture, and the largest portion of the economy, tourism. But these endeavors remain constrained by the islands' landforms and left to the whims of Nature which plays a grand role in changing the landscape every few decades. As more on-Island studies are completed, general awareness, mitigation, and management of precious resources such as soil, sand, and tourism, will undoubtedly help Grenada to continue providing for its inhabitants.

Keywords

Grenada • Volcanic • Hurricane • Petroglyph • Ecotourism • Beach • Rainforest

Note
Throughout this chapter, the word Grenada is used to denote both the main island and the tri-island nation itself. When discussing Carriacou or Petite Martinique, those names are used specifically. Every effort has been made so the distinction between Grenada-the-Tri-Island-Nation and Grenada-the-Main-Island is clear throughout this chapter.

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16.1 Introduction

Though it officially administers over a dozen islands, The Nation of Grenada is often referred to as a "tri-island nation", as only three main islands are permanently inhabited (Fig. 16.1). The main island of Grenada (*gruh-nay-duh*, with an area of 306 km^2) straddles the twelfth degree north latitude line, with a population varying between 95,000 and 110,000. Carriacou (*carry-uh-coo*, with an area of 34 km^2, see Fig. 16.2), 37 km north of the main island, hosts a population of ∼4500, and its northern tip, Gun Point, is unique because it technically represents a land border with St. Vincent and the Grenadines. When the Grenadine islands were split between St. Vincent and Grenada for the purpose of administrative efficiency, the boundary accidentally

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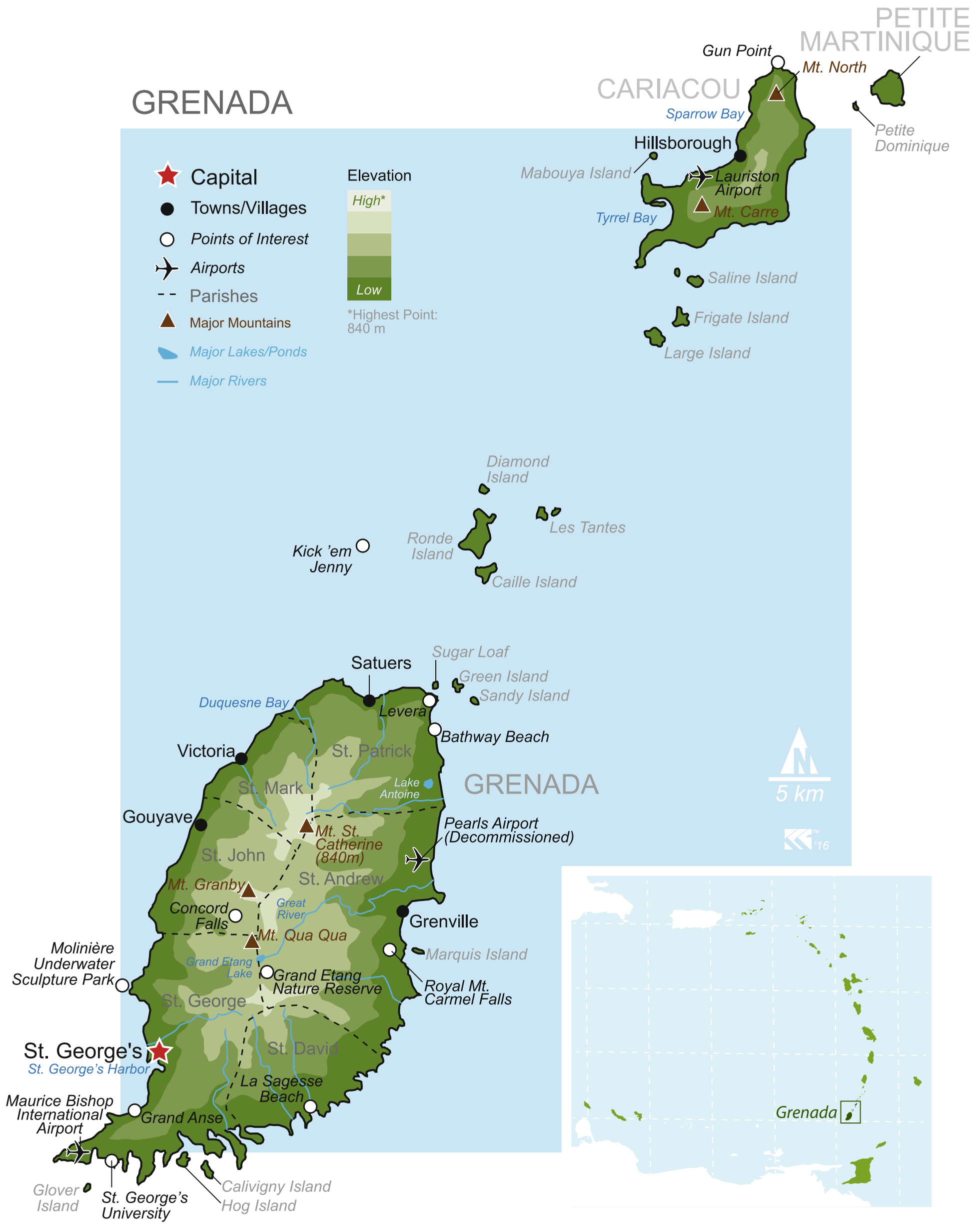

Fig. 16.1 General physiographic map of Grenada, Carriacou, and Petite Martinique, along with smaller adjacent islands. Various uninhabited islands surround the main island of Grenada, as well as in between Grenada and Carriacou. Cartography by K.M. Groom

transected the northern-most portion of Carriacou. Though Gun Point is officially part of St. Vincent and the Grenadines, it is left to Carriacou's jurisdiction (though the "point" itself and the surrounding land are actually privately owned). Petite Martinique (*peh-tee-mar-tin-eek*, with an area of $\sim$3 km^2, see Fig. 16.3) another $\sim$4 km east of Carriacou boasts a population of $\sim$1000. Situated between St. Vincent and the Grenadines to the north, and Trinidad and Tobago to the south then, the Tri-Island Nation of Grenada lies approximately 160 km north of Venezuela and represents the southernmost Windward Island of the Lesser Antilles, resting near the Lesser Antilles arc where the North and (the extreme northeast portion of the South) American plate subduct west under the Caribbean Plate.

A volcanic island with a mountainous interior, Grenada's main island rises to its highest point at Mt. St. Catherine (840 m) in the central-northern half of the island (Fig. 16.4). Evidence of volcanic activity includes the crater lakes of Lake Antoine, Levera Pond, Grand Etang Lake, the twin calderas at Port Louis and St. George's harbor, and the geothermally active River Sallee "Boiling Springs." Numerous rivers radiate from the center of the island, and Grenada's mountainous terrain allows for several dramatic waterfalls, including those at Concord, Mt. Carmel, Seven

Fig. 16.2 Carriacou as seen from the south. The island is not as small as the visitor might believe—the faint mountains in the background are still the same island—and is very hilly, especially for its size. Even though Carriacou represents the largest Grenadine island (area-wise), it is still part of the tri-island nation of Grenada. Photo by C.D. Allen, 2016

Fig. 16.3 Island of Petite Martinique as seen from the north side of Carriacou (*foreground*). While Petite Martinique (large island, *center right*) is part of the tri-island nation of Grenada, Petit St. Vincent (*left*), Fota (small rock island *mid-center*), and Petit Dominique (*mid-center-right*) are not. Photo by C.D. Allen, 2016

Sisters, and Annandale. For their sizes, both Carriacou and Petite Martinique are mountainous as well, with high points of 291 and 230 m, respectively.

The main island of Grenada has 121 km of coastline and, like other Caribbean Islands, a number of beautiful beaches, including Grand Anse Beach—the island's most popular, and one of its most picturesque. There are a number of dive sites around the island, including shipwrecks and a protected underwater sculpture park (Molinière Sculpture Park) that can be viewed by snorkelers or SCUBA divers. Carriacou is known locally as the "Land of The Reefs" and its most notable dive site is Magic Garden, which features bubbling geothermal vents (Crask 2012). In addition to supporting the tourist industry, Grenada's largest portion of its economy, these reefs are also home to fish—Grenada's third-largest economic sector. Inland, agricultural production (Grenada's second largest economic sector) has a foothold in the islands' rich and productive volcanic soil.

Grenada's original name, given by the Amerindian inhabitants, was *Camerhogne*, the meaning of which is unknown. Its first European name, given by Christopher Columbus, was *Concepción*. Later, Grenada's mountainous green terrain led to its renaming, *Granada*, by Spanish sailors (Martin 2007). During the subsequent French takeover, it was changed to *Grenade*, and then, under British control, Grenada (*gruh-NAY-duh*). As plantations flourished and the island was found to support various cash crops, different spices were cultivated, eventually leading to the island's *Isle of Spice* moniker. Today, the Amerindian influence on Grenada has largely been lost—except for the rock art (petroglyphs) found around the island, and small

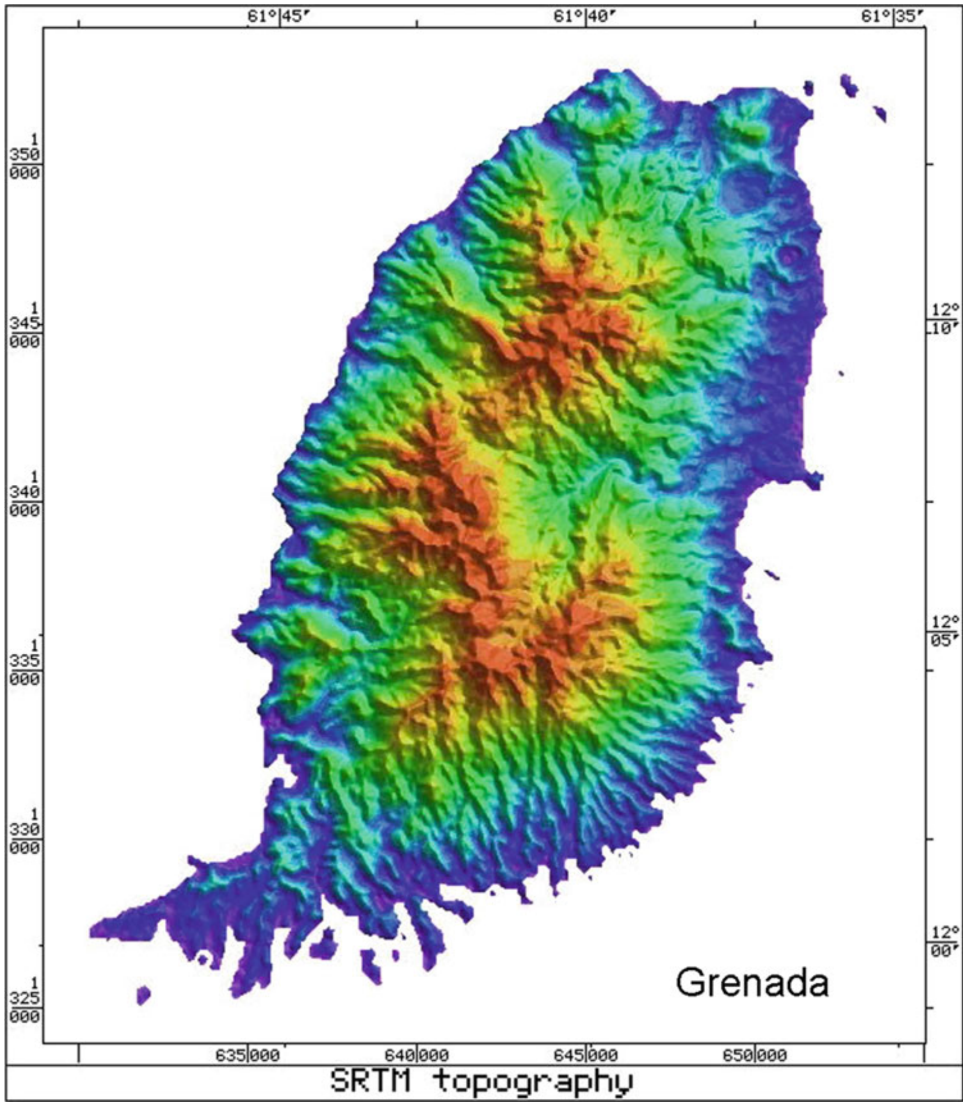

Fig. 16.4 Digital Elevation Model (DEM) of Grenada, with highest points represented by the *orange*, rust-colored region in the island's interior. Although rather steep in the interior, notice the gentle slopes on the islands east (windward) and southern sides (*purple* and *dark blue-colored regions*). Carriacou and Petite Martinique share a similar topography as Grenada, with a mountainous interior and scattered, flatter areas of sediment accumulation leading to beach creation. DEM courtesy of http://caribbeanvolcanoes.com/radar-grenada/. Retrieved Oct 2016

archaeological sites scattered predominantly on the Island's Eastern coast—though some locals claim to be of Carib or other Amerindian ancestry.

The tri-island nation of Grenada has a humid tropical marine climate, characterized by an average temperature range of 24–30 °C. Little variation in length of day, temperature, or relative humidity occurs due to its near-equatorial latitude. The dry season generally lasts from January to May, and the wet season from June to December. During the wet season, residents on Carriacou and Petite Martinique, which have no rivers or streams, collect rainwater for drinking (AQUASTAT 2012). As with other Caribbean Island Nations, Grenada can be dramatically affected by natural events. Although it lies at the cusp of the Caribbean Hurricane Belt, 50-year events continue to wreak havoc. In recent history, Hurricanes Emily (2005), Ivan (2004), and Janet (1955) devastated the Island, and some areas are still recovering from the effects of Emily and Ivan more than a decade later. While large volcanic events on the islands have ceased, geothermal activity and an offshore underwater volcano, Kick 'em Jenny—which erupted most recently in 2015 and continues to rumble and cause the occasional earthquake—demonstrate continuing potential for volcanic impacts.

16.2 Geologic Setting

Geologically speaking, Grenada is largely composed of andesite domes, basalt flows, and the (sedimentary) Tufton Hall Formation (Fig. 16.5). While all three main islands share similar geologic compositions, the largest island

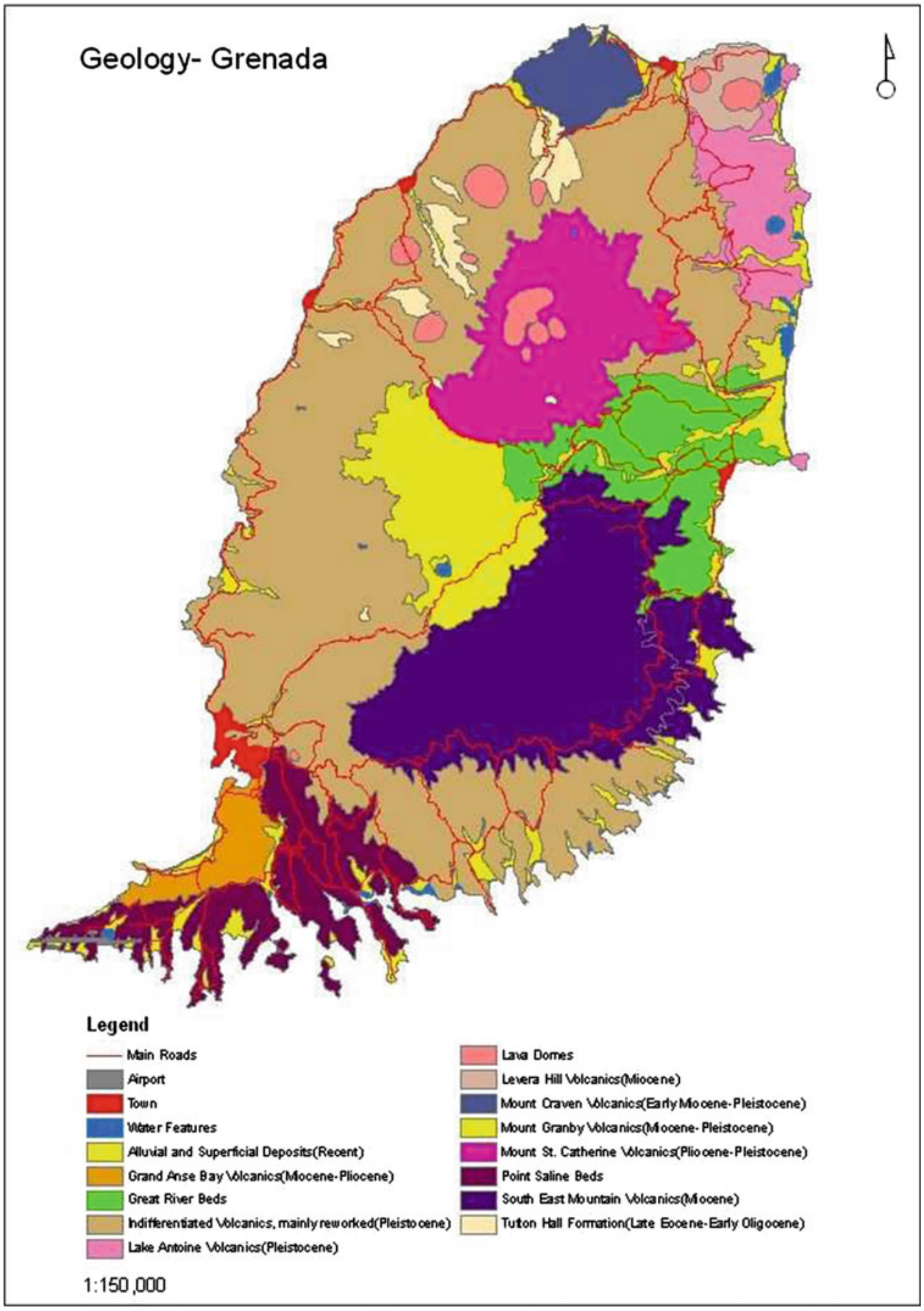

Fig. 16.5 Geologic map of Grenada. Even though Grenada was formed volcanically like other West Indian islands, it retains a geologic diversity such as lava (andesite) domes (salmon-colored ovals in the north of the map), Miocene volcanics, and Late Eocence–Early Oligocene sedimentary uplift regions (*light tan-colored* blotches in the northwest of the map). Map courtesy of Working Together for Grenada, an initiative sponsored by The Caribbean Natural Resources Institute (CANARI), available online here: https://sites.google.com/site/grenadabioconserv/home. Retrieved Oct 2016

features the most prominent geology. Northern Grenada holds the oldest volcanic rocks on the islands, with andesite domes of Mt. Alexander, Mt. William, and Mt. Rodney having been dated to 21 mya (Arculus 1976). Levera Hill and Levera Island (also known as Sugar Loaf) are examples of andesite intrusion through the Tufton Hall Formation, and Grand Etang Lake and Lake Antoine are well-preserved examples of explosion craters dating back to the Pleistocene (Arculus 1976). Volcanic activity in Grenada has mostly ceased, with one exception being the active submarine volcano Kick 'em Jenny, approximately 8 km north of Grenada and 20 km south of Carriacou. Additionally, a few hot springs remain on the island indicating continued geothermal activity. Generally, Grenada's coasts exhibit less relief than the interior geomorphology, having been subjected to mass movement episodes. Mudslides, landslides, lahars, and fluvial deposits have largely covered Grenada's southern regions, forcing a gentler topography. Similarly, eastern

Grenada is composed of volcanic deposits and sediment. While past and present watersheds and mass wasting events have helped shape the southern and eastern coasts into less rugged terrain, the western coast still displays the steeper landscape typical of Windward Islands due to asymmetric volcanic eruptions and windward–leeward differences (Grenada Forestry Department 1988).

16.3 Landforms

Analyzing Grenada's geomorphologic past represents a challenging exercise for even the most well-versed geomorphologist. Like other tropical islands, vegetation is dense and rock decay has worked its magic creating (sometimes thick) soils. Grenada also hosts great topographic relief, making stratigraphic recreation problematic. Additionally, between the Eocene (50 mya) and Miocene (~25 mya), the Lesser Antilles volcanic arc underwent extreme geologic stresses, twisting, buckling, and warping. Though these activities occurred mostly underwater, the result was a fresh reorganization of geology, driven by still-active volcanic processes (Arculus 1976). Today, Grenada's current volcanically dominant landscape remains underlain by this Lower and Upper Miocene basement sedimentary rock, known as the Tufton Hall Formation, which formed in the then-shallow sea and consisted of mainly mud, sand, and silt. Between Tufton Hall stratum, volcanics have been found (Arculus 1976), leading geologists to believe that volcanic activity was occurring here even during the Ologicene (~37 to 25 mya). Uplifted, folded, and faulted in many locations during this ancient timeframe, remnants of the Tufton Hall Formation can still be seen on the surface, primarily in the northwest of the main island and near Annandale Falls.

16.3.1 Grenada's Volcanism and Tectonics

While some studies focused on geochemistry tectonics are available (Saunders et al. 1985; Urzua et al. 2015; White 2015; Speed et al. 1993; Tomblin 1974, 1975; Weeks et al. 1971), gaining precise geologic understanding of Grenada is still difficult due to a host of factors: changing volcanic centers, rock type/age mixing, unknown rock sources, and inter-event erosion, to name a few. Arculus (1976) wrote perhaps the most definitive work, though he also acknowledges that much data is missing. According to Arculus (1976), Grenada's greatest volcanism occurred during the Pliocene (5–2 mya) and into the Pleistocene (2 mya–10,000 ya). Pyroclastic events, basaltic and andesitic lava, and intense volcanic eruptions associated with the Mt. Granby and Mt. Qua Qua regions happened during this timeframe. The geologic record displays these sometimes-furious events in the transition from basaltic and andesitic lavas, exhibiting the eruptions' cyclical character. Southern Grenada showcases the lava flows, tuff deposits, and lahars associated with this timeframe, though the source evidence for these events is probably buried (Arculus 1976; White 2015). These events, however, most likely resulted in the comparatively mild relief of the island's southern portion (Arculus 1976; White 2015).

Mt. Alexander features one of only a few examples of exposed limestone in Grenada, providing strong evidence for geologic uplift after the Pleistocene, as the area has limestone soils not present in other parts of the island nation. Iron and aluminum oxides dominate soils in the interior of the island, giving the latosols distinct red and yellow-red colors. These nutrient-poor soils require close management as they are fragile and easily disrupted (Grenada Forest Department 1988). Arculus (1976) speculated that perhaps Grenada's most recent volcanic massif is Mt. St. Catherine, which probably had its genesis during the Pliocene, but lasted throughout the Pleistocene. The dacitic and andesitic lava flows located northwest of Mt. St. Catherine's summit lay on top of extrusive basaltic lavas, while to the summit's west, some of the highest volume pyroclastic flows can be found (Arculus 1976).

Grenada's high volcanic activity ended violently, with massive explosions around the island, as evinced by the large calderas of Lake Antoine, Grand Etang, and the St. George's area. St. George's harbor and its neighboring Port Louis represents one of the most unique landforms on Grenada, being one of a few examples worldwide of a double caldera (Fig. 16.6; Hearn 1890). The inner harbor was once swampy, and blocked from access by baymouth bars, but these were originally removed by the Colonial French to improve marine access, and dredging continues to this day (Martin 2007, 2013). Arculus (1976) notes the Lake Antoine caldera (in the island's north) as being Grenada's best example of a true tufaceous ring, while the (rare) double caldera of St. George's harbor and Port Louis give Grenada its two main natural harbors and a large source of gravel (scoria) used in construction. Perhaps the most obvious caldera on the island, Grand Etang, represents the youngest volcanic structure, forming from three closely spaced events around 12,000 years ago (Arculus 1976). Recent history records scant volcanic activity on Grenada, except for its geothermal activity in the form of hot springs. While most of these are found around the Mt. St Catherine area, a few

Fig. 16.6 This image (created from three separate photographs "stitched" together), taken from Fort George, displays a rare double caldera—making the ports of St. George's Harbor (bay on the *left*) and Port Louis (bay on the *right*) possible. St. George's Harbor, locally known as the Carenage, was naturally deep and used since Colonial times for commerce and visitors alike. It also hosted the island's first cruise ship terminal until the early twenty-first century, when it was moved to the Esplanade, located on the other side of the hill. Commercial vessels and ferries still depart from St. George's Harbor. Port Louis, originally a swamp dredged by the Colonial French, is now the main marina and harbor for boating tourists to moor. Photos by C. D. Allen, 2016, stitching of panorama by K.M. Groom, 2017

others are known near River Sallee and Peggy's Whim Springs—the former being more sulfurous, the latter not so much, and both of which are more lukewarm than hot.

16.3.2 Underwater Volcanism

Approximately 8 km north of Grenada, however, between the main island and Carriacou, lies an active submarine volcano, Kick 'em Jenny. Roughly 180 m below sea level, it has erupted at least a dozen times since record keeping began nearly a century ago. Thought to be the only active submarine volcano in the Eastern Caribbean, Kick 'em Jenny is 1300 m high and 300 m wide at the summit (Global Volcanism Program 2005; Gilser 2006; Seismic Research Center 2016). Although no eruption has broken the surface since 1939, there is still cause for concern, as an eruption in 2001 made the ocean surface bubble, prompting more monitoring and studies (Gilser 2006). In July 2015, the University of West Indies Seismic Research Center noted highly unusual activity (extreme bubbling, regular earthquakes), leading them to issue a warning about its impending eruption in the near future.

16.3.3 Geomorphological Features

Numerous examples of Grenada's geomorphological past remain evident around the island, and for the casual observer, many can be seen readily along most roadsides. Driving the main road around the Island, for example, affords opportunities to view classic lahars, prominent geologic contacts (Fig. 16.7), and pyroclastic flows, as well as coastal features such as tombolos, sea stumps (Fig. 16.8), and long stretches of beach (Fig. 16.9). Moving through Grenada's interior, baked soils (Fig. 16.10), laterite, and (small) feral relief is visible from a vehicle. The keen observer will also note occasional buried soils, pillow basalts (Fig. 16.11), sea caves (Fig. 16.12), sea arches (Fig. 16.8), and the aforementioned andesite cones and calderas (Fig. 16.13).

On the northeast side of the island, Lake Antoine is a mere 6.5 m above sea level, with a maximum depth of 30 m. The lake was formed 12,000–15,000 years ago during the final stages of volcanic activity in the area and is approximately 16 acres in size, second only to Grand Etang Lake (UNDESA). Lake Antoine is a national landmark in Grenada located near the River Sallee Boiling Springs, south of Levera National Park. The six springs reach varying temperatures, but never more than of 35 °C, and the largest measures 5 m wide and 2 m deep. Though undeveloped, these springs are designated as a protected natural landmark and have a religious significance for some local inhabitants, as evinced by their use by a local church for baptisms. There are other sulfur springs, formed by the combination of rainwater and volcanic hydrogen sulfide, and scattered around the northern end of the island. Though also referred to as boiling springs, most are tepid, but indicate continued geothermal activity.

From Levera, on the north end of Grenada, the confluence of the Atlantic Ocean and Caribbean Sea is visible from the shore. The Atlantic is frequently choppy with a great deal of turbidity and suspended sediment that renders the water a kind of deep blue opaqueness. Lower turbidity and suspended sediment loads mean the waters of the Caribbean

Fig. 16.7 Geologic contact between volcanic tuff (*bottom*, *lighter-colored* layer) and lahar deposits (*top*, rocky layer), common in the southeastern areas of the island. This contact can be seen along the La Sagesse road in St. David's parish. Photo by C.D. Allen. May 2013

Fig. 16.8 Common coastal features along Grenada's rugged, northern horn coasts: a small sea stump (*background*, in sea) and sea arch (*foreground*, *center*) just off the north coast outside of the town of Sauteurs. Photo by C.D. Allen, 2009

have greater visibility than the Atlantic (Crask 2012). The striking difference between the east and west side of the island is easily visible on a map (Fig. 16.1). The island's windward side is typified by the consistent Northeast Trade Winds that stunt and twist vegetation as well as create rough sea currents, steep cliffs, and sea caves (Fig. 16.14). Much of the plant growth is scrub, including cacti in such profusion that the French dubbed an area on the south end of the island

Fig. 16.9 A view from Duquesne bay, looking northeast. Visible in the far background, Ronde Island lies ~9 km off Grenada's north coast, and the underwater volcano, Kick 'em Jenny lies approximately 5 km west of Ronde Island. Photo by C.D. Allen, 2012

L'Anse aux Epines ("Bay of Spines"). The leeward side is typified by calm waters and sheltered bays, allowing for the formation of coral reefs and uniform beaches with well-sorted, well-rounded sand grains (Fig. 16.15). White sand beaches result from (mostly) crushed shells, coral, and other sediments. Several beaches also exhibit a combination of the two types with the slightly larger black sand grains settling on top of the white sand (Destination Guide nd), while others, such as Levera Beach, host white sand adjacent to a lava flow, due to extreme currents in the region. Black sand beaches on Grenada are the result of (mostly) decaying basalt flows being eroded over thousands of years and re-deposited on the shore.

Each of the islands—Grenada, Carriacou, and Petite Martinique—were shaped by their volcanic pasts, and some of these striking landforms have been recognized and protected by the government. Officially, the tri-island nation contains four national parks: Grand Etang, Mt. Saint Catherine, Levera, and High North (on Carriacou) (Huber et al. 2012). There are also 31 nationally protected natural sites, both inland and marine, ranging from Concord Falls Natural Landmark to Mt. Hartman Dove Preserve (Arce 2008; Huber et al. 2012). Additionally, two historic sites in the city of St. George's are on the tentative list for UNESCO designation. Mt. St. Catherine National Park boasts Grenada's tallest point (840 m), as well as three other points above 610 m: Mt. Granby, Mt. Lebanon, and Mt. Sinai. Grand Etang National Park hosts some of the most dramatic features on the island, including Grand Etang Lake—a 36-acre freshwater lake in a caldera 550 m above sea level with an average depth of 6 m (Fig. 16.16). Grand Etang Lake provides the majority of freshwater for the island, and numerous streams feed into and run off the lake (Fritz et al. 2011). Seven Sisters Falls, considered one of the most beautiful waterfalls on the island, is also located within Grand Etang National Park.

16.4 Landscape

16.4.1 Historical Occupation

Prior to the influx of European influence in the 1700s, Grenada had not seen widespread landscape transformation. The Arawak and, subsequently, Carib peoples left a relatively minor agricultural and developmental footprint on the island, and there is no evidence of significant deforestation pre-European contact. The island was first noted by Christopher Columbus in 1498, and he named it *Concepción*. Grenada's mountainous green terrain led to its renaming to Granada by Spanish sailors, but despite its visual familiarity, the Spaniards were unable to establish a colony on Grenada due to violent resistance from the Carib Amerindian. The French were the first European power to

Fig. 16.10 Geologic contact between Pleistocene lava flow and paleosol. Here, as hot lava flowed over the then-established soil, it "baked" and oxidized the soil, turning the soil to a *rusty orange* color. This feature can be found along River Road which runs in a generally east–west direction, just south of the National Stadium. Photo by C.D. Allen, 2009

establish a settlement, in the south, by bartering to buy property from the Caribs. They quickly overstepped their welcome by attempting to expand their control to the whole island, beginning a period of sustained conflict with the Caribs. This conflict culminated in a battle during which the remaining Caribs are said to have jumped to their deaths rather than be taken as slaves. Although little historical evidence exists to support this claim (it is more likely they jumped into the ocean and swam to safety to escape the French forces), a monument to their plight exists on a cliff in the town of Sauteurs, which takes its name from the French, *Le Morne de Sauteurs* ("Leaper's Hill")—the location where the mass suicide supposedly occurred (History & Culture nd). Even though no physical evidence of the "leap" exists, "The site attracts visitors who are probably awed by the self-sacrifice but the outcome nonetheless evokes sadness and anger" (Martin 2007, p. 140).

16.4.2 The Rise of the "Spice Isle"

During the subsequent French takeover, Grenada's name was changed to *Grenade*, and finally, once under British control, formalized to Grenada (*GRUH-nay-duh*). During

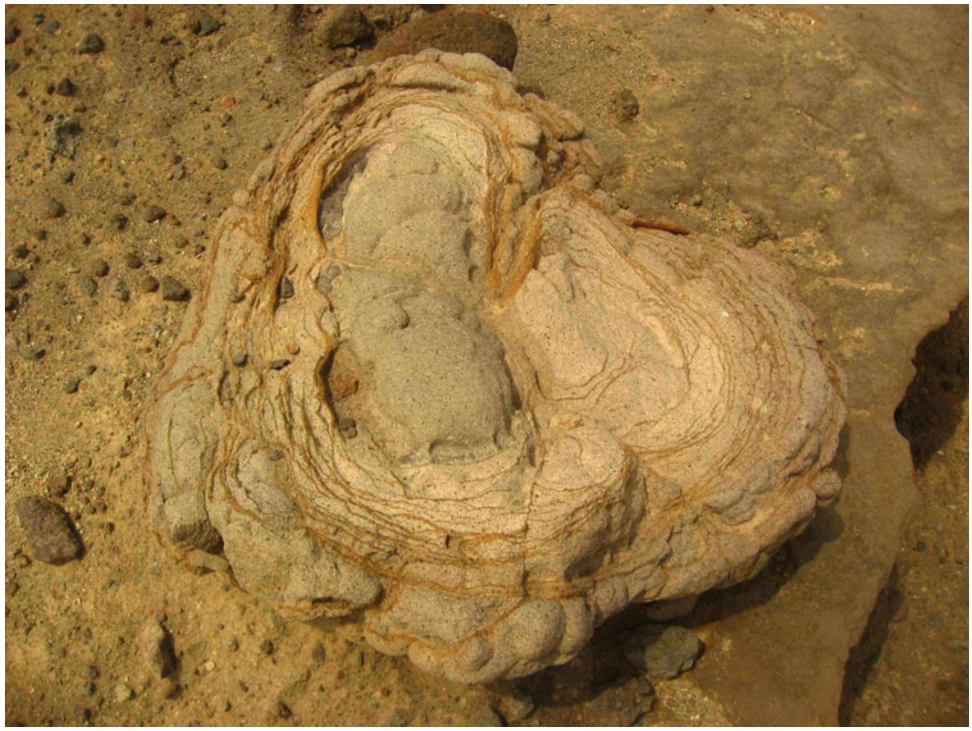

Fig. 16.11 Exposed pillow basalt on the coast of Fort Juedy Point. Photo by C.D. Allen, 2009

Fig. 16.12 Sea cave at Fort Juedy Point with considerable-sized swells entering the cave, various terraces in the foreground, and people in the background for scale. Photo by C. D. Allen, 2009

the French–British tug of war over the island, what is now St. Georges was settled, Fort George was built, and indigo, cocoa, and coffee were brought to Grenada. Fort George, originally built as Fort Royale by the French, is an example of colonists responding to the natural landscape. Built on a volcanic spire, the fort was constructed back-to-front, to defend against attacks from the interior (Kilgore and Moore 2011). When the British took stable control of Grenada in 1783 as part of the Treaty of Versailles, they brought sugarcane and slave labor to the

Fig. 16.13 Iconic andesite cone of Sugar Loaf off the coast of Levera Beach on the northern tip of Grenada. Photo by C.D. Allen, 2011

Fig. 16.14 This image, taken from Galby Bay on Grenada's eastern coast, typifies the island's windward side coastal features, including low-lying, windswept vegetation (on the hillside, *right*), wave cut notches and rock fall debris (*right*), rough headlands (*center-left*), and a sea arch (*left-center*). At the headland's tip, a couple stands overlooking the Atlantic Ocean for scale. Photo by C.D. Allen, 2004

island Sugarcane, and the production of rum became the dominant form of economic production on the island. A water-intensive crop, sugarcane also requires a substantial amount of cleared land. While the first is not an issue for Grenada (average annual precipitation <1000 mm for the Nation), the latter has had lingering impacts on the island (AQUASTAT 2012).

In the mid-1800s, as the Far East spice markets were being decimated by pests, Grenada began experimenting with the growth of nutmeg (*Myristica fragrans*), and through

Fig. 16.15 Looking northward along the famous Grand Anse Beach on Grenada's southern west coast. The capital, St. Georges, is visible in the *upper left corner* of the image. Photos by C.D. Allen, 2009

trial and error discovered it to be a viable cash crop. Other spices, such as clove, cinnamon, allspice, and the Tonka bean (similar to vanilla), soon followed. Coffee was attempted, but never took hold, and eventually was replaced by cocoa. In the early twenty-first century, Grenada claims between one-fourth and one-third of the world nutmeg market (depending on the year), second only to Indonesia. The Island's other spice exports including cocoa are nominal on the world market, but function as a significant component of the Nation's economy. Cocoa, in the form of chocolate and its associated products, has become a boutique/niche crop for the island, with two main companies vying for market shares. Though it has yet to break into the world market at large, Grenada's chocolate has won several international awards over the years. Still, for such a small island to hold a disproportionate world market share of such an important spice (nutmeg), is remarkable, and Grenada prides itself on being *The Isle of Spice*.

16.4.3 Carriacou's Landscape

Carriacou, the second largest Grenadian island, stretches 1.6 km between Pegus Point in the south and Gun Point in the north. Just south of Gun Point lies Petite Carenage Bay, home to the Kido Ecological Research Station. Petite Carenage Beach, Mangrove Wetlands, Sparrow Bay, and Anse La Roche together comprise the Nation's largest nesting area for Hawksbill and Leatherback sea turtles, and the Petite Carenage Mangrove Wetlands represent the most developed mangrove ecosystem, while also serving as a bird sanctuary. Carriacou also hosts three marine protected areas: Sandy Island (off its west coast), Petite Dominique Protected Area (between the northeast coast of Carriacou and southwest of Petite Martinique), and Gun Point Marine Protected Area, which encompasses the northern tip of Carriacou (Caribbean Conservation Association 2003).

Carriacou rivals Grenada for snorkeling and dive sites, including Magic Garden, off Mabouya Island to the west of Carriacou, a dive site known for beautiful reefs and underwater volcanic activity (Nagel nd). Secluded Anse La Roche is considered the most scenic beach on Carriacou, and a popular snorkeling spot. Hillsborough Beach, however, with its white sand running the entire length of its namesake village (and Carriacou's largest populated village), proximity to amenities, and nearly transparent water makes it one of the more popular beaches on the island for snorkeling (Fig. 16.17; Attractions n.d.). Paradise Beach (also called L'Esterre), however, is located between Tyrrel Bay and Hillsborough and is the most popular local beach, spanning the length of the village of L'Esterre (~4 km). Mt. Carre (288 m, also called Chapeau Carre), the second highest point on Carriacou, is clearly visible from Tyrrel Bay (Crask

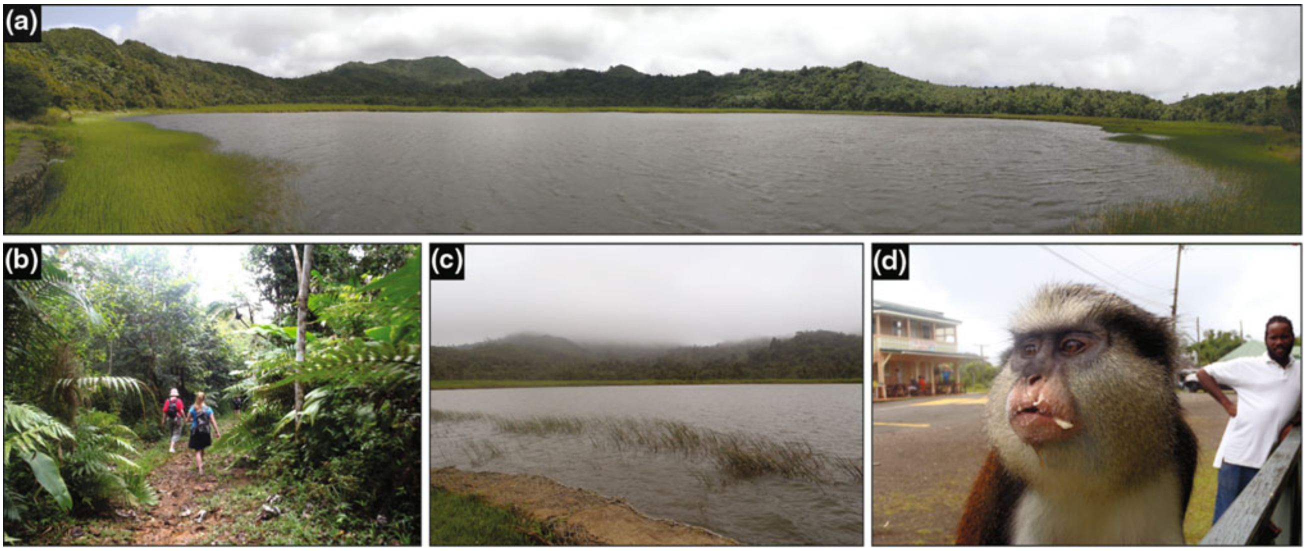

Fig. 16.16 Various features and attractions found in Grand Etang National Park. **a** Panorama of Grand Etang Lake in the center of the park. Steep slopes of the caldera surround the lake and thick reeds grow around the lakeshore. Photo by C.D. Allen, 2010. **b** One of the many lush hiking trails that transect the park, offering visitors the opportunity to immerse themselves Grenada's wilderness. Photo by K.M. Groom, 2012. **c** A closer view of Grand Etang Lake from the shore. Note the artificial retaining wall in the foreground intended to limit sedimentation and bank erosion into the island's main fresh water supply. Photo by K. M. Groom, 2012. **d** One of highlights of visiting the Grand Etang National Park is the possibility of feeding the wild Mona monkeys that inhabit the rainforest. Not native to the Caribbean, the Mona monkey population can be genetically traced back to a single pregnant female that was unintentionally transported to the island aboard in a slave ship from Africa. Photo by K.M. Groom, 2012

Fig. 16.17 Town of Hillsborough, Carriacou, as seen from the Princess Royal Hospital (Carriacou's only hospital and one of its main tourist vistas). Visible in this image are the island's lone airstrip (*upper center*), the main docking area/port authority (*center*), Hillsborough and Paradise beaches (*light-colored* sands running "up" from dock), and Sandy Island (the boomerang-shaped small island in the bay)—a popular day-trip snorkeling location. Photo by C.D. Allen, 2016

2012). High North Nature Reserve and National Park contains Mt. North (291 m), the highest point on Carriacou, (Natural, nd). The park has the least human impact of any area on Carriacou, and the ecology ranges from dry thorn scrub deciduous and evergreen forests to mangrove ecosystems (Huber et al. 2012).

16.4.4 Petite Martinique's Landscape

Like Grenada and Carriacou, Petite Martinique is also volcanic in origin. While significantly smaller than the other two islands, its interior is still mountainous, but unlike Carriacou and Grenada, it has no natural watersheds. There are three beaches on Petite Martinique, but only the one on the western shore, Main Beach, is open to the public. One of the other beaches is owned by a fuel company and serves as a way-lay station for their ships, and the third is restricted to government access (Home nd).

16.4.5 Expansion and Infamy

Housing has dramatically altered Grenada's landscape in recent decades. Since the late 1980s, Grenada has seen a steady influx of expatriates. While some of these people settled in the tourist hubs of Grand Anse and St. George's, others began searching for more secluded areas such as Westerhall and Fort Jeudy, and expanding into L'Anse Aux Epines. In the late twentieth and early twenty-first centuries, Grenada began to see a return-migration of locals who had made their fortune overseas and returned with disposable income. These factors have resulted in large swaths of land being deforested, hillsides being dug into, and even high-end resorts being built on smaller islands such as Hog and Calivigny Islands. Many of these homes are used only a few weeks each year by their owners and offered for rent during the year's remainder. Development has not been as apparent on Carriacou and Petite Martinique, though property is continually offered at reasonable prices.

One of Grenada's largest employers is St. George's University. Founded in 1976 as an American-run offshore medical school, it has since gained an international reputation for its programs, and now offers a full suite of university courses, including undergraduate studies. SGU had humble beginnings with a small campus located on Grand Anse beach, but later expanded to True Blue (and Prickly Bay) on the island's southwest peninsula, where the majority of its buildings are housed and classes are taught today. Since the 1990s, the campus has continued to expand, presently covering over 42 acres and hosting more than 50 buildings and nearly 6500 students in residence. The University is perhaps most remembered as being the focus of *Operation Urgent Fury*. In 1983, at the request of several Eastern Caribbean States, Ronald Reagan used the evacuation of mostly American students as a pretense for intervening in a bloody military coup, led by his former second-in-command, Bernard Coard, that ended with the execution of Prime Minister Maurice Bishop and several of his cabinet members. Memorials of the 1983 tragedy can be found around the island, and Grenada's Thanksgiving Day celebrated each year on 25 October—when the intervention began—serves as remembrance of that tumultuous time.

16.5 Heritage and Tourism

The impacts of tourism and management of heritage are often overlooked, especially in connection with geomorphologic value (Goudie 2002). Grenada depends heavily on tourism to help sustain its economy and provide the means to improve infrastructure, but management of its limited resources has often been misguided and detrimental, requiring improved practices that seldom come to fruition. While resort complexes still do not resemble the mass tourist locales of other islands (a consequence of Bishop's 1979 "New Tourism"), the tourist sector in Grenada continues to expand, and there is concern among some parties that large corporations will begin to put pressure on governmental officials to allow taller buildings. Currently, Grenada's landscape is attractive to tourists—not only for its beautiful beaches and splendid ocean activities, but also for its inland waterfalls and cultural heritage.

16.5.1 Beaches

Beaches represent a significant tourist draw for Grenada. Although the main island claims no fewer than 40 beaches, a three km stretch of white sand, Grand Anse beach, represents the island's most visited. Nearby Grand Anse are several other beautiful beaches, deserving of their names: Morne Rouge, Magazine, Parc a Beouf, and Pink Gin. More secluded and pristine beaches easily accessible on a short drive include La Sagesse, Bathway, Levera, and Sauteurs. With a little more effort, deserted and unspoiled beaches can be found, though sometimes they are named after their respective Bay or town/village, such as Grand Mal, Flamingo, Duquesne, Antoine, La Tante, Bacolet, and Granby to name several (Fig. 16.18).

As Grenada's Grand Anse beach becomes more crowded, tourists are looking for more unique beaches to spend their time. Two very different beaches offering a more undeveloped feeling are La Sagesse and Levera. La Sagesse, a "Nature Center" with nice lodging and a locally sourced restaurant, is nestled in a secluded bay with nearly a full km of gentle sloping beach. Though La Sagesse proper is shaded with palm trees and a couple cabanas, several hikes around the Nature Center are well marked and have outstanding views of the surrounding landscape, including wave cut platforms, small headlands, and ancient lahar deposits, as well as an abundance of tropical flora. The pristine setting

Fig. 16.18 Examples of Grenada's diverse beaches, in *both* color and surrounding landscapes. **a** Black sand beach at Black Bay as seen from off shore. The large basalt boulders on the *right-hand side* of the photograph exemplify the volcanic rocks that serve as parent material for the beach's black sand. Photo by C. D. Allen, 2013. **b** Mixed sands at Levera Beach. Golden colored sand with scattered patches of black sand occupy the center foreground of the image with rough basalt terrace covered with red-colored lithified scoria/lava flow in the background. Photo by C.D. Allen, 2012. **c** Tranquil white sands of the secluded La Luna Beach. The shallow waters display ample coral reefs (possible source for the white sand), and the layered volcanic lava flows that compose much of the headlands along the western coast are visible in the background. Photo by C.D. Allen, 2004

lures even the most hectic visitor to "lime"—a term Grenadians use to mean relaxing and being with friends and family.

At the other end of the island, Levera Beach is about as far away from the main tourist hub as a person can get. The beach also serves as a nesting area for the endangered leatherback turtle, adding to the area's lure. Though seemingly untouched, clear cutting in the early 2000s for a resort golf course increased water and sediment runoff in the area, and with increased interest from other private stakeholders for resorts on Grenada's northern shores, the probability of increased coastal erosion remains high. If the coastline is altered too drastically, it could greatly reduce the available area for nesting sea turtles (Maison et al. 2010). Likewise, the removal of ecologically important mangroves in the area increases the speed of erosion and destroys habitat for multiple species of land and water fauna (Moore et al. 2015). While currently stalled, should development continue in this region, it would be imperative the areas be carefully managed with insight from locals, authorities, environmental groups, and the resorts themselves.

16.5.2 Ocean-Based Tourism

An increasing threat to ecosystem stability and maintenance of natural resources are snorkelers and SCUBA divers visiting Grenada's beautiful coral reefs. While snorkeling and diving excursions represent a very important mode of revenue for the island, they also represent ways in which further degradation can occur. To help partially mitigate visitor impact to this fragile ecosystem, an underwater attraction—the world's first underwater sculpture gallery—was created in 2006 just off Grenada's west coast in Molinère Bay.

The artist, Jason deCaires Taylor, has since become renowned for his work and several subsequent underwater sculpture parks of his creation can now be visited at various locations around the world. The statues in Molinère Underwater Sculpture Park provide an artificial reef for wildlife and plants after much of the area's natural coral reefs were damaged and destroyed following hurricanes Ivan and Emily (Gocova 2013). Whether or not this unique attraction helps offset the damage caused by the hurricanes requires further study, as the benefits may be offset by the increased rate of visitation from divers to this unique area.

16.5.3 Waterfalls

Waterfalls represent another frequently visited geotourism attraction on Grenada (Fig. 16.19). Most popular among these are Annandale (Fig. 16.19a) and Concord Falls (Fig. 16.19b), though Royal Mt. Carmel Falls (Fig. 16.19c) is also an easy and rewarding hike. A fourth waterfall discovered just this century, St. Margaret Falls—locally known as Seven Sisters—sits near Grand Etang National Park but requires a guide and some scrambling. Annandale Falls has relatively easy road access and a short, self-guided, paved walking path from the small parking area to the falls. The road to Concord Falls, on the other hand, remains less developed—though recent improvements have been made to sections affected by landslides—and is accompanied by several souvenir stands and a snack bar. At Concord, easy views of the falls can be found on the built decks and stairs leading to the base, and visitors can descend all the way to the bottom for a different view, or for a dip in the water at the falls' base. With increased tourism, however, comes increased degradation, unless policies to the contrary are enacted. Concord's landscape was first altered by the addition of cement stairs and small shops overlooking its pristine location. To help ease Concord's congestion from multiple simultaneous tour groups, a large parking area above lower Concord Falls was completed in 2015. Though the project removed/rearranged a few tons of topsoil and altered both forest cover/ecology and tributary hydrology in the short term, the site recovered quickly and is now better equipped to handle large tourist groups, with streamflow turbidity and discharge back at normal levels, and surrounding vegetation replanted with thriving native flora barely a year later (Fig. 16.9b).

Containing two sets of falls, including the island's tallest, Mt. Carmel Falls' "entrance" begins at one of the main road's many hairpin turns on Grenada's eastern side. The short walk wanders the hiker through private, cultivated agricultural area including bananas, oranges, star fruit, nutmeg trees, and more. Visitors here are rewarded with cool, fresh water, and multiple pools for swimming.

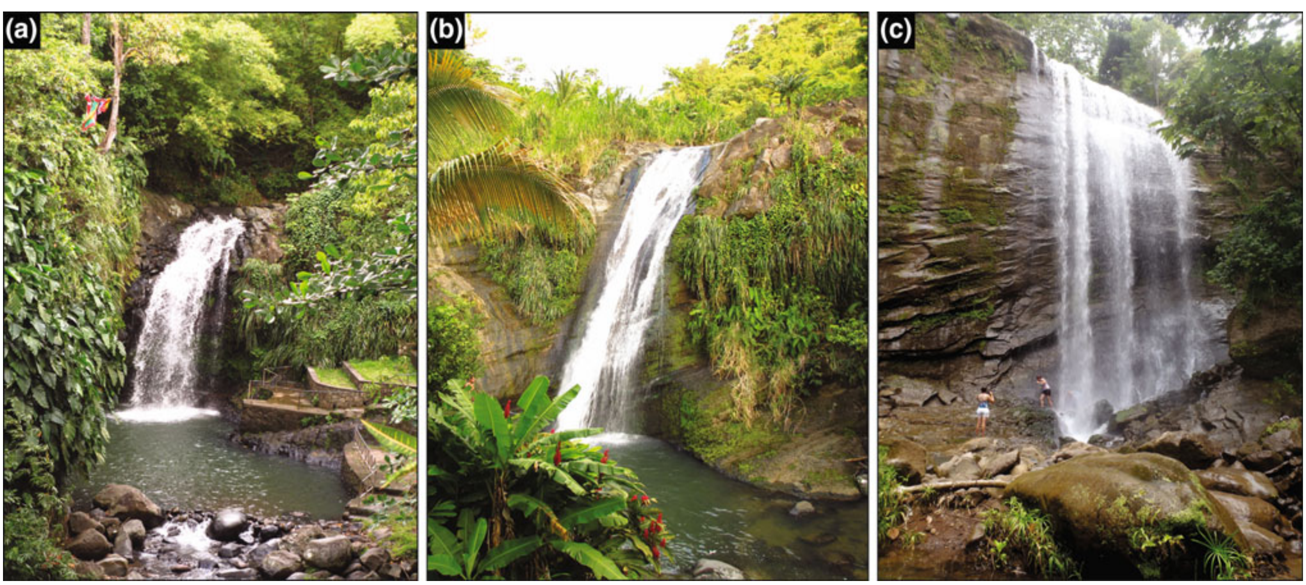

Fig. 16.19 Three of Grenada's most famous waterfalls. **a** Annandale Falls from the nature walk and gardens leading to the falls. A half-kilometer to the northwest of the falls, an exposure of the Tufton Hall can be seen. The Grenadian flag in the *upper left* and viewing platform in the *lower right* of the image provide scale. Photo by C.D. Allen, 2015. **b** Concord Falls from the steps leading down to the river. From this pristine vantage point, the large parking lot, built above the fall in 2014, is no longer visible. Photo by C.D. Allen, 2016. **c** Mount Royal Carmel Falls, the tallest waterfall on Grenada, during the dry season. In the wet season, the falls span the entire knick point. Note the people for scale. Just downstream is a much lesser-graded waterfall with slick algae covered rocks, making a natural waterslide popular with tourists and locals alike. Photo by K.M. Groom, 2014

16.5.4 Amerindian Heritage and Tourism

Rock art (petroglyphs) on the island interests some tourists and also provides an important link to Grenada's Amerindian Heritage. Commonly referred to as "Carib Stones" and often found alongside cupules (grind/work stones), these engravings are named for the most recent Amerindian inhabitants (the Carib Indians), although they were more likely created by the Island Arawak/Taino people (Martin 2007, 2013; Thomas 2010; Dubelaar 1995; Marquet 2009). While several petroglyph sites exist on the island, management efforts have been haphazard at best, with best intentions often doing more damage than good to these priceless cultural heritage resources.

For example, after Hurricane Ivan (2004), funds were procured to help mitigate decay of the motifs by erecting a small cement wall around a large petroglyph panel at Duquesne Bay. While a good idea in theory, the enclosure has had the opposite effect of enhancing decay because it now traps sea water from storm surges as well as effluence from surrounding houses (Allen and Groom 2013a, b), though recent attempts have been made to remedy this problem. Similarly, a motif-abundant site near Mt. Rich previously in overall good condition was "cleaned" in mid-2015. When left to the elements, rocks naturally develop a patina (rock coating). These coatings often develop over hundreds and sometimes thousands of years depending on the environment, and usually serve to protect the rock from decaying. In an apparent effort to make the Mt. Rich petroglyphs more visible to tourists, local "caretakers" inadvertently scrubbed the rock coating off the stones, potentially leaving the motifs even more susceptible to rapid decay (Fig. 16.20). Though long-term outcome is still being studied, this act—done with the best of intentions to help a struggling economy but lacking appropriate technique and education—has possibly weakened the host rock and enhanced decay processes, possibly erasing a priceless heritage resource quicker than normal conditions. In 2016, a reassessment was conducted of the host rock geologic stability, and it was found to be recovering better than expected. To compound management issues, Grenada's petroglyph sites have no official protection and remain highly under studied. Still, monitoring efforts continue keeping a watchful eye of these priceless cultural heritage resources.

On Grenada's east coast lies Pearls Airport—once Grenada's main airport until Operation Urgent Fury in 1983—an archaeologically rich site of Arawak and Carib artifacts. While a few active digs took place before and after Pearls Airport ceased operations, official digs have not really occurred after 1990. The area holds high volumes of pottery sherds and figurines (Keegan 1991), but a large strip of the area remains covered by a runway that is now only used for occasional drag races by locals. While archaeological artifact sale is officially illegal in the Caribbean, some entrepreneurial locals dig their own pits looking for well-preserved pieces of pottery to sell to unsuspecting tourists that visit the airport for primarily historic reasons: Pearls contains a

Fig. 16.20 Comparison of the Mt. Rich petroglyphs before and after being "cleaned". **a** Large boulder containing the majority of Mt. Rich's petroglyphs, surrounded by thick vegetation. Dark rock varnish covers most of the rock's surface. Photo by C.D. Allen, May 2014. **b** The same boulder from a similar vantage point a year later. Much of the protective rock coating has been removed (compare coloration of the main boulder in the background with the smaller boulder in the foreground, which was not cleaned) leaving the petroglyphs more visible but completely exposed to potentially more intense decay processes. Large portions of the surrounding vegetation has also been cleared and stacked for burning. Photo by C.D. Allen, May 2015

derelict USSR (Soviet) and Cuban aircraft left behind after *Operation Urgent Fury*. While a seemingly harmless endeavor to dig up artifacts, doing so severely impacts site integrity and reduces the number of artifacts available for study. Currently, there is one official dig in the area at La Poterie, north of Pearl's, but no plans to preserve what remains there or at Pearl's. Still, that locals are becoming aware of these cultural heritage sites as potential tourist attractions, speaks to the growing economic importance tourism is having on the island, and means more educational outreach must be conducted if protection/conservation/ management is desired.

16.5.5 Tourism on Carriacou and Petite Martinique

Carriacou and Petite Martinique receive far fewer tourists and house a much smaller permanent population. As tourism to Grenada increases, however, it remains like that visitation to these smaller islands will also increase. Ferries provide daily back-and-forth access between Grenada and Carriacou (and Carriacou to Petite Martinique), and during tourist season, the ferry company increases the number of return trips. This trend shows no sign of waning and may further alter the seascape between, as well as on the islands themselves. More construction will be required to accommodate visitors for overnight stays on Carriacou and Petite Martinique, which may lead to increased erosion of coastline, forest, and stone. As tourism remains Grenada's primary economic sector, it is important that the nation continues to develop that industry and strikes a balance between expansion and careful management of resources and habitats.

16.6 Hazards

Like other Lesser Antillean islands, Grenada has been, and will continue to be, susceptible to a myriad of hazards. At 12° north of the equator, the island nation lies on the hurricane belt's edge, but still impacted by the Inter Tropical Convergence Zone's (ITCZ) varying oscillations north and south over the equator throughout the year. The ITCZ is characterized by a band of clouds that circle the globe and produces often erratic weather patterns alternating between the static and the violent. Grenada's location leaves it vulnerable to tropical depressions, tropical storms, and the occasional high-category hurricanes. Additionally, the island nation is at risk of experiencing tsunamis and volcanic activity.

16.6.1 Hurricanes

Hurricanes and tropical storms are frequent in the Caribbean Sea, concentrated largely in what is known as Hurricane Alley. These storms begin formation at or near the equator off the west coast of Africa over warm ocean currents, strengthening as they move west and north. Grenada sits at the border of Hurricane Alley and, as a result, avoids many of the hurricanes that are directed north toward the Gulf of Mexico and east coast of the United States by the Coriolis Effect. However, several hurricanes have hit Grenada in recent history with devastating results. As a developing nation, Grenada is ill-equipped to recuperate from most high-category storms, and each major occurrence leaves the nation more susceptible to detrimental impacts of the next.

The most catastrophic event in recent history was Hurricane Ivan in 2004. The hurricane initially formed as a tropical depression, strengthening to a tropical storm on 03 September 3. On September 05, 2004, approximately 1850 km east of Grenada, the storm strengthened and was classified a category 3 hurricane on the Saffir-Simpson hurricane wind scale. The rapid strengthening of the storm at its latitude in the Atlantic Basin is a rare occurrence and, as the hurricane continued west, it weakened briefly and appeared to begin a northward path, but then shifted toward the Grenada with increasing ferocity. Nearly caught off guard, safety and mitigation processes were not in place when the newly strengthened now-category 3 (and building) Hurricane Ivan hit the nation on September 07, 2004. Originally believing Ivan had been downgraded and posed a less significant threat, residents were unprepared for its ferocity. Damage was severe and far-reaching, affecting every part of the tri-island nation, killing 39 people, and causing destruction to more than 80% of the island, resulting in more than $815 million USD damages—more than twice Grenada's GDP—prompting locals to rename the storm "Ivan the Terrible" (World Bank 2005; Ministry of Finance 2005). Barely a year later, in 2005, Hurricane Emily reached the northern end of Grenada as well as Petite Martinique and Carriacou, causing further damage and an additional death. Previous twentieth Century hurricanes had little effect on Grenada, other than Hurricane Janet (1955), which killed over 100 people and caused widespread damage to the Nation (Associated Press 1955).

But Hurricane Ivan affected more than infrastructure, as watersheds were effectively rearranged by the extensive damage which affected 90% of the vegetation, some of which is still recovering over a decade later (World Bank 2005). Additionally, 60% of cocoa trees, 60% of nutmeg trees, and nearly the entire banana crop were lost, as well as more than 50% of Grand Etang's rainforest canopy (World Bank 2005). The loss of nutmeg crops is particularly devastating as Grenada is responsible for more than one-third of the world's nutmeg supply, and nutmeg trees take over a decade to produce usable fruits. In conversation with a still-recovering nutmeg co-op outside of Gouyave, it was found that one plantation went from employing more than 100 people in 2004 to employing five after Ivan the Terrible (Allen 2012).

While Hurricane Ivan was a dry storm, the widespread demolishing of land cover led to extreme flash flooding during Hurricane Emily the following year. Nutrient-rich soils were moved or stripped away completely during this time, altering possible future crop yields. While damage from Hurricane Ivan was more moderate on Petite Martinique and Carriacou, these islands sustained heavier damages during Hurricane Emily. The potential for future damage and alteration to Grenada's islands from hurricanes is great. While large storms are more common north of the small island nation, increased erratic weather patterns as a result of climate change may change that, even though locals note a roughly 50-year cycle between major hurricane events. Still, future storms will increase erosive processes as a result of altered vegetation cover and damage to existing watersheds.

16.6.2 Mass Wasting

Deforested areas are far more susceptible to landslides and other erosion events, serious impact from flooding, and loss of top soil crucial for agricultural production. On a mountainous island such as Grenada, this can have serious consequences for development. Landslides can damage homes and agricultural land, and the potential for mass wasting events heightens concerns about infrastructure during hurricanes (Howell 1991). Of particular concern involving deforestation are precious mangrove forests. Mangroves not only provide a critical coastal habitat for a variety of species, but also serve to strengthen the coastline and prevent serious erosion from occurring during storms and storm surges. Beach sand also remains important for enhancing coastline strength but is threatened by sand mining efforts. The two resources—sand and mangroves—help buffer the coastline from wave impact, absorbing energy and limiting damage inland. Much of the western coast, which faces the powerful Atlantic Ocean, has been significantly deforested. This subjects the main road to erosion from waves at far greater frequency than would be the case if natural protections remained in place (Howell 1991).

16.6.3 Sand Mining

The Grenadian government recognized the negative impacts of sand mining on the environment, and in 2009, the practice was banned. Unfortunately, the resource limitations on such a small island meant that the need for sand in construction-pitted development interests against environmental concerns. Predictably, development won out. In 2013, Grenada reversed the ban on sand mining for two beaches on the island. The growth of the tourism sector and, to a lesser extent, business and housing has taken precedence over potentially irreversible environmental impacts. This move ignores the fact that sand mining puts Grenada's number-one tourist draw, its beaches, in crisis (Local News 2013).

16.6.4 Volcanic Hazards

Volcanic and seismic activity also poses a threat to Grenada and surrounding islets. Several extinct volcanic remnants exist on Grenada, but Kick 'em Jenny, Grenada's submarine volcano continues to cause concern. With increased activity of Kick 'em Jenny (its most recent eruption, as of publication, was July 2015; Seismic Research Center 2016), remote sensing and observation have been employed to monitor it. A safety perimeter has also been established to prevent divers and snorkelers from entering the area within 1.5 km of the cone (5 km during times of high activity), and boats must also steer clear of the area. An eruption, however, can alter the buoyancy of local sea water, posing a threat to passing ships (Gisler et al. 2006).

Eruptions on record have mostly been minor with little area disturbance, but a large eruption has the potential to breach the surface and release ash. It is not likely that Kick 'em Jenny will cease activity in the near future as its location on the Lesser Antilles arc acts to sustain conditions conducive to continued small eruptions (Seismic Research Center 2016). Submarine volcanoes have the potential to alter the landscape through continued eruption and increase in seamount size. Those that continually increase in size can breach the ocean's surface and form new islands. Once a volcanic island is formed, future eruptions would then impact nearby nations in perhaps severe ways through volcanic activities. Kick 'em Jenny's location near the equator could have high consequences for future global climate should the seamount breach the surface, as ash clouds block incoming solar radiation, and near the equator where solar radiation is the most constant, such affects are a prospect. Currently, however, research suggests that the potential for tsunami or catastrophic eruption events related to Kick 'em

Jenny is low, and it is most likely that impacts from future eruptions will remain minimal (Boruff and Cutter 2007; Seismic Research Center 2016).

16.6.5 Climate Change

Climate change will also be a factor in the hazards Grenada faces in the decades to come. Current models suggest a continued upward trend in average temperatures in the Caribbean, which is likely to cause longer dry seasons, erratic weather patterns, higher ocean temperatures, and an increased danger of drought (Cashman et al. 2010). Rising ocean temperatures have been attributed to fishery collapse in nearby Venezuela, and Grenada is already experiencing reduced populations of bait fish (Rustad 2012). The islands depend on fish resources, and a collapse could be calamitous. In addition to fish resources, the islands depend heavily on agriculture, which will be strained as temperatures rise and weather patterns alter. As tourism increases, further strain is placed on an already taxed water infrastructure that fluctuates with wet and dry cycles, as well as seasonal tourism. Additionally, sea level rise could dramatically reshape the islands, reducing available land for residents, visitors, and agriculture. According to a brief released in partnership between the Government of Grenada and the German Agency for International Cooperation (2014), a rise in sea level of 20 cm would reduce Grenada's beach areas by at least 40%. Warming waters will also contribute to the expansion of lionfish and other invasive species in the area.

16.6.6 Coral Reefs

The nation is also seeing degradation of coral reefs, perhaps due to climate change. Grenada has a substantial insular shelf, with an area of 3100 km^2. Because insular shelves tend to be shallower, and therefore receive more sunlight, and they tend to host the most expansive and diverse reef ecosystems (Howell 1991). There are 160 km^2 of coral reefs around Grenada, most extensively on the north, east, and south sides of the island, where the insular shelf is widest. The reefs off the north coast are considered to be the best and healthiest, while reefs to the south increasingly show reef degradation. This is likely correlated to rapid tourist development in the south raising levels of sewage, agrochemical pollution, and sedimentation from development processes (Bouchon 2004).

The combination of climate change and hazards—past, present, and future—in Grenada tends to increase difficulty for maintaining future goals. Landslides, floods, volcanic eruptions, tsunamis, and storms will remain a constant issue for Grenada. It is inevitable that Grenada will continue to be physically shaped by these events, but continuing to strive for proper management and mitigation will put the nation on the path to lower vulnerability and higher resilience.

16.7 Conclusion

Grenada, like its other Lesser Antillean cousins, offers stunning scenery full of a natural beauty and cultural richness. Its volcanic past has shaped it into an attractive landscape with accompanying striking landforms, and this variety is reminiscent of other Leeward Islands. From the north, where visitors to Levera Beach can ogle at andesite cone volcanics and lava flows while watching their step to avoid disturbing turtle nesting sites, to the interior's rainforest, where dramatic waterfalls such as Seven Sisters, Concord, Annandale, and Mt. Carmel invigorate the hiker—and from placid Grand Etang Lake surrounded by lush vegetation, to the southern coast and postcard-worthy Grand Anse Beach—Grenada offers something different at seemingly every turn. Though L'anse aux Epines and La Sagesse are less than half an hour's drive from each other on the southeast coast, L'anse aux Epines is a windswept area dominated by cactus, while La Sagesse remains a sheltered cove with soft sand and a vast beach next to a substantial mangrove. While there are no longer pure-blood Amerindians on the island, their presence is still felt in cultural sites such as Pearls Airport and La Poterie, their petroglyphs carved into basalt, and in place names. These important parts of Grenada's heritage are at risk of being lost, but interest and education could reverse the current path of loss and mismanagement. Cultural remnants from more recent developments face the same struggles as the Amerindian Heritage sites. There are abandoned plantations with unused water wheels and other holdovers from Grenada's colonial past, as well as numerous cultural sites—some that could offer meaningful insight into the history of the island, like Leaper's Hill, and some that offer incredible island views, such as Fort Frederick.

For the geomorphologist, Grenada offers an array of viewing and research choices: volcanic extrusions and sedimentary inclusions, fragile forests, endangered mangroves, delicate coral reefs, pristine beaches, beautiful bays, safe ports, and rugged cliffs. The Spice Isle also offers a variety of sites that may be of interest to cultural geomorphologists, such as Amerindian sites, historical plantations, sugar mills, rum distilleries, spice plantations, and festivals. From a biogeomorphologic perspective, Grenada also hosts an impressive number of flora and fauna, given its small areal extent, including several endemic species. And for those interested in climate change, hazards, and climatic geomorphology, the island nation offers a superb case study.

All these characteristics aside, for the past several decades, Grenada's natural resources have been taxed. Soil erosion, changing hydrologic regimes, stream and drinking water sedimentation, and even habitat loss represent serious concerns for the small island nation. Similar quandaries exist anthropogeomorphologically as well, where a lack of oversight regarding cultural resources continues to negatively impact important archaeological and historical sites. At the same time, however, to bolster the country's main economic component (tourism), better developed natural and cultural attractions are necessary. With increased catering to tourism, such as the completion of a Sandals resort in the southern part of the island, Grenada is facing a new set of challenges. Development is taking a toll on the landscape, and further challenges about tourist site suitability are continually raised because of the likelihood of landslides and increased concerns related to climate change events such as increased hurricanes, rising sea levels, and loss of beach material. Still, if Grenada can find a balance between the challenges of a growing tourist industry with protecting its natural beauty, The Spice Isle will continue to provide a wealth of experiences for residents and visitors alike far into the future. Indeed, as with most Caribbean tourist-driven economies, geomorphological wonders will play a pivotal role in shaping visitors' experiences.

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Trinidad and Tobago

17

Jeanette C. Arkle, Lewis A. Owen and John C. Weber

Abstract

The nation of Trinidad and Tobago comprises the two southeastern-most islands in the Caribbean. Despite being neighbors and part of the same nation, the two islands have markedly different geology, landforms and landscapes. The geologic framework of these islands is the result of protracted and complex tectonism associated with Mesozoic rifting of Pangaea, circum-Caribbean subduction, and currently, Caribbean-South American transform plate motion. Tectonism, climatic shifts, and associated sea-level fluctuations throughout the Quaternary have shaped the islands' wetlands, drainage systems, modern and ancient reefs, marine terraces, and morphology of their shallow continental shelf. The islands proximity to mainland South America resulted in unique and diverse biota of continental origin and also had a marked influence on the migration and settlement of the earliest people in the West Indies. The natural landscapes, as well as society, and policies, of Trinidad and Tobago have been affected by agriculture, mining, urban development, and the hydrocarbon industry. Continued natural and human-induced environmental change, particularly related to sea-level rise, will lead to dramatic changes of the islands' landscapes.

Keywords

Landscape evolution • Tectonics • Tropical erosion • Quaternary geology • Caribbean

17.1 Introduction

Trinidad and Tobago emerge in the southeastern-most part of the Caribbean as a pair of islands separated by <30 km on NE corner of the South American continental shelf (Fig. 17.1). Despite being neighbors and part of the same nation, the two islands have markedly different landscapes. This is a consequence of their unrelated origins in the early Mesozoic circum-Caribbean and their different and protracted geologic and tectonic histories associated with interactions between the Caribbean and South American plates. Trinidad and Tobago's diverse geologic frameworks provide the context for the islands' varied landscapes, landforms, and geomorphic evolution, which have played a critical role in the nation's socioeconomic development, particularly as the leading producer of oil and gas in the Caribbean.

The Quaternary landscape evolution of Trinidad and Tobago is a product of their positions along the southeast corner of the Caribbean plate, their shallow emergence on the South American continental shelf, and, as a result, an impressive combination of geomorphic processes. Differential vertical tectonism has uplifted coral reefs, created marine terraces, and also caused extensive subsidence (e.g., Snoke et al. 2001; Weber 2005). The Central Range transform fault

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Fig. 17.1 General physiographic map of Trinidad and Tobago. Note Trinidad's low-lying plains in the south and highlands along its northern coast, as well as Tobago's more mountainous topography. Cartography by K.M. Groom

in Trinidad, which defines the Caribbean-South American plate boundary, has generated a striking topographic scar across the entire width of central Trinidad and other tectonic landforms including shutter ridges, linear drainages, and offset ridges (Prentice et al. 2001, 2010; Weber et al. 2001a, 2011).

Sea-level fluctuations, associated with climatic shifts, have exposed portions of the shallow continental shelf and resulted in the development of an extensive offshore network of paleochannels (Soto et al. 2007, 2011). These base-level changes have caused adjustments to fluvial systems and the redistribution of sedimentation and erosion throughout the islands' interior landscapes (Ramcharan 2004; Arkle et al. 2015). Periodically connected with mainland South America during sea-level low stands, Trinidad and Tobago are home to unique flora and fauna of continental origin (Kenney 2008). The severe tropical climate has caused intense weathering, ubiquitous landsliding, and flooding (ODPM 2014). Strong, sediment-rich ocean currents dominate coastal sedimentation and erosion and influence coral reef development (Darsan et al. 2012). Collectively, these dynamic geomorphic processes have sculpted a spectacular variety of landscapes and landforms throughout Trinidad and Tobago.

Since the initial arrival of humans in Trinidad at ~8 ka, the landscape has been modified by agriculture, mining, biotic resource extraction, and urban development (Harris 1973; Boomert 2000; Pagán-Jiménez et al. 2015; Siegel et al. 2015). In the twentieth–twenty-first centuries, the hydrocarbon industry and an emerging tourism sector have further transformed the landscape. Continued natural and human-induced environmental changes will result in more dramatic landscape changes. Sea-level rise associated with human-induced climate change, mass wasting, and frequent seismicity and large magnitude earthquakes are some of the greatest threats to Trinidad and Tobago (Nurse et al. 1998; ODPM 2014). The future of the islands' landscapes and their management remains in a critical balance between employment, tourism, ecological protection, and sociopolitical factors (Dillman 2015).

17.2 Setting

17.2.1 Current Setting

Trinidad and Tobago are located in the SE corner of the tectonically and geologically complex Caribbean-South American plate boundary. Currently, the plate boundary is a transform margin that strikes eastward, south of Venezuela's northern Cordillera de la Costa, steps to the right in the Gulf of Paria, and then strikes ENE through central Trinidad. The current relative Caribbean-South American plate motion is ~20 mm/yr to the east, directed ~N86°E in Trinidad (Weber et al. 2001a, 2011). The majority of the dextral shear strain, ~12–15 mm/yr, is accommodated on the Central Range fault that strikes ~N72°E through Trinidad and continues offshore where it essentially merges with faults and structures of the Barbados accretionary prism (Pérez et al. 2001; Weber et al. 2001a, 2011; DeMets et al. 1994; see Fig. 17.2). Given this configuration, the southern half of Trinidad is moving westward with the South American plate, while land north of the Central Range fault, including northern Trinidad and Tobago, travels with the east-directed Caribbean plate.

Trinidad is structurally characterized by an alternating series of roughly ENE striking mountains and basins (Fig. 17.3). The Northern Range, Trinidad's tallest mountains, that rise to 940 m above mean sea level (amsl), exposes low-grade metamorphic rocks that were derived from Mesozoic passive-margin sedimentary rocks (Fig. 17.4). Late Cretaceous to Pleistocene sedimentary rocks underlie central and southern Trinidad (Erlich et al. 1993). These sedimentary rocks are folded and faulted to form two sets of low-relief hills, the Central and Southern ranges, which are bounded to the north by the Northern and Southern basins, respectively.

Tobago is dominantly composed of Mesozoic oceanic-arc and forearc rocks that rise to 572 m amsl in the mountains called the Main Ridge (Snoke et al. 2001; Fig. 17.5). These rocks are structurally sunken and covered by a Pleistocene coralline raised reef in the lowlands of southern Tobago (Fig. 17.6). Tobago is characterized by a northern highland and southern lowland that are associated with a series of horst and graben blocks formed by Pliocene-Recent regional extension.

Trinidad and Tobago have a tropical maritime climate with wet (June–December) and dry (January–May) seasons. Mean annual temperatures range from ~21 to 31 °C and the humidity is high, ranging from ~50 to 100% and averaging >80% (WRA 2001). Mean annual rainfall is ~2000 mm with extreme events delivering over ~5000 mm in areas of the Northern Range in Trinidad and in the Main Ridge of Tobago (WRA 2001; Hijmans et al. 2005). The islands experience relatively constant and strong easterly trade winds, and sporadic wet season tropical storms (WRA 2001). Although located outside of the main Atlantic hurricane belt, hurricanes occasionally track across the islands. The most infamous hurricane was Flora in 1963, which was devastating for Tobago (ODPM 2014).

The Guiana Current is the principal ocean current that impacts Trinidad and Tobago's coastal ecology and morphology (Van Andel 1967). The Guiana Current flows northward along South America and then bifurcates to the west through the Columbus Channel along southern Trinidad, and to the north along the coastlines of eastern Trinidad

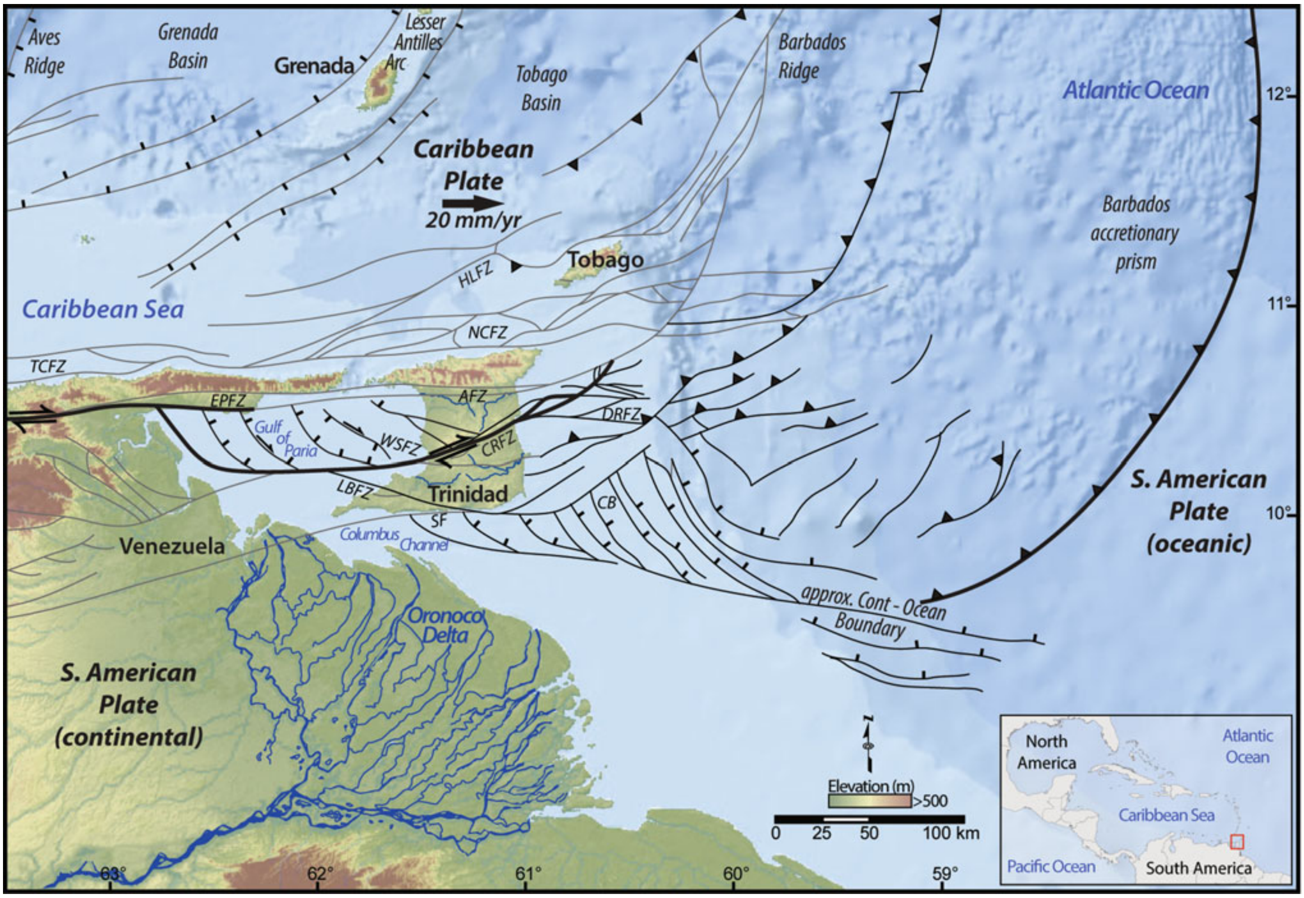

Fig. 17.2 Overview of the southeast Caribbean showing topography (0.5 km DEM from the US Geological Survey), bathymetry (from ESRI base maps and contributors therein), and major (*bold black lines*) and minor faults (*thin gray lines*) that show relative motion where known as thrust (teeth), normal (*bar*), and strike-slip (*arrows*) (after Soto et al. 2007, 2011; Prentice et al. 2010; Garciacaro et al. 2011 and references therein). Relative Caribbean-South American plate motion vector and velocity from Weber et al. (2001a, 2011), Pérez et al. (2001), and DeMets et al. (1994). *TCFZ* Tortuga Coche fault zone; *EPFZ* El Pilar fault zone; *AFZ* Arima fault zone; *CRFZ* Central Range fault zone; *WSFZ* Warm Springs fault zone; *LBFZ* Los Bajos fault; *SF* Soldado fault; *DRFZ* Darien Ridge fault zone; *CB* Columbus Basin; *NCFZ* North Coast fault zone; *STFZ* Southern Tobago fault zone; and *HLFZ* Hinge Line fault zone. Cartography by J.C. Arkle

and SE Tobago (Van Andel 1967). This current carries vast quantities of suspended sediment and plant detritus from the Orinoco and Amazon River deltas, which critically impacts coastal sedimentation and erosion, and, in large part, inhibits reef formation, particularly around Trinidad (Van Andel 1967; Laydoo 1991; Lapointe et al. 2010).

17.2.2 Geologic Setting and History

Trinidad and Tobago's geologic setting is complex and both islands have different geologic histories, structures, and rocks. Understanding the geological history is critical because it defines the context and "initial conditions" for the development of Trinidad and Tobago's landscapes and landforms.

Tobago's bedrock framework consists of three main lithologic belts that strike approximately eastward across the island and include: (i) a Cretaceous metavolcanic province, (ii) a Cretaceous intrusive igneous province, and (iii) a Plio-Pleistocene sedimentary sequence (Snoke et al. 2001; see Fig. 17.5). The Mesozoic oceanic forearc and arc rocks of Tobago formed far west of their current position and were rotated clockwise, possibly >90°, as they were translated eastward during oblique collision along the leading edge of the Caribbean plate (e.g., Erlich and Barrett 1990; Snoke et al. 2001). The intrusive igneous suites were emplaced at upper crustal levels during the late Cretaceous and experienced a protracted period of slow exhumation, through at least the Eocene (Cerveny and Snoke 1993), and then a pulse of increased exhumation during the late Neogene (Arkle et al. 2014). The metavolcanic and plutonic belts are bounded by the Central Tobago fault system (see Fig. 17.5). This normal-sense fault system and ductile shear zone strikes NE with down-to-the-south displacement and are interpreted to be related to extension that accommodated exhumation of the deep Tobago oceanic-arc rocks (Cerveny and

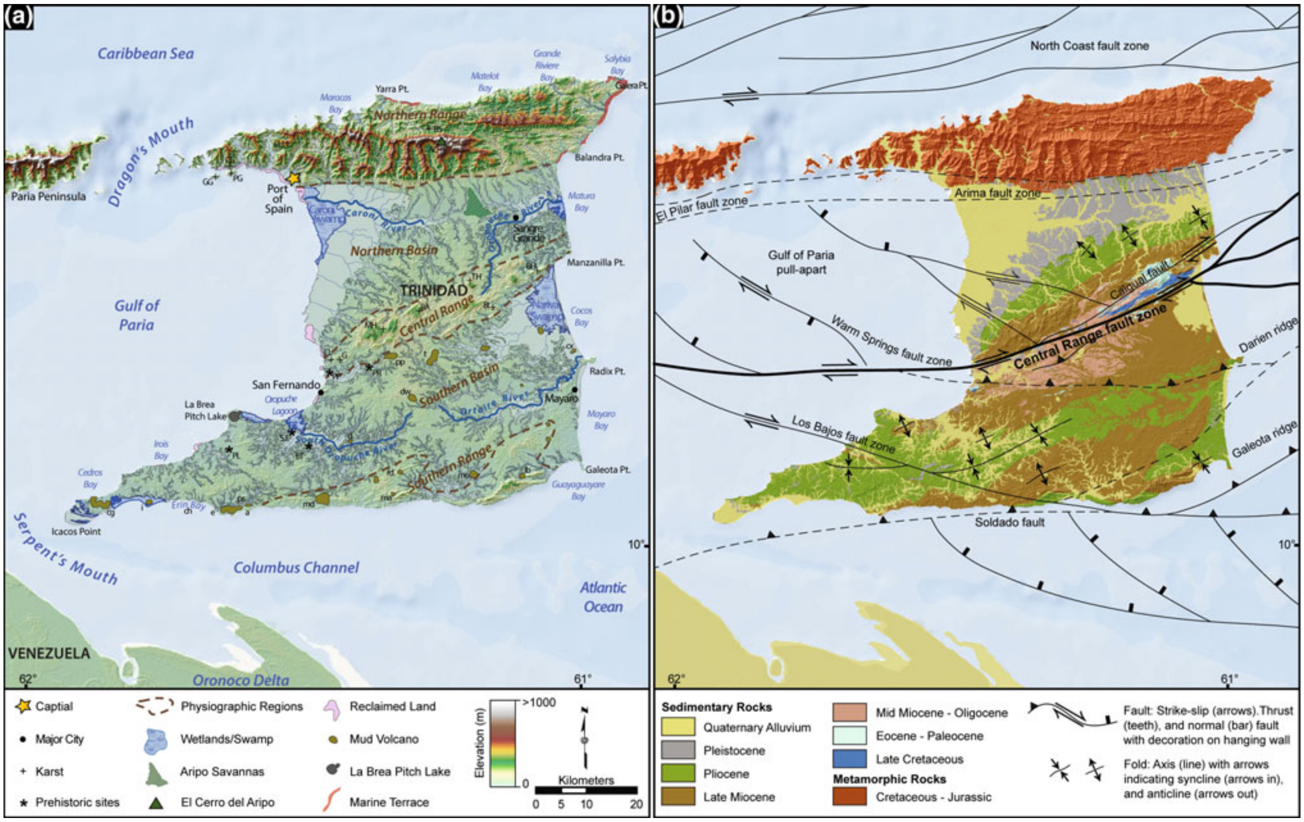

Fig. 17.3 Maps of Trinidad showing **a** the topography (30 m DEM from USGS Earth Explorer), the major highland (Northern, Central, and Southern Range) and lowland (Northern and Southern Basin) physiographic regions (*brown dashed lines*), trunk rivers (*bold blue lines*), and minor streams (*thin blue lines*), and **b** the geology. Approximate location of wetlands, swamps, lagoons, and reclaimed land are from the geologic map of de Verteuil et al. (2006). Prehistoric sites from Harris (1973): *PP* Pointe-a-Pierre; *PR* Poonah Road; *BT* Banwari Trace; *PL* Parrylands; *SJ* St. Johns. Mud volcanoes from Deville and Guerlais (2009) and Deville et al. (2003): *cg* Columbus group; *i* Islote; *ch* Chatham; *e* Erin; *ps* Palo Seco; *a* Anglais Point; *md* Morne Diablo; *ma* Marac; *rd* Rock Dome; *mo* Moruga; *lb* Lagon Bouffe; *d* Digity; *pp* Piparo; *dw* Devil's Woodyard; *t* Tabaquite; *cx* Cascadoux. Select karst outcrops from Erlich et al. (1993) and Day and Chenoweth (2004): *CL* Concord Limestone; *G* Gasparillo Limestone; *GL* Guaracara Limestone; *TL* Tabaquite Limestone; *TH* Tamana Hill; *BL* Biche Limestone; *BH* Brigand Hill; Hills; *C* Chaguaramas; *GG* Gaspar Grande; *PG* Point Gourde; *C* Cameron *AC* Aripo Cave; *BS* Brasso Seco; **b** Simplified geologic map of Trinidad modified from de Verteuil et al. (2006), Soto et al. (2007, 2011), and Prentice et al. (2010). Cartography by J.C. Arkle

Snoke 1993; Snoke et al. 2001). The Central Tobago fault system is offset by a series of younger oblique-slip faults that strike NNW (Snoke et al. 2001).

The deep meta-arc rocks of Tobago's Main Ridge are structurally sunken and covered by the Rockly Bay Formation and a coralline platform in the south (see Fig. 17.5). The clastic rocks of the Rockly Bay Formation were deposited during the middle Pliocene as a graben-fill sequence and are also likely a transgressive unit associated with concordant sea-level rise (Donovan 1989). The coralline limestone platform of southern Tobago formed during the Pleistocene and is well exposed in parts of the Tobago lowlands (Donovan and Jackson 2010). The Southern Tobago fault system and additional extensional faults cut and down-drop this limestone platform (Snoke et al. 2001; Donovan and Jackson 2010). Active extension continues today in south Tobago. The 1982 earthquake swarm and the 6.7 M_w 1997 Tobago earthquake are testaments to active extension (Weber et al. 2015a).

Trinidad's Northern Range is composed of metasedimentary rocks with Jurassic-Cretaceous protolith ages. These rocks are a continuation of the rocks exposed to the west in Venezuela's Paria Peninsula and Coasta de Cordillera. The Northern Range metasedimentary rocks were probably initially deposited along a north-facing South American passive margin during the Mesozoic (Algar and Pindell 1993). Miocene oblique collision of the Caribbean plate with the South American passive-margin, deformed, metamorphosed, and exhumed Northern Range bedrock and was synchronous with folding and thrusting in south Trinidad (Algar and Pindell 1993; Weber et al. 2001b; Cruz et al. 2007). The Caribbean-South American plate boundary

Fig. 17.4 View of the Northern Range, Trinidad from the north coast. Photograph by J.C. Arkle

stepped southward and changed to the current phase of transform plate motion at ~10 Ma (Pindell et al. 1998). The transition in plate motion from oblique collision to transform motion probably also marked the onset of low-magnitude, upper-plate collapse and extension that dominate the youngest tectonic features in and around Tobago (Snoke et al. 2001; Weber et al. 2015a).

In central and south Trinidad, the bedrock is sedimentary. The oldest exposed units are composed of Late Cretaceous passive-margin organic-rich marlstone (Erlich et al. 1993). The Paleogene-Early Neogene section was deposited in a distal foreland basin in front of the advancing Caribbean plate. Late Pliocene to Pleistocene sedimentary rocks in Trinidad were mostly deposited in the paleo-Orinoco delta system (Erlich et al. 1993). On the north flank of the Central Range, the Late Neogene-Pleistocene rocks were deposited after intense folding and thrusting of pre-Middle Miocene strata. This succession of rocks was then tilted to the north. In south Trinidad, folding and faulting, probably related to bends and steps in the transform system, continued into the Pleistocene.

Paleoclimate records from the Cariaco Basin in Venezuela show climatic shifts, most broadly, from a cold and dry period at the end of late Pleistocene into the Holocene (~11.5 ka) that transitions to a protracted warm and wet period until the middle Holocene (10.5–5.4 ka), and then a gradual shift to cooler and arid conditions throughout the late Holocene (~5.4–2.8 ka; Peterson et al. 2000; Haug et al. 2001). Quaternary temperature records for tropical South America are limited and regionally variable, but most studies indicate that temperatures were ~5 °C cooler than present in low-latitude areas of South America during global glacial stages (van der Hammen and Hooghiemstra 2000; Baker and Fritz 2015). Climatic transitions into cooler and arid periods likely caused rapid shifts between arid grassland and wet forest and shifts montane vegetation downslope (van der Hammen and Hooghiemstra 2000; Hughen et al. 2004).

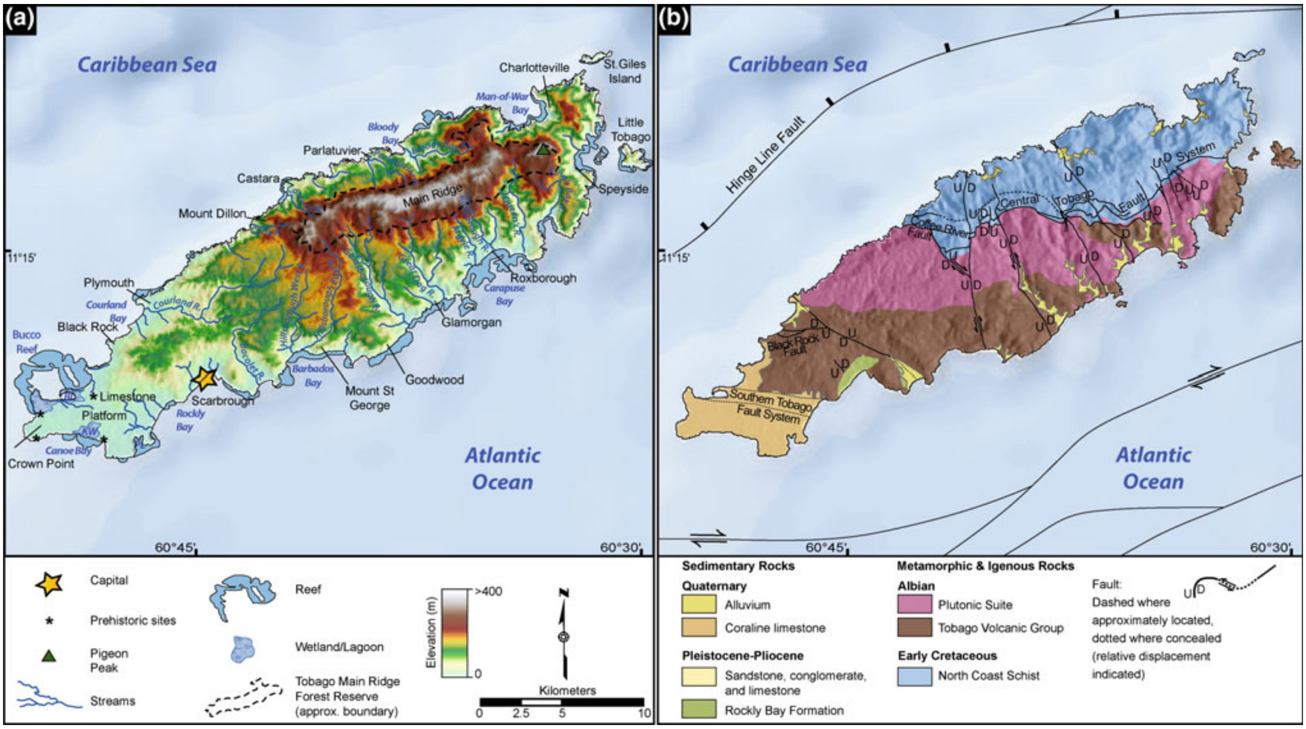

Fig. 17.5 Maps of Tobago showing **a** the topography (30 m DEM from USGS Earth Explorer), the Main Ridge Mountain highlands, the coralline limestone lowland, and major streams (*blue lines*), and **b** geology simplified from Snoke et al. (2001) and offshore faults from Garciacaro et al. (2011 and references therein). Reefs are from Hassanali (2013) and prehistoric sites from Steadman and Stokes (2002). Cartography by J.C. Arkle

Differential tectonic uplift in the region makes it extremely difficult to determine the absolute magnitudes of local sea-level fluctuations and the timing of when the islands were connected to mainland South America. However, if consistent with eustatic sea-level changes, the Caribbean may have been ~120 m lower than at present during the global last glacial maximum (e.g., Muhs et al. 2011, 2012). Trinidad, positioned aside the shallow (<30 m depth) Gulf of Paria, was likely connected to South America as recently as the Holocene, and Tobago was likely connected with the mainland during the Pleistocene (e.g., Boomert 2000).

17.3 Landforms

17.3.1 Tectonic Landforms

The large-scale (>10 km^2) landforms of Trinidad and Tobago reflect their complex tectonic and paleoclimatic history. The framework of Tobago's large-scale geomorphology is largely controlled by horst and graben structures. The island emerges as a structural high, as part of a series of regional extensional horst and graben blocks, positioned on the slightly stretched and extended southern edge of the Caribbean plate. The southern Tobago lowland lies over a down-dropped half-graben south of the South Tobago fault system, which also brings up the elevated horst block of the Main Ridge to the north. The Pleistocene limestone platform that forms the southern lowland is one of Tobago's most prominent sunken tectonic landforms. The seismically defined Southern Tobago fault system strikes eastwards across the platform, but is mostly buried and generally lacks surface expression (Snoke et al. 2001). Sea-level fluctuations and tectonic motion in southern Tobago have also generated numerous modern fringing reefs, which are more abundant and developed on the leeward side of the island, protected from severe weather tracks and sediment-laid ocean currents.

Past oblique-collision and active dextral Caribbean-South American plate deformation has created a suite of ENE striking bedrock structures that form the fundamental framework of Trinidad's large-scale geomorphology. This is highlighted by the occurrence of the alternating series of small topographic highs and low basins on the island (Fig. 17.1).

The geomorphology of Trinidad's Northern Range is dominantly controlled by neotectonic subsidence in the west and surface uplift in the east, in combination with a steep east-to-west gradient in rainfall (Weber 2005; Ritter and Weber 2007; Arkle et al. 2015). Eastern and western "blocks" of the Northern Range "split" at Yarra Point and are defined by an *en echelon* dextral break in the main

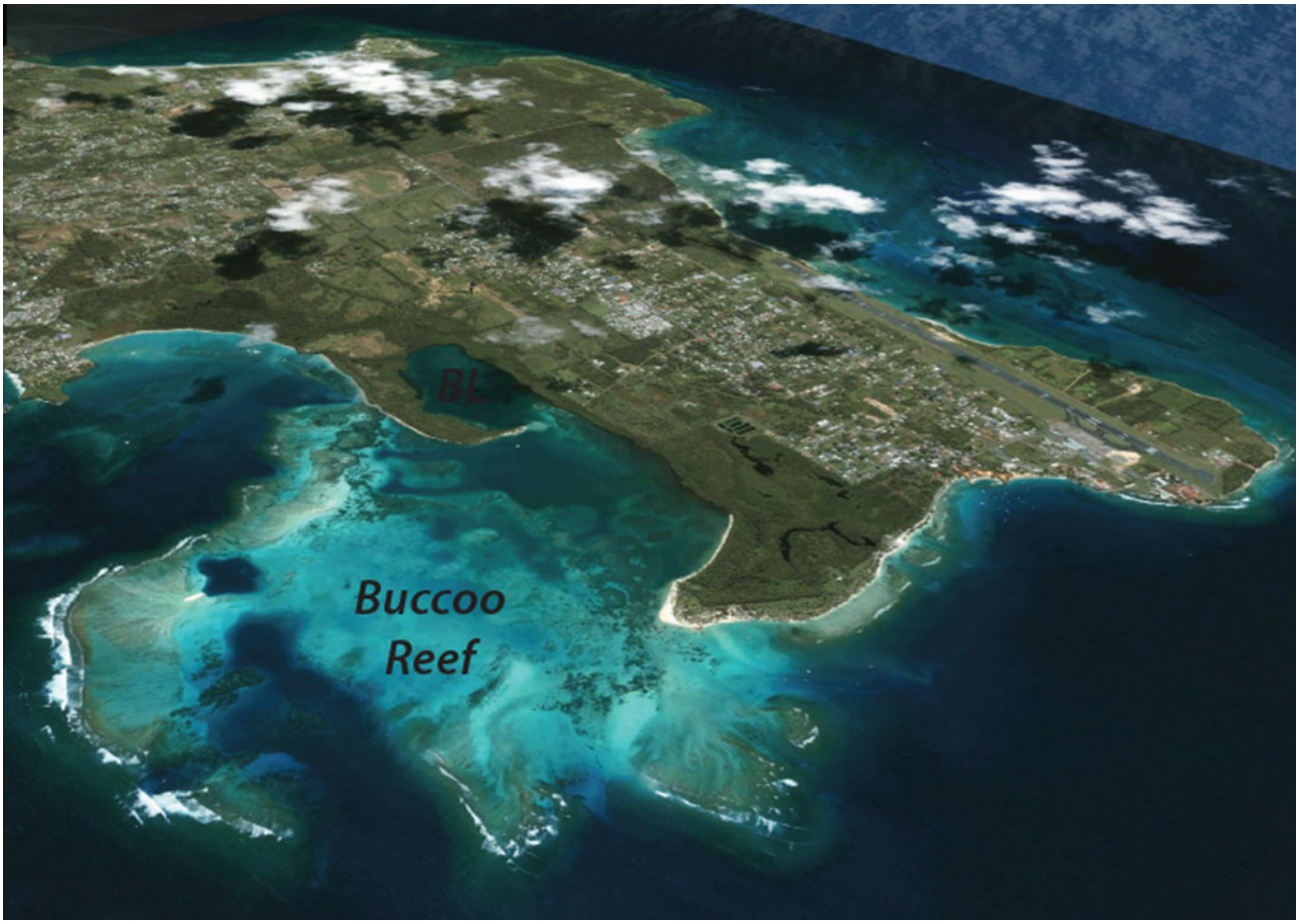

Fig. 17.6 Oblique areal view to the southeast of the coralline limestone raised reef and the relatively flat, low-lying topography of Tobago's southern lowlands. The foreground shows Buccoo Reef and the Bon Accord Lagoon (BL), Tobago's largest modern reef system and wetland. Photograph from Google Earth ca. December, 2004

ridgeline (N–S drainage divide; see Fig. 17.3). Geomorphic transitions include a relatively straight coastline punctuated by marine terraces in the east, to a highly scalloped and embayed coastline in the west, drowned island topography in the Gulf of Paria, and westward decreases of mountain front sinuosity and catchment outlet elevations. Alluvial fans bound the eastern mountain front, yet the correlative alluvial units in the west have subsided to depths over 100 m and are concealed by the Caroni Swamp (Weber 2005; Ritter and Weber 2007; Arkle et al. 2015). Quaternary erosion rates for catchments that drain the Northern Range are ~8 times greater in the east compared to those of the western catchments, reflecting both tectonic eastside-up tilting and high precipitation in the east (Arkle et al. 2015).

The Arima fault-line scarp bounds the southern flank of the Northern Range and defines a sharp transition from Trinidad's high-relief topography of the Northern Range to the Northern Basin (Algar and Pindell 1993; Weber et al. 2001b). Fault gouge is present along the Arima fault trace, yet there is no geomorphic or geodetic evidence of recent motion along this fault (Algar and Pindell 1993; Weber et al. 2001b). This suggests that it is probably an inactive exhumed fault with differential erosion of the relatively harder schist and quartzite to the north versus the softer slate to the south. The fault-line scarp strikes eastward and is exposed from the western offshore islands near Gaspar Grande, along the foothills of Port of Spain, and near the Village of Arima (Algar and Pindell 1993).

Southern and central Trinidad are characterized by a well-defined ENE structural and topographic grain, which is also parallel to the active Central Range fault zone. The contact between the weak shale-rich rocks of the Nariva Belt and more resistant Pliocene-Pleistocene Orinoco sand-rich deltaic rocks of the Southern Basin also forms a major eastward-trending escarpment (Fig. 17.7). This escarpment traverses the entire width of the island and from Point Radix in the east, continues offshore as the Darien Ridge, and is likely a fault-bounded contractile ridge. The Southern Range consists of a series of east striking *en echelon* ridges such as the Trinity and Cat's

Fig. 17.7 Low-relief hummocky hills of the Southern Basin, Trinidad. Photograph by J.C. Arkle

Hills. Collectively these features, both ancient and active, control the distribution and nature of Quaternary sedimentation, fluvial systems, coastline geometry, and endogenic landforms (e.g., mud volcanoes and asphalt seeps) in central and southern Trinidad.

The Central Range fault, the modern transform plate boundary, creates a major topographic lineament that strikes $\sim 072°$ across the entire width of central Trinidad (Prentice et al. 2001, 2010; Weber et al. 2001a; see Fig. 17.3). Linear drainages and saddles and troughs are topographically aligned along the Central Range fault. Small, steep-sloped hills mark a series of shutter ridges that block and pond streams. Linear scarps striking NNE along the fault trace appear as subtle low-relief rolling bulges. Deflected ridges and streams that drain the hills across the fault trace have right-lateral offsets (Weber et al. 2001a; Crosby et al. 2009; Prentice et al. 2010). These landforms are subtle in the Central Range hills, probably due to the intense weathering and erosion of the soft shale-rich bedrock rock in Trinidad's tropical climate, as well as substantial modifications to the landscape due to agriculture, historically, mostly sugarcane cultivation (Crosby et al. 2009; Prentice et al. 2010).

Soto et al. (2007, 2011) used 3D seismic reflection data to map the submarine continuation of the Central Range fault eastwards for another 60 km into the offshore. They also map several other faults and structures, and a complex network of paleofluvial systems that are developed in the apron of young, shallow continental shelf sediments. Offsets along these paleofluvial channels provides long-term slip rate estimates of ~ 17–19 mm/yr along the Central Range fault offshore (Soto el al. 2007, 2011), which is consistent with the onshore geodetic estimates (Pérez et al. 2001; Weber et al. 2001a, 2011).

17.3.2 Mud Volcanoes and Related Landforms

Trinidad's most unique and transient landforms are generated by asphalt seeps and mud volcanoes, which are concentrated in southern Trinidad (Fig. 17.8). Related active hydrocarbon features are regionally widespread and extend over several hundred kilometers, from the Barbados accretionary wedge into Venezuela (e.g., Higgins and Saunders 1974; Babb and Mann 1999; Pindell et al. 1998). Active petroleum generation occurs offshore and onshore in southern Trinidad, resulting in oil and gas accumulations in complex faulted and folded structures (Babb and Mann 1999; Pindell et al. 1998). Onshore Trinidad, most mud volcanism is located in clay- and sand-rich folded sedimentary rocks. It is driven in part by active oil and gas generation at depth, with local temperature and pressure changes likely controlling the cyclic activity and eruptive style (Dia et al. 1999; Deville and Guerlais 2009).

Eruption styles of mud volcanoes in southern Trinidad range from slow, continuous expulsion, to punctuated, effusive catastrophic eruption, which creates an assortment of landforms (e.g., Higgins and Saunders 1974; Deville and Guerlais 2009). Fields of mud (tassiks) surround small, steep-sloped (>25°) cones and domes composed of stacked mudflows that reach over 150 m in height and span from a few cm up to 2 km in diameter (Higgins and Saunders 1974; Dia et al. 1999; Deville et al. 2003; Deville and Guerlais 2009). The surfaces of tassik fields solidify and desiccate into forms that include concentric and hexagonal shapes; some are capped by polygenic breccia with clasts that include quartz and sulfide pebbles (Higgins and Saunders 1974; Dia et al. 1999; Deville et al. 2003).

Mud pools and lakes are dynamic and range from a few cm up to several hundred meters in diameter. Lagon Bouffe, for example, expels mud continuously from several vents and forms large pools (>100 m wide) of fluid and viscous mud (Dia et al. 1999; Deville and Guerlais 2009; see Fig. 17.3). Mud pools can generate very smooth-textured "stemmed glass" surfaces, and convection processes in larger pools are associated with displaced mud flanked by ribbed, ring-shaped rolls (Higgins and Saunders 1974; Dia et al. 1999; Deville et al. 2003; Deville and Guerlais 2009). Some of these landforms are short-lived. For example, in 1964 the Chatham mud island located in Erin Bay along the Columbus Channel formed an ~8 m high by an ~0.1-km^2 island in just a few days. However, the mud island only lasted ~8 months above sea level as it became compacted and was quickly eroded to below sea level (Higgins and Saunders 1967).

Pitch Lake, a popular tourist destination in Trinidad (~20,000 annual visitors), is the largest natural active asphalt deposit in the world, spanning an area of >0.5 km^2 with an estimated depth of >75 m (UNESCO 2015; see Fig. 17.8). It is located on Trinidad's southwest peninsula, ~1 km from the coast, near the village of La Brea, and is elevated to ~85 m amsl, and is on the crest of an anticline of Neogene sedimentary rocks (Kugler 1959). Pitch Lake expels a mix of heavy oil, bitumen (asphalt), and water. In aerial view, this asphalt lake forms hexagonal surface textures, concentric ribbed and ringed rolls, and small mounds composed of brecciated rock. Convection cells generate meter-sized bulges and features analogous with spreading ridges, smoothed fissures, and mini-subduction zones.

Pitch Lake is recorded in Sir Walter Raleigh's ship's log as a source of pitch that was used for patching his damaged ships. Amerindian pottery and the partial remains of a prehistoric fauna are preserved in Pitch Lake (UNESCO 2015). Several asphalt streams shown on Kugler's (1959) geological map of Trinidad indicate that Pitch Lake used to flow freely into the Gulf of Paria. However, mining of the pitch has lowered the level of the "lake" and it no longer drains externally, and only minor traces of asphalt streams can be seen in the topography today.

17.3.3 Drainage Networks and Fluvial Landforms

Drainage networks and streams developed in Trinidad and Tobago are relatively small, and many are ephemeral. Flash flooding is common, especially during the wet season (July–December), and occurs as overbank channel floods and as sheetwash flow. Landslides, slumping, and severe erosion also occur frequently during wet season floods and form serious natural hazards (ODMP 2014).

In Tobago, surface runoff is limited mainly to ephemeral streams in the lowlands, as surface water quickly infiltrates this porous limestone platform (Lapointe et al. 2010). Streams that drain the leeward (NW) flank of the Main Ridge are short, with steep gradients compared to streams on the windward (SE) flank that have developed longer, more entrenched and comprehensive watersheds. The majority of the streams in the Main Ridge, including the Coffee, Hillsborough, Goldsborough, and Queens rivers, are developed along oblique-slip faults that strike NNW. The headwater regions of streams typically have bedrock channels that transition downstream, to boulder covered, and then to coarse-to-fine-grained alluvial channels. The resistant

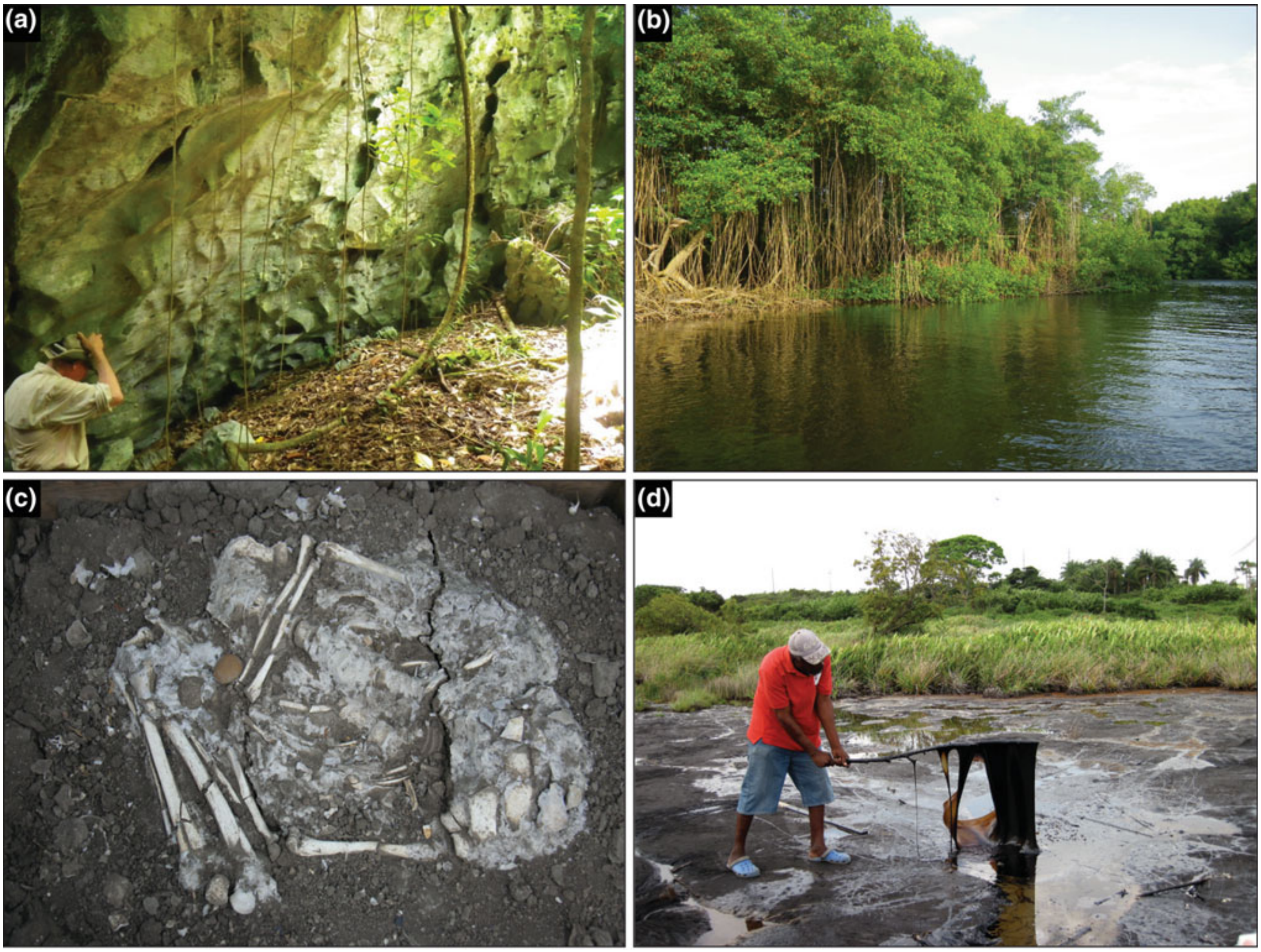

Fig. 17.8 Selected special features in Trinidad. **a** Karren dissolution developed on Cretaceous-Jurassic metalimestone bedrock exposed in a corridor of blocks (~10 m height) near the Aripo Cave in the Northern Range. Photograph by J.C. Arkle. **b** Mangrove wetlands in Caroni Swamp, the largest brackish water ecosystem in the country and habitat for the national bird, the scarlet ibis (Eudocimus ruber). Photograph by J.C. Arkle. **c** The Banwari skeleton, collected from a burial site in San Francique, southeast Trinidad, is estimated at 6000–8000 cal yr BP and is the oldest known archaeological site in the Caribbean. Photograph courtesy of the Department of Life Sciences, The University of the West Indies, St. Augustine. **d** Pitch Lake, the largest active asphalt deposit in the world, is located on Trinidad's southwest peninsula in the village of La Brea. A tour guide pulls viscous asphalt into the air with a stick to show tourists. Photograph by Dr. B. Crowley, University of Cincinnati

bedrock units form numerous stepped and hanging waterfalls and plunge pools, such as Argyle (Tobago's highest at ~55 m) and Twin Rivers (~30 m high) waterfalls (see Fig. 17.9), which commonly occur at major lithologic transitions.

Trinidad has four low-gradient truck rivers in the lowlands that generally flow along the axis of four major drainage basins; in the Southern Basin, the Ortoire and South Oropuche rivers, and the Caroni and North Oropuche rivers in the Northern Basin. These main truck rivers have broad, alluvial channels and small tightly spaced meanders. Low-gradient alluvial tributary streams drain the low-relief hills in central and southern Trinidad and dissect the soft shale-rich bedrock. Streams draining the north- and south-oriented catchments of the Northern Range are relatively evenly spaced and have numerous waterfalls and plunge pools. Stream channels on the east side of the mountains are V-shaped, and some have steep (>45°), narrow (<1 m) channels. Streams in western catchments have relatively flat, broad (>1 km) valley floors that cover the basement with over 100 m of sediment (Weber 2005; Ritter and Weber 2007; Arkle et al. 2015). Small river terraces (<20 m long) are present along several streams that drain the south flank of the Northern Range (Kugler 1959).

Holocene sea-level rise caused the islands' rivers to aggrade, and created and modified many of the coastal wetlands (Ramcharan 2004). During sea-level low stands, streams flowed through subaerial portions of the Gulf of

Fig. 17.9 Waterfall (~5 m high) in Castara River, northwest coast of Tobago, developed along NNW striking structures in the North Coast Schist. Photograph by J.C. Arkle

Paria. Trinidad's eastern coastline was ~80 km east of the present shoreline during Pleistocene glacial stages (Warne et al. 2002). The morphology of the eastern offshore is characterized by a gradual eastward sloping continental shelf composed of crystalline basement with a cover of Cretaceous to Quaternary strata. The Quaternary sediment on the slope is incised by a deep and complex network of paleofluvial channels, with depths to channel bases of >100 m below modern sea level (Soto et al. 2007, 2011). East-directed paleofluvial systems there align with some of the modern drainages in eastern Trinidad (Soto et al. 2007, 2011).

The offshore paleofluvial systems may have been important conduits, in terms of the geobiological history of the modern fluvial networks in the Northern Range. Northern Range streams are habitat for the freshwater guppy (*Poecilia reticulata*), which, from an evolutionary perspective, is one of the most well-studied animal species on Earth (e.g., Alexander et al. 2006; Willing et al. 2010). Highly differentiated guppy populations in the Northern Range are concentrated on the north flank of mountains, and on the south flank in the Caroni River watershed and in the Oropuche River watershed (Alexander et al. 2006). The west-flowing Caroni and east-flowing Oropuche Rivers are separated by a major but subtle drainage divide that overlies the Guatapajaro Anticline in the Northern Basin (see Fig. 17.3). Phylogenetic and morphological analyses indicate that the Caroni network guppies are closely related to Venezuelan populations to the west of Trinidad, whereas their Oropuche neighbors share features with populations to the south of Trinidad and in eastern Venezuela and Guyana (Alexander et al. 2006; Willing et al. 2010). Weber et al. (2015b) postulated that, in addition to distal fluvial connections during sea-level low stands, range-wide eastside-up tilting during the Quaternary may have contributed to partial and progressive replacement of guppy stocks in the Northern Range streams. One possibility is that as northern Trinidad was tilted, the Guatapajaro divide may have acted like a rolling hinge, where streams were captured and added to either the Caroni network, with eastern hinge roll, or the Oropuche network, with western hinge roll, which would have then separated the two stocks of guppies (Weber et al. 2015b).

17.3.4 Alluvial Fans

Alluvial fans are not well developed on Tobago, and alluvial deposits are concentrated mainly along streams draining the Main Ridge, such as the Courland River. In contrast, impressive alluvial fan complexes are present in northern Trinidad, particularly along the southern mountain front of the Northern Range (see Fig. 17.3). The alluvial fan deposits are only exposed along the eastern mountain front and have been mapped recently as the Valencia gravels (e.g., de Verteuil et al. 2006). The Valencia gravels were initially mapped as the Pleistocene Cedros Formation on Kugler's (1959) geologic map, which is a type section in southern Trinidad of sediment that was interpreted to have been deposited by the Orinoco River. However, the vein-quartz-pebble gravels and clean quartz sands clearly indicate that the Valencia alluvium was derived from the Northern Range. In the western Northern Basin, range front alluvial fans that correlate with those in the east have subsided to depths over 100 m and are covered by the Caroni Swamp and swamp sediment. These deposits are well known as "the Northern gravels" and are a very important source of groundwater in and around Port of Spain (Weber et al. 2011).

The northern alluvial fans are highly dissected by modern streams and tributaries that flow southward out of the Northern Range. These alluvial fans consist of multiple lobes with abandoned elevated terrace surfaces. Alluvial fan deposits are broad relative to the contributing upstream catchments (see Fig. 17.3). South-flowing streams from the Northern Range deeply entrench the alluvial fans, and modern deposition is focused along the alluvial fan toes. Fan-head entrenchment likely results from a combination of dynamic climatic and tectonic interactions including a reduction of the magnitude and rate of Northern Range erosion during Holocene warming, sea-level rise, and neotectonic uplift of the eastern Northern Range (Weber 2005; Arkle et al. 2015).

17.3.5 Wetlands

Trinidad and Tobago contain a variety of coastal and inland wetlands including swamps, bogs, marshes, and lagoons (see Figs. 17.3 and 17.5). In Trinidad, the majority of wetlands occur along the coastlines, such as the Los Blanquizales Lagoon and Rousillac Swamp, whereas other small wetlands have developed along streams, such as the North and South Oropuche lagoons. The majority of wetlands in Tobago are developed along coastal outlets of streams that drain the Main Ridge such as in Bloody Bay and Lucy Vale in Speyside and are protected by ephemeral barrier beaches. Wetlands located on Tobago's southern limestone lowlands include the Kilgwyn and Little Rockly Bay wetlands, and the Petit Trou Lagoon.

Bon Accord Lagoon is the largest wetland in Tobago covering an area of ~ 1 km^2 and is bound by the Buccoo Reef along the southwest coast (Laydoo 1991; see Figs. 17.5 and 17.6). Biologically, the lagoon supports sea grass, dominantly turtle grass (*Thalassia testudinum*), and is fringed by several species of mangrove (Kenny 1976). Freshwater exchange occurs through small perennial streams and by groundwater transport through the porous limestone (Lapointe et al. 2010). Inflowing water, however, carries pollutants from the developed lowlands, including those from several sewage treatment plants, which put the water quality and ecological health of the lagoon and Buccoo Reef at risk (Lapointe et al. 2010).

The Caroni Swamp in Trinidad is the largest brackish water ecosystem in the country, covering an area of >55 km^2, and is characterized biologically as an herbaceous and mangrove forest wetland (Gibbes et al. 2009; see Fig. 17.8). The Caroni Swamp is a coastal wetland located in the western Northern Basin and is fed by the Caroni River and several streams that drain from the Northern and Central ranges. Tidal exchange occurs over the low-lying topography along the western coast, which is associated with tectonic extension and subsidence in the Gulf of Paria. Local communities harvest fish, crabs, and oysters, as well as other fauna and flora, and the swamp is a popular ecotourism destination due, in part, to its proximal location to Port of Spain. The areas around and within the swamp boundaries have been intensely modified and developed into agricultural and urban land (Gibbes et al. 2009). In addition, land along the northern edge of the swamp has been altered and polluted by Trinidad's large Beetham Landfill.

The Nariva Swamp in Trinidad is the country's largest freshwater wetland, covering an area of >62 km^2 (Gibbes et al. 2009). The swamp is located along the east coast and is bound to the north by the Central Range and to the south by the Darrien Ridge escarpment. The Nariva Swamp and the majority (90%) of coastline along this stretch is, on average, <2 m amsl (Ramcharan 2004). Radiocarbon ages and fossil pollen show a varied vegetation history and that the wetland has existed since at least 6 ka (Ramcharan 2004). The Nariva River drains the swamp, which flows in a shore-parallel depression, bound by the Manzanilla barrier beach and subsidiary sandbars. The Manzanilla barrier beach protects the wetland from high-energy Atlantic waves and assists in regulating salinity levels in the swamp (Gibbes et al. 2009).

Freshwater lakes are limited to artificially constructed reservoirs, such as the Hollis, Navet, and Arena reservoirs in Trinidad, and the Hillsborough Reservoir in Tobago (WASA 2015). The nation's wetlands, both natural and constructed, serve as important ecological habitats for biota including the national bird, the scarlet ibis (*Eudocimus ruber* common to the Caroni Swamp), and the West Indian manatee (*Trichechus manatus* present in the Nariva Swamp), among many others (WASA 2015). Communities around these wetland areas are dependent on their resources.

17.3.6 Coastlines and Coastal Landforms

17.3.6.1 Shorelines and Coastlines

The coastal regions of Trinidad and Tobago vary from the high-energy, windward coasts bordering the Atlantic Ocean to the relatively protected leeward coasts bordering the Caribbean Sea and Gulf of Paria.

Tobago's windward SE coast, bordering the Atlantic, consists of numerous large bays and beaches. In the SW, the coastline along the limestone platform consists of elevated wave-cut cliffs that contain small sea caves and are punctuated by beaches composed of coarse-grained carbonate sand. The central and northern portions of the SE coast consist of large arcuate bays where the resistant oceanic-arc bedrock crops out along the shorelines. Numerous sea arches and sea stacks have formed in the rocky headlands, as well as fringing reefs (see Figs. 17.5 and 17.10).

Although wave and wind action are less intense along Tobago's leeward NW coast, the bathymetry and onshore topography steepen to the NE. Thus, the north and central stretch of this coastline is rocky with steep sea cliffs and hillslopes and consists of intermittent beaches formed in small embayments. Some barrier beaches, baymouth bars, and lagoons occur along stream outlets that drain the Main Ridge, such as those at Bloody Bay. To the south, the continental shelf is shallow and supports numerous, large fringing reefs such as the Buccoo Reef (Fig. 17.6). This segment of coastline consists of long beaches and bays with prominent headlands including Crown Point, Pigeon Point, Mt. Irvine, Black Rock, and Plymouth (from south to north).

Trinidad's Northern Range rises from the Caribbean Sea to form a rugged northern coastline, which is shaped by its bedrock geology and high-energy wave and wind action (see Fig. 17.4). Yarra Point marks a significant transition in coastal morphology, from a highly embayed, drowned coastline in the west, to a semi-linear, elevated coastline in the east; this transition is controlled by Quaternary eastside-up tilting of northern Trinidad (Weber 2005; Arkle et al. 2015). To the east of Yarra Point, steep sea cliffs, marine terraces, rocky headlands, and occasional sea stacks characterize the coastline. Subsidence to the west of Yarra Point, has led to the capture of watersheds by the sea and has left drainage divides and their flanks elevated at or near sea level, where small beaches bound by semi-circular bays have developed, such as Maracas Bay (Weber 2005). Sandbars, beach berms, and barrier beaches are present to both the west and east of Yarra Point. Back-bay areas that contain localized brackish tidal channels, isolated wetlands, and lagoons, including the Maracas Swamp and Madamas Lagoon (see Figs. 17.3 and 17.11), are critical for protection of the delicate wetland biota in the northern bays.

The eastern Atlantic coastline of Trinidad has the longest and straightest beaches on the island, namely Matura, Manzanilla, and Mayaro beaches. Manzanilla Beach is an impressive ~20-km-long barrier beach composed of fine sand and silt across which small ephemeral streams drain (Fig. 17.3). The beaches, sandbars, and shoreline along the east coast are maintained by sediment brought by the Guiana Current (Darsan et al. 2013). However, human-induced erosion from agriculture and recreation has caused severe coastal erosion. Manzanilla Beach may also likely be undergoing severe and rapid retreat due to sea-level rise (e.g., Bedell et al. 1997).

Trinidad's southern coast consists of sea cliffs, beaches, and small wetlands. This coastline is bordered in the east by the Trinity Hills of the Southern Range that rise to 325 m amsl, by low coastal plains in the west, and by the Columbus Channel to the south. The Columbus Channel is a shallow (maximum depth of ~55 m) and narrow waterway that separates Trinidad from mainland South America—by only ~14 km at Icacos Point (see Fig. 17.2). The west-directed Guiana Current flows through the Columbus Channel and has created narrow asymmetric beaches that contain abundant silt and nutrients transported from the Orinoco and Amazon rivers (Darsan et al. 2012). Beach erosion and hillslope failures are severe along the southern coastline due to strong the currents and weakly consolidated sedimentary bedrock (Darsan et al. 2012; Darsan and Alexis 2014).

Trinidad's west coast borders the Gulf of Paria, a large extensional pull-apart basin where submerged and buried normal faults connect the El Pilar and Central Range transform faults (Flinch et al. 1999; Babb and Mann 1999). Tectonic extension results in surface subsidence along the west coast. This creates drowned islands and rocky embayments in the north, mudflats and mangroves along the central-west coast, and low-lying beaches and cliffs in the south (Darsan et al. 2012). The Gulf of Paria is a major depocenter of Orinoco River-derived sediment, with very shallow water depths that, aside from the deep inlets and outlets, reaches to only ~30 m below mean sea level (Van Andel and Sachs 1964). Although the Gulf of Paria is a major depocenter, coastal erosion is a severe problem for

Fig. 17.10 Rocky headlands along the northeast Atlantic coast of Tobago south of Speyside, showing a sea arch and sea stacks. Photograph by J.C. Arkle

many of the shorelines along this stretch of coast (Darsan et al. 2012; Darsan and Alexis 2014).

17.3.6.2 Marine Terraces

Marine terraces are present in both Trinidad and Tobago. The Pleistocene coralline raised reef of southern Tobago's lowlands is exposed over an area of >27 km^2 and has an average thickness of 12 m (Wadge and Hudson 1986; see Fig. 17.6). The dominant fauna are benthic mollusks and hermatypic corals, which are nicely preserved in many areas (Trechmann 1934; Maxwell 1948). This fossil reef formed over the oceanic-arc and forearc bedrock of Tobago in a structurally low, down-dropped half-graben, likely during the last interglacial (Wadge and Hudson 1986; Snoke et al. 2001; Donovan and Jackson 2010). Subsequent uplift and tilting has exposed the reef platform to heights of up to ~10 m amsl along the SSW coast and up to ~30 m amsl in the NE (Donovan and Jackson 2010). The sharp unconformity between the underlying Mesozoic bedrock and the overlying coral limestone is apparent in coastal outcrops at Back Bay to the north of Plymouth (Donovan and Jackson 2010).

In Trinidad, marine terraces occur both as single platforms and as multiple terrace flights that punctuate the emergent NE coastline. Marine terraces are intermittently exposed between Yarra and Galera points and then southward to near Balandra Point at elevations from a few up to ~45 m amsl (Kugler 1959; Barr 1963). Most of the marine terraces consist of an eroded metamorphic strath surface with an overlying cover of unconsolidated quartz-rich, sand- to gravel-sized sediment that generally lacks any carbonate marine fossil debris. The terraces are all mapped as Pleistocene (Kugler 1959; Barr 1963), but recent OSL dating on quartz-rich sands and gravels indicates some may be as young as the late Holocene (Arkle et al. 2015). At least four flights of marine terraces are present and well preserved near

Fig. 17.11 Barrier beach berm, and lagoon of the Madamas River outlet along the north coast of Trinidad. Photograph by J.C. Arkle

the villages of Blanchisseuse and Yarra, but dense vegetation and tropical weathering have degraded and perhaps concealed the continuation of well-defined terrace flights along this coastline. In contrast, at some localities such as Tompire Bay, along the NE coast, a marine terrace is nearly continuously exposed for over 0.5 km at elevation ~20 m amsl (see Fig. 17.12).

17.3.6.3 Reefs

Reefs are abundant around Tobago, but are limited in Trinidad due to the high sediment load derived from the Orinoco and Amazon Rivers and, where present, tend to be dominated by sediment-tolerant species (Bouchon et al. 2008; Kenny 2008). Trinidad's only extensive coral reef is located along the NE coast and forms a flat, broad reef platform that extends ~100 m offshore from Salybia Beach. Reef growth in Salybia Bay is enhanced by its connection with the Caribbean Sea and its protected location (Kenny 2008). Salybia Beach is Trinidad's only white sand beach, composed of broken branching coral and other primary reef-dwelling carbonate fragments.

Tobago is flanked by numerous active patch and fringing reefs that stretch for >90 km around its coastline (nearly 50% of Tobago's coastline) (Laydoo 1991; Kenny 2008; see Fig. 17.5). Tobago's NW coastline, along the Caribbean Sea, is largely protected from the NE weather tracks and high-energy waves and has a higher diversity of coral species than on the Atlantic side of the island (Bouchon et al. 2008). Reefs on the Caribbean coasts support coral-gorgonian communities, whereas macro-algae and sponges dominate on the Atlantic coasts (Bouchon et al. 2008). Fringing reefs also occur along many of Tobago's satellite islands and are particularly abundant along Sisters Rocks, Little Tobago, and Saint Giles Islands.

Buccoo Reef is the largest modern reef system and covers an area of >7 km^2 extending seaward from between Booby

Fig. 17.12 Marine terrace, a metamorphic strath surface with an overlying cover of unconsolidated sand-gravel raised about 30 m amsl, located at Tompire Beach along the northeast coast of Trinidad. Photographs by J.C. Arkle

Point and Pigeon Point in SW Tobago (see Fig. 17.6; Laydoo 1991; Kenny 2008). Freshwater streams enter the reef at Buccoo Bay and in the Bon Accord Lagoon. Buccoo Reef is arcuate and consists of numerous emergent reef flats, which are structurally continuous but fragmented and covered by sediment in places (Laydoo 1991; Kenny 2008). Buccoo Reef Marine Park was established in 1973 as a designated protected marine area. The reef attracts tens of thousands of visitors per year, and this together with urban development and industrial activities in the southern lowlands has caused severe damage, erosion, and alteration to the reef (Laydoo 1991; Hassanali 2013).

17.3.7 Karstlands and Karst Landforms

Trinidad and Tobago have an impressive variety of karst landforms and landscapes, although these are fairly limited in area (Day and Chenoweth 2004). According to Day and Chenoweth (2004), limestone outcrops represent only $\sim$1.6% of Trinidad's and $\sim$8.1% of Tobago's land areas, with most karst located in Trinidad's Northern and Central ranges and in Tobago's southwestern lowlands.

Karst is present only in the coralline limestone platform of the southern lowlands in Tobago (see Figs. 17.5 and 17.13). Rugged and pitted dissolution surfaces are present where the limestone is devoid of vegetation and soil, particularly along the southern coastline. Dry valley systems, $\leq$16 m wide, $\leq$1 km long, and $\leq$2 m deep, are present on the relatively flat carbonate platform. Dolines also occur across the platform surface and are usually $\sim$5 m in diameter and <2 m deep (Day and Chenoweth 2004). Several small caves are formed in the sea cliffs along the south coast including Robinson Crusoe Cave (Eshelman and Grady 1990). Narrow openings generally impede access to these caves, but the subterranean cave system is likely fairly

Fig. 17.13 Karst and collapse features developed in the Late Pleistocene coralline limestone near the Robinson Crusoe cave along the south coast of Tobago. Photograph by J.C. Arkle

extensive with complex networks of tunnels and subcaverns (Eshelman and Grady 1990; Day and Chenoweth 2004).

Karst features are present throughout central Trinidad and are developed mainly in the Miocene limestones, particularly in the Tamana Formation, which crops out in the Central Range (Kugler 1959; Erlich et al. 1993; Day and Chenoweth 2004; see Fig. 17.3). The limestone bedrock is exposed as resistant topographic highs, distinct from their softer bounding sedimentary rocks, in a series of northeast trending hills, e.g., the Tamana, Biche, Bassin, and Brigand hills. Ephemeral streams, springs, and dolines are present in the Tamana and Brigand hills (Day and Chenoweth 2004). An impressive cave system on the north flank of Tamana Hill consists of the Tamana Main (>130 m long) and Tamana Dry (~50 m long) caves (Darlington 1993). The cave consists of several large walk-in chambers, throats, and chimneys, and narrow crawl shafts. The Tamana Main chamber is floored by a small northward-flowing stream that drains beyond the generally accessible passage into the "Far Deep" (Darlington 1993). A variety of depositional and dissolution speleothems occur in this wet and humid cave, including fluted stalactites and flowstone. The Tamana cave system also harbors a significant ecosystem, including ~11 species of bats with a population that can exceed 1.5 million (Goodwin and Greenhall 1961).

The most extensive karst and cave systems in Trinidad are developed within the metacarbonate bedrock (Cretaceous to Jurassic protolith ages; Cenozoic metamorphic ages) of the Northern Range and in the western offshore islands (Shaw 1993; Day and Chenoweth 2004; see Fig. 17.8). Development of karren is abundant on uncovered surfaces and dolines, and associated ephemeral springs are common. The largest known cave system in Trinidad, the Aripo Main Cave, is >860 m long, and is located south of El Cerro del Aripo peak at an altitude of ~800 m amsl (Shaw 1993; see Fig. 17.3). The cave walls and ceiling are lined with intricate and colorful flowstone and speleothems that are generally bulky and include coned stalagmites, large, rounded stalactites, and ribbed columns.

Small vegas, flat-floored intermountain valleys, similar to poljes in karst nomenclature (e.g., Ford and Williams 2007) are scattered throughout the Northern Range. These intermountain valleys are consistently located where metacarbonate layers have been mapped and identified in hillslopes and stream channels (see Fig. 17.3). Some of these vega regions were developed into prolific cocoa plantations during colonial times because of their rich soils and originally tall, dense forest cover and cool, damp microclimates. Segments of metacarbonate stream channels also form small gorges, some of which are lined with tufa, and many of which form several lithologically controlled knickpoints or waterfalls with associated plunge pools such as the 20-m-high Sobo Falls near Brasso Seco.

Day and Chenoweth (2004) identify an area of >6 km^2 of polygonal cockpit karst in Cameron, a block of hills at ~350 m located between Maraval and Petit valleys (see Fig. 17.3). They describe cockpit depressions that reach diameters of 100 m and are generally 15–20 m deep, bound by moderately steep hillslopes (~25°) and serrated ridges. Day and Chenoweth (2004) describe similar features on Paramin Hill, a region famous for the cultivation of culinary herbs, which is located between Maraval village and Maracas Bay. The Cameron karstscape is drained by a star-shaped centripetal drainage system formed along the hillslopes and is perhaps internally drained through concealed cave systems (Day and Chenoweth 2004).

The western offshore islands are composed of the Cretaceous Laventille limestone that contains abundant karst and caves, which are situated both below (drown caves) and above sea level, including the popular Gasparee Cave (Shaw 1993). Caves in northern Trinidad are of great ecologic importance as they harbor unique fauna such as the oilbird (*Steatornia caripensis*; Day and Mueller 2004), blind catfish (*Caecorhamdia urichi*; Shaw 1993), and numerous species of bats (Goodwin and Greenhall 1961).

17.4 Landscape

17.4.1 First Human Interactions with the Landscapes

Trinidad and Tobago have a protracted history of settlement and the longest documented human interactions with landscapes in the West Indies (e.g., Boomert 2000; Siegel et al. 2015). Trinidad has the oldest documented archaeological sites in the West Indies, Banwari Trace, and St. John, which date the earliest people (Amerindians) on the island to ~8 ka (Harris 1973; Boomert 2000; Pagán-Jiménez et al. 2015; see Fig. 17.8). (Note: archaeological ages reported have been calibrated to calendar years.) Archaeological evidence from Tobago indicates earliest occupation of Amerindians before ~5.2 ka, which currently postdates the occupation ages on other West Indies islands farther to the north such as Grenada (~5.6 ka; Siegel et al. 2015).

Trinidad is considered the "first step" on the path of initial human migration and diffusion out of mainland South America into the West Indies (Boomert 2000, 2002; Wilson 2007). This view is based on the Banwari Trace and Trinidad's proximity to the South American mainland, their intermittent connections during sea-level low stands, as well as navigational ease, and resource availability. Although the exact timing and location of a land bridge(s) between mainland South America to Trinidad and Tobago is not known, Trinidad's last mainland connection was likely during the early Holocene and Tobago's most recent connection may have been during the Pleistocene (Boomert 2000). The Gulf of Paria likely did not exist, and Trinidad was connected with the mainland during the global last glacial maximum, while Tobago was likely connected to Trinidad along the NNE coast (Boomert 2000).

Waterways were likely critical for the Amerindians (Boomert 2000, 2009). Boomert (2009) suggests that coastal routes were generally more favored than overland travel routes and interisland migration and trade routes were likely assisted along stream networks, lagoons, and wetlands. Thick tropical vegetation and the Northern Range and Cordillera de la Costa likely formed significant barriers to early human interisland migration and interaction (Boomert 2009; see Fig. 17.2). Early people in central and southern Trinidad interacted most intensely with those in bordering regions of mainland South America, whereas early people that settled along Trinidad's north coast were aligned more closely with other maritime occupants along the Venezuelan coast, Tobago, and the southern islands of the Lesser Antilles (Boomert 2000, 2002, 2009). Throughout early occupation, waterways facilitated Trinidad's development into an important center of cultural exchange and communication (Boomert 2000, 2013; Wilson 2007).

Trinidad and Tobago offered varied geologic and biotic natural resources for Amerindians. Stone artifacts recovered from Amerindian sites on the two islands include intricate ornamental artifacts carved from the islands' different lithologies, and the hard bedrock from Tobago was particularly valuable for cutting tools (Boomert 2000, 2009, 2013). Trinidad and Tobago's intermittent connections and proximity to the mainland also influenced their unique terrestrial biota, which are primarily of continental origin, similar to that of nearby South America (Kenny 2008). The species richness was likely advantageous for the initial occupants providing opportunistic foraging, collecting, fishing, and hunting, including the widespread availability of large game (Steadman and Stokes 2002; Boomert 2013; Siegel et al. 2015).

Paleoenvironmental evidence from Nariva Swamp indicates that the Amerindians used fire to manage and maintain habitats (Siegel et al. 2015). Pagán-Jiménez et al. (2015) identified numerous cultivar and wild taxa from starch grains on stone artifacts collected at the St. John Archaeology Site (see Fig. 17.3). These authors suggest that Trinidad's early occupants (~7.7 ka) perhaps transported domesticated and wild plant species from mainland South America. Collectively, these findings offer a significant insight into human interactions with the landscape, as highlighted by Siegal et al.'s (2015) submission that the earliest-known occupants of Trinidad were modifying, creating, and managing the landscape roughly 8 ka.

17.4.2 Landscapes Transformed: Colonization to the Twenty-first Century

In 1498, on his third voyage, Christopher Columbus sighted the Trinity Hills in the Southern Range, landed on Trinidad, and claimed the island as a Spanish colony. This "ownership" lasted until 1797 when Trinidad was claimed as a British colony. Tobago, a western spelling of the Amerindian word for tobacco, was fought over by the Spanish, British, French, and Dutch because of its strategic position and fertile land, until 1889 when both Trinidad and Tobago became a British territory. Upon the arrival of Europeans, the Amerindian populations of Trinidad and Tobago were very quickly reduced. The natural vegetation and landscapes of Trinidad and Tobago were transformed by agriculture and plantation-style farming throughout the sixteenth–nineteenth centuries. Trinidad and Tobago developed slave and indentured servant populations during this period. Large areas of Trinidad and Tobago's landscapes were cultivated for tobacco, cacao, and sugarcane (Newson 1976).

Development and proliferation of the country's hydrocarbon industry that quickly followed the drilling of Trinidad's first oil well in 1857 brought significant and irreversible changes to Trinidad and Tobago's landscapes (Higgins 1996). Oil extracted from Trinidad constituted ~40% of the British Empire's total oil production by 1930 (Dillman 2015). In 1962, Trinidad and Tobago gained independence from the British Empire and then became a republic in 1976. The two-island nation is now the leading producer of oil and gas in the Caribbean, which comprised ~45% of their GDP in 2012 (Ministry of Energy and Energy Industries 2015). Although, the agricultural economy has declined during the twentieth–twenty-first centuries, cultivation of Trinidad and Tobago's lands including dredging and modification of wetlands, river channels, and other ecologically sensitive areas has caused significant landscape changes. Extensive limestone quarrying has significantly modified some of the karst terrains such as in the Laventille and Montserrate hills. The diverse landscapes of Trinidad and Tobago have been a great asset and have helped directed the trajectory of people there for roughly 8000 years.

17.5 Heritage and Tourism

17.5.1 Heritage Tourism

Trinidad and Tobago have a diverse and rich cultural blend of people, locally called a "callaloo," that includes Amerindian, Spanish, French, English, African, Indian, Chinese, Syrian, and Lebanese influences. Heritage tourism is an emerging focus for both islands. Tourism contributes only ~4% annually to the economic output (TDC 2015) and employs only ~10.4% of the labor force. Of all Caribbean overnight visitor arrivals in 2011, Trinidad and Tobago had ~400,000 visitors representing only ~2% of Caribbean tourism (TDC 2015). The Government of Trinidad and Tobago recognize the potential and positive economic impacts that tourism could have and has an active policy of encouraging the growth of the tourism trade (Wall and Ali 1977; TDC 2015). With the hydrocarbon industry's dominance in Trinidad, tourism on the island is promoted for its heritage activities, including major annual events such as Carnival, whereas Tobago is better positioned to become a typical "sun, sea, and sand" island of leisure like many of the other Caribbean islands (TDC 2015).

Trinidad and Tobago's heritage sites and historic landmarks include the karat-roofed leepay homes of indentured servants, sugar and cocoa sheds, the barrack houses of slaves, urban chattel houses, the great houses of the Port of Spain Savannah, various estates (plantations), and historic churches, mosques, and temples (Jordan 2013). These historic landmarks, however, are overshadowed by Trinidad's annual Carnival that is celebrated before Ash Wednesday, typically in February or March. The Carnival is responsible for the largest influx of tourists, over ~40,000 annually, which come from around the world (TDC 2015). The Carnival dates to the eighteenth century and showcases the island's heritage through traditional music, dance, and food, and two major street parties—J'Ouvert ("I arise"), a "dirty" mud and cocoa butter nighttime masquerade, which is followed by the daytime "pretty" masquerade. While this event takes over nearly the whole of Port of Spain, it (particularly the "pretty" masquerade) is centered on the Queen's Park Savannah, which is the largest (>1 km^2) public space in Trinidad, and the oldest recreation ground (165 years old) in the West Indies (Jordan 2013). The large number of visitors during this roughly weeklong celebration has lead to tremendous pollution problems in the city and surrounding areas, and it is taxing on the country's natural resources. The need for infrastructure to support such an event, as well as the rapidly growing urban population, has lead to significant changes of the landscape, particularly in the form of hasty development and expansion, particularly in and around Port of Spain (Wall and Ali 1977).

17.5.2 Ecotourism

The natural landscapes of Trinidad and Tobago have the potential for becoming a major destination for ecotourism, particularly because it is one of the most unique and species-rich nations in the region (Kenny 2008; TDC 2015). Notably, the Trinidad and Tobago National Commission was successful in having three sites added to UNESCO's World Heritage Tentative Listing in 2011. These included the Banwari Trace Archaeological Site (cultural), La Brea Pitch Lake (natural), and the Tobago Main Ridge Forest Reserve (mixed) (Jordan 2013; UNESCO 2015).

Trinidad and Tobago's rainforests, habitat to unique biota of continental origin, are popular ecotourism destinations (UNESCO 2015). The Main Ridge Forest Reserve on Tobago encompasses nearly 40 km^2 of mountainous rainforest and is the oldest (since 1776) piece of protected land and forest reserve in the Western Hemisphere (UNESCO 2015). Trinidad's Northern Range includes significant biopreservation sites such as the Asa Wright Nature Reserve (www.asawright.org) that contains over 2200 flowering plant species, 97 native mammals, 400 birds, 55 reptiles, 25 amphibians, and 617 butterflies. Impacts of tourism on Trinidad and Tobago' rainforests have not been quantified. However, undisturbed rainforest in Trinidad's Northern Range has been reduced to isolated patches due to piecemeal degradation related to urbanization, agriculture, mining, and timber production (Day and Chenoweth 2004).

Snorkeling and scuba diving are popular tourist activities, concentrated mainly in Tobago along the southwest coast and around its northeastern satellite islands. The Buccoo Reef Marine Park was designated as a marine protected area in 1973; it has also been a Ramsar Site (see http://www.ramsar.org/) since 2005, and the Buccoo Reef Trust and the University of the West Indies started monitoring at Buccoo Reef Marine Park in 2007 (Laydoo 1991). However, local communities are very dependent on tourism, and thus, land on the nearby limestone platform has been developed for tourist accommodations and corals have been harvested for tourist souvenirs (Wall and Ali 1977; Hassanali 2013). Other threats to Buccoo Reef include sewage pollution, climate change and associated mass-bleaching events, and various coral diseases (Bouchon et al. 2008; Laydoo 1991; Lapointe et al. 2010).

Sandy beaches along the north and east coasts of Trinidad are home to the second largest nesting assemblage of the leatherback sea turtle (*Dermochelys coriacea*) in the Atlantic (e.g., Mycoo and Gobin 2013). Roughly 3000 turtles nest annually on the beach at Grande Riviere along the northeast coast (Mycoo and Gobin 2013). These delicate nesting sites are impacted by both natural and human influences including coastal development, illegal harvesting, climate change, coastal erosion, and thick accumulations of seaweed (*Sargassum*) on the beaches (Mycoo and Gobin 2013; Weber et al. 2015c). The village of Grande Riviere serves as an excellent model for how regions can transition from exploitation to protected ecotourism destinations.

Many other areas of ecological importance and popular ecotourism destinations are present throughout the interior of Trinidad, including the Aripo savannah, and the Caroni and Nariva swamps (see Fig. 17.3). The Aripo savannah is a unique edaphic landscape in the Northern Basin, designated an Environmentally Sensitive Area in 2007, that covers roughly 18 km^2. The area contains several localized dry savannahs with the dominant grass (*Paspalum pulchellum*) developed on clay-rich sandy soil (Richardson 1963). The Caroni and Nariva swamps were designated as protected areas in 1936 and 1968, respectively, and are both major tourist attractions. Traditional activities such as castnet fishing, small-scale rice farming, and the harvest of many of the marine and brackish species, such as oysters, are permitted in the swamps. These activities, as well as ecotourism, have in large part, driven controversial land cover shits in the Caroni and Nariva swamps (e.g., Gibbes et al. 2009). Perceptions of Trinidad and Tobago's landscapes, and thus management of them, remain perched in critical balance between employment, tourism, and conservation, among other environmental and social-political factors (Dillman 2015).

17.6 Hazards

Trinidad and Tobago have experienced several destructive natural disasters, which have been recorded since the seventeenth century. The largest historic earthquake to shake Trinidad was in 1766 and is estimated to have had a magnitude of ~ 8. Earthquake damage was so severe that Trinidad's people petitioned the King of Spain for resettlement to another Caribbean island. The largest recorded earthquake (M_w 6.7) occurred in 1997, ~ 5 km offshore south of Tobago along an unnamed fault and caused over US$25 million in damages, injured several people, and left many people homeless in Tobago (ODPM 2014; Weber et al. 2015a).

Even though Trinidad and Tobago are positioned outside of the main Atlantic hurricane belt, the islands have been damaged by several hurricanes. In 1963, Tobago was devastated by one of the deadliest Atlantic hurricanes (Category

3) in recorded history, Hurricane Flora, with winds >160 km/h. The hurricane destroyed or damaged 6250 of Tobago's 7500 houses and at least 18 lives were lost. Property and crop damage on the island amounted to US $30 million (ODPM 2014). The islands regularly experience large tropical storms often associated with distant hurricanes, particularly during the wet season, and annually cause tremendous damage to infrastructure and occasional loss of life (ODPM 2014).

Fires and droughts are among the most common natural hazards in Trinidad and Tobago (ODPM 2014). They are typically associated with the dry season, and year-round high winds. Floods and mass movements are also common. Mass movements range from landslides on steep hillslopes like those in the Northern Range to slow, but destructive creep, especially in the expanding clay soils in central and southern Trinidad. Liquefaction of unconsolidated sediment and long-term subsidence in western Trinidad collectively result in erosion and have caused dramatic changes to the landscape.

Sea-level rise, frequent seismicity, and large magnitude earthquakes pose some of the greatest threats to the islands' (Nurse et al. 1998; ODPM 2014). Low-laying coastal areas in Trinidad and Tobago, like those in other small-island nations of the Caribbean, are extremely vulnerable to sea-level rise as a consequence of human-induced global climate change (e.g., Nurse et al. 1998). This is particularly confounded in Trinidad and Tobago because the islands' major population centers and infrastructure are located along its coastlines. Trinidad's capital, Port of Spain, is built in part on reclaimed land and located along the western coast, which is tectonically subsiding. Sea-level rise and climate change are also linked to potentially devastating hazards such as the loss of agricultural land and delicate ecosystems, coastal erosion, increased pollution, coral reef destruction, changes in aquifer volume and quality, and many other complex direct and indirect environmental responses to global climate change (e.g., Nurse et al. 1998). Efforts to minimize, respond to, and recover from natural hazards are a major concern of local government, community organizations, as well as other West Indian nations and non-governmental organizations abroad (ODPM 2014).

17.7 Conclusions

Trinidad and Tobago's distinct geologic histories and their shallow emergence along the southeast corner of the Caribbean plate throughout the Quaternary provide the context for the two islands' varied landscapes, landforms, and geomorphic evolution. Dynamic geomorphic processes have sculpted a spectacular variety of landscapes and landforms in Trinidad and Tobago. Tectonism, climatic shifts, and associated sea-level fluctuations have shaped the islands' wetlands, modern and ancient reefs, marine terraces, alluvial fan development, and shallow continental shelf. Significant changes in local and regional base level have caused adjustments in fluvial systems, and the redistribution of sedimentation and erosion throughout the islands' interior landscapes (e.g., Ramcharan 2004; Weber 2005; Soto et al. 2007; Arkle et al. 2015). The severe tropical climate causes ubiquitous landsliding and flooding and contributes to intense weathering and to the development of a variety of karst and cave systems (e.g., Day and Chenoweth 2004; ODPM 2014). Strong, sediment-rich ocean currents dominate coastal sedimentation and erosion and influence coral reef development (Darsan et al. 2012).

Trinidad and Tobago's geologic and geomorphic histories have also influenced their biota, the migration and settlement of its people, colonization, and economy. Intermittently connected to mainland South America throughout the Quaternary, the two islands were populated with rich and diverse continental flora and fauna (Kenny 2008). Trinidad played a critical role as a "first step" for initial human migration out of mainland South America and then as a central hub for trade as early Amerindians dispersed into the West Indies (Boomert 2000, 2002; Wilson 2007). Geologic structures, both ancient and active, control the distribution and nature of active hydrocarbon systems, and the most transient landforms on Trinidad, mud volcanoes and asphalt seeps. As the leading hydrocarbon producer in the Caribbean, tourism is an important and emerging economic sector for Trinidad and Tobago, with its diverse culture heritage, unique biodiversity, and varied landforms.

Natural and human-induced environmental changes continue to cause dramatic modifications of the islands' landscapes. Potential natural hazards include frequent and large magnitude earthquakes, climate change and associated sea-level rise, tropical storms and associated flooding, mass wasting, wind damage, and dry-season fires. Perceptions of the landscape and its management require a delicate balance between employment and tourism, and ecological protection (Dillman 2015).

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18 Aruba, Bonaire, and Curaçao

Phillip P. Schmutz, Amy E. Potter and E. Arnold Modlin Jr

Abstract

Aruba, Bonaire, and Curaçao consist of five islands that make up the Leeward Islands of the Dutch Antilles off of the northern coast of South America, often referred to as the ABCs. Because of location, the islands share similar characteristics of climate, geology, geomorphology, and history, though each bears a variation of these characteristics. These largely limestone islands are part of the southern Caribbean dry zone. Historically, they were important centers of livestock grazing, aloe vera production, and salt export. All three islands in the twentieth century have been impacted by the growth of oil export in Venezuela. Curaçao, once the tourism leaders among the Dutch Caribbean Islands, is trying to catch up with Aruba in stopover tourists, while Bonaire has smaller but strong "active" tourism for its size. While their climate in the past was considered less than desirable for large-area agricultural pursuits, presently their dry, warm weather largely outside the hurricane belt is an attractive asset to the millions of tourists who visit them annually.

Keywords

Tourism • Dutch • Slavery • Salt • Oil

18.1 Introduction

Aruba, Bonaire, and Curaçao consist of five islands off of the northern coast of South America and comprise the Leeward Islands of the Dutch Antilles.[1] Although nicknamed the ABCs, when actually approaching the islands from west to east, the physical order of the islands would be Aruba, Curaçao, and then Bonaire. The islands range from 29 km off of the Venezuelan coast of South America in the case of Aruba, to 92 km off of the South American coast for Bonaire. All three territories are connected to the Netherlands, though in slightly different ways. Aruba and Curaçao are constituent countries of the Kingdom of the Netherlands, while Bonaire is a special municipality within the state of the Netherlands.

Aruba (Fig. 18.1) has a land area of approximately 179 km^2. Two islands comprise Curaçao (Fig. 18.2): the main island of Curaçao (444 km^2) and the uninhabited "little" or Klein Curaçao southeast of the main island, which is 1.7 km^2 in size. Bonaire (Fig. 18.3) comprises the larger, inhabited island of Bonaire (287 km^2) and the smaller uninhabited island of Klein Bonaire (6 km^2) off its west coast. Elevations for all three islands range from sea level to a height of 165 m (Mt. Yamanola) on Aruba, 240 m (Brandaris Hill) on Bonaire, and 372 m (Mt. Christoffel) on

[1]The application of Leeward here is not to be confused with its use in the greater Lesser Antilles Caribbean region.

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Fig. 18.1 General physiographic map of Aruba. Notice the long sandbars along the island's southern coast and the Arikok National Park covering much of the eastern end. Cartography by K.M. Groom

Fig. 18.2 General physiographic map of Curaçao. The slender island has many inland bays and waterways. Cartography by K.M. Groom

Fig. 18.3 General physiographic map of Bonaire. The southern end of the island is dominated by large salt flats and inland bays. There are saline lakes in the northwest but not nearly as large. The northern pools are also included in the Washington Slagbaai National Park. Cartography by K.M. Groom

Fig. 18.4 **a** Christoffel Mountain, the highest point on Curaçao at 372 m, with a small salt pan visible in the foreground. Photograph by Amy Potter, May 2012

Curaçao (Fig. 18.4). Both Klein Bonaire and Klein Curaçao are low islands just a few meters above high tide. Geologically, the islands are similarly composed of the Late Cretaceous and Paleogene volcanic and sedimentary rocks overlain by multiple sequences of Quaternary limestone terraces.

Located in the southern Caribbean dry zone, characterized by a tropical steppe, semiarid hot climate, the ABCs' average temperatures range seasonally between 26 and 29 °C (Department Meteorologio Aruba 2010; Meteorological Department of Curaçao 2016). Annual rainfall is characterized by extreme interyear variability, with a distinct dry season from January to September and an October to December wet season. Total annual rainfall varies between the islands: Aruba averages 470 mm, Curaçao averages 550 mm, and Bonaire averages 490 mm. The northern and eastern coasts for all three islands are exposed to consistent easterly trade winds and experience high wave energy, whereas the southern and western coasts are characterized by low-energy leeward conditions.

Curaçao has the largest population, with 158,986 people as of January 2016 (Central Bureau of Statistics Curaçao 2016). Aruba's population was 101,484 according to the 2010 census (Central Bureau of Statistics 2010), while Bonaire's population stood at 18,413 on January 1, 2014 (Centraal Bureau voor de Statistiek 2015). This puts the population density at 358 people per km^2 in Curaçao, 551 people per km^2 in Aruba, and 64 people per km^2 in Bonaire. Each of the islands has shown growth since their last censuses in either 2010 (Aruba) or 2011 (Curaçao and Bonaire).

18.2 Geologic Setting

Aruba, Bonaire, and Curaçao lie along a 200 km segment of the east–west-trending Leeward Antilles ridge within the Caribbean-South America plate boundary zone (Hippolyte and Mann 2011; Zapata et al. 2014). The Leeward Antilles ridge formed as part of the Cretaceous Great Arc of the Caribbean, as the arc was thrust against the northern margin of the South American continent during the westward advance of the Caribbean plate from the Pacific Ocean (Beardsley and Ave-Lallemant 2007; Gorney et al. 2007; Van der Lelij et al. 2010; Neill et al. 2011). This collision and the subsequent uplift of the continental margin, more than 5 km of vertical displacement, in the Late Cretaceous and Paleogene caused the folding, faulting, and metamorphism of the allochthonous igneous rocks that constitute the geologic core of the Leeward Antilles ridge and ABCs (Beets 1972; Beets et al. 1984; White et al. 1999; Beardsley and Ave-Lallemant 2007; Gorney et al. 2007). The ABCs were emergent throughout the Paleogene, upon which significant denudation of the volcanics occurred producing, in places, thick layers of clastic sedimentary rocks (Westermann 1932; De Buisonje 1974).

The geologic core of all three islands is similarly composed of the Late Cretaceous and Paleogene volcanic and sedimentary rocks; however, the lithology and sequence phases differ slightly between the islands. Aruba contains a basement sequence of stratified basalt flows, volcano-clastic deposits, and epiclastic strata, which are subsequently intruded by a large tonalitic batholith (Fig. 18.5; Westermann 1932; De Buisonje 1974; White et al. 1999; Van der Lelij et al. 2010). The greater part of the tonalitic batholith has been removed through denudation; however, segments of the batholith formation are still evident by the large boulder structures located in the central plain of Aruba (Fig. 18.6). On Curaçao, the geology is divided into three stratigraphic sequences: the Curaçao Lava Formation (tholeiitic basalts), the Knip Group (silica-rich rocks and clastic sediments), and the Midden-Curaçao Formation (conglomerate, sandstone, and shale) (Fig. 18.7; Beets 1972; De Buisonje 1974; Fouke et al. 1996; Kerr et al. 1996; White et al. 1999). On Bonaire, the basement sequence (Washikemba Formation) is composed of basaltic flows and pyroclastic deposits interbedded with pelagic chert and limestones (Fig. 18.8). This formation is overlain by three sequences of sedimentary strata: the Maastrichtian Rincon Formation (limestone clasts interbedded in turbidite conglomerates), the Soebi Blanco Formation (conglomerates, sandstones, and shales of fluviatile origin), and limestones of the Seroe Montagne Formation (Pijpers 1933; Beets 1972; Beets et al. 1977).

Sea-level fluctuations combined with a slow tectonic rise of the Leeward Antilles ridge throughout the Neogene and Quaternary produced numerous limestone terraces that unconformably overlay the Cretaceous and Paleogene volcanic and sedimentary rocks (Alexander 1961; De Buisonje 1974). On Curaçao and Bonaire, the limestone formations occur along the coast rim and within portions of the interior of the islands; however, on Aruba, the limestone terraces occur extensively along the leeward side of the island and, in small, isolated patches along the windward coastal rim (De Buisonjé 1974). The oldest limestone terrace is the Miocene formed Seroe Domi Formation, which occurs almost exclusively along the leeward coast of all three islands (De Buisonje 1974; Fouke et al. 1996). Fouke et al. (1996) established that the Seroe Domi Formation experienced three major episodes of limestone diagenesis and dolomitization taking place following successive Mio-Plio-Pleistocene depositional and subaerial exposures. The Seroe Domi Formation is in turn overlying Quaternary limestone terraces composed of lagoon and fringing reef coral–algal grainstones (Alexander 1961; Bandoian and Murray 1974; De Buisonje 1974; Fouke et al. 1996). The terraces are preserved as a set of four marine accumulation sequences, from oldest to youngest: Highest (150–90 m), Higher (80–50 m), Middle (15–45 m), and Lower (<10 m). The Highest terrace is found only on a narrow portion of Curaçao, while the Higher terrace is located along the windward sides of all three islands. The Middle and Lower terraces developed during a transgressive period of sea-level fall and are present along both the windward and leeward sides of all three islands. Both the Middle and Lower terraces show the most complete development and can be divided into three biozones [barrier reef and two lagoonal zones] (De Buisonje 1974; Fouke et al. 1996). Due to the level of reef development, the Middle and Lower terraces are separated by steep cliffs, which have extensive karst (e.g., cave and fissure) structures (Fig. 18.9). Eolianites deposits, up to 15 m thick in places, can be found atop the Higher, Middle and Lower terraces on the windward sides of all three islands (De Buisonjé 1974).

18.3 Landforms

Even though the ABCs were primarily formed by plate collisions that resulted in igneous rocks being formed and subsequently exposed, much of their surficial landforms remain sedimentary. This occurred during the Upper Eocene when the volcanics were overlain by sedimentary events such as reef terraces. Today, remnants of the volcanics can be seen on the surface in such formations as the Ayo and Casibari Rock Formations (Fig. 18.6), and the Hooiberg (haystack) on Aruba (Fig. 18.10), and the Brandaris on Bonaire (the island's highest point, at 241 m; Fig. 18.11). Karstic features are visible on the ABC's coasts as well, such as the limestone features at Shete Boka (Seven Inlets) National Park on Curacao's northern coast (Fig. 18.12). Though relatively flat in relief compared to most of their Lesser Antillean island cousins, the ABCs still boast significant geomorphologic areas, the most prominent types of which are featured in this section.

18.3.1 Coastal

The ABCs include a variety of sandy beach environments, varying from small sheltered coves to extensive stretches of

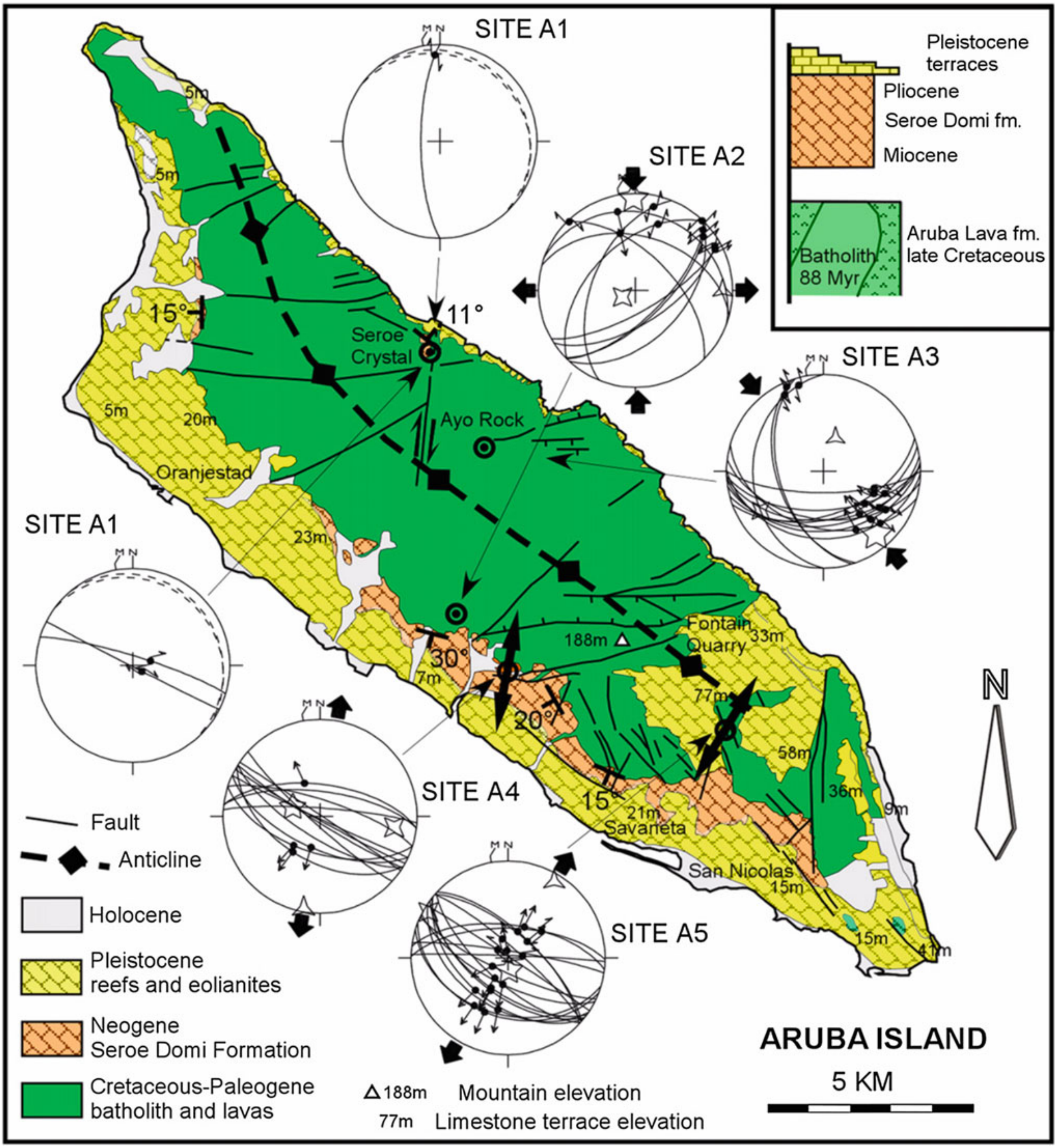

Fig. 18.5 Geologic map of Aruba displaying relative rock ages, faulting and folding, and a basic stratigraphic column. Rock ages generally decrease from east to west, with some scattered Holocene geology. Map from Hippolyte and Mann (2011, p. 263), available online for download at https://www.researchgate.net/publication/222888734_Neogene-Quaternary_tectonic_evolution_of_the_Leeward_Antilles_islands_Aruba_Bonaire_Curacao_from_fault_kinematic_analysis. Retrieved January 2017

white sand. Beaches along the windward coast tend to be rocky and experience high wave energy, whereas the western leeward side of the islands have more stretches of sandy shorelines. The most prevalent beach type on Curaçao and Bonaire is the sheltered pocket coves bordered by rocky headlands, whereas the extensive stretches of white sandy beaches are located in the central leeward coast of Aruba (e.g., Eagle, Palm, and Manchebo beaches) and throughout

Fig. 18.6 Ayo Rock Formation found in central Aruba. It is one of a number of boulder fields scattered throughout the island formed from the erosion of the tonalitic batholith. Photograph by Phillip Schmutz, May 2012

the uninhabited islands of Klein Curaçao and Klein Bonaire (Halcrow 2010).[2]

In addition to the sandy beach environments across the ABCs, the coastal landscape displays extensive coarse sediments and boulders. Recent studies have attributed this coarse debris along the coastal zone to the occurrence of three paleotsunamis that struck the islands around 450–500 BCE, 1500 BCE, and 3500 BCE (Scheffers 2002, 2004; Scheffers et al. 2005). Prior to these studies, tsunami impacts were unknown for the ABCs, and the debris formations were exclusively attributed to hurricane generated waves (e.g., De Buisonjé 1974). The extensive nature of tsunami deposits across the islands are illustrative of powerful systems that deposited several million tons of debris and boulders as far inland as 400 m and up to 12 m above mean sea level. The debris deposits are predominantly located along the windward coastlines of the islands with the most extensive geomorphic evidence on Bonaire and a significant reduction of deposits on Curaçao and Aruba due to a shadowing effect. Scheffer (2004) found three distinct geomorphic assemblages of tsunami debris: rubble ridges, rampart formations, and boulder fields with each formation exhibiting a distinct morphology and geographic distribution that the author related to coastal landform configuration. Although three different types of coarse debris deposits are documented, this does not mean that each of these deposits represents a single tsunami event. Radiocarbon dating from samples around the islands found that the different debris assemblages were deposited contemporaneously (Scheffer 2004; Scheffer et al. 2005).

18.3.2 Estuarine

A number of inland pocket bays dot the coastal landscape of Bonaire and Curaçao, which result from the drowning of paleo-"rooien" (small rivers) valleys eroded into both the interior igneous rocks and limestone terrace rim. At least two such bays formerly existed on Aruba (e.g., Druif and Spaansch Lagoen), but the interior portions have been filled with alluvium (Alexander 1961). As a consequence of the

[2] Detailed studies on the sandy beach environment of the ABCs are severely lacking, yet the many travel websites (e.g., aruba.com, Curaçao.com, and tourismbonaire.com) provide photographs and descriptions of the most popular beaches across the islands.

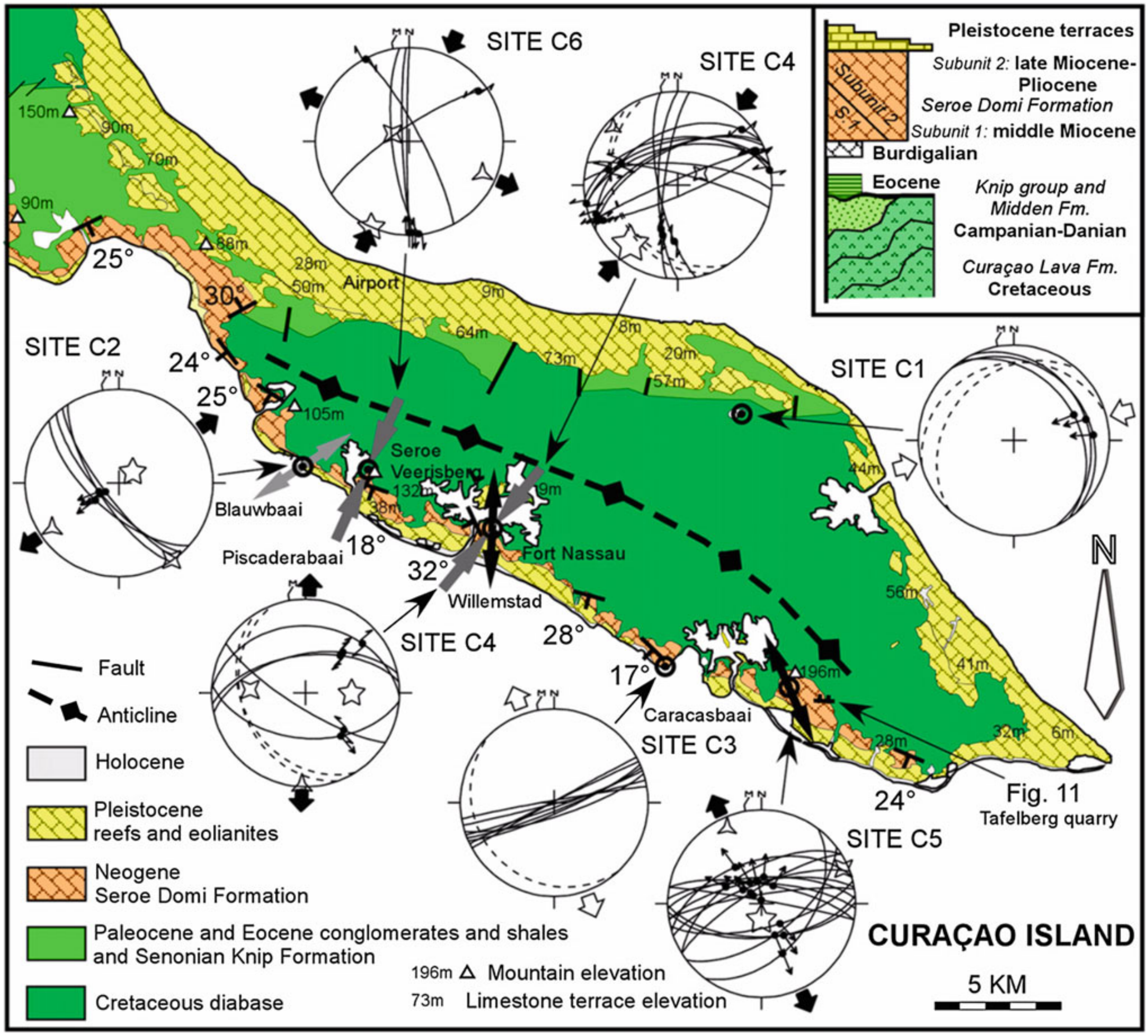

Fig. 18.7 Geologic map of Curaçao's middle and southern regions showing relative rock ages, faulting and folding, and a basic stratigraphic column. Note the juxtaposition of Cretaceous rock (*dark green*) with Pleistocene sedimentary. Compare with geology of Aruba (Fig. 18.5) Map from Hippolyte and Mann (2011, 265), available online for download at https://www.researchgate.net/publication/222888734_Neogene-Quaternary_tectonic_evolution_of_the_Leeward_Antilles_islands_Aruba_Bonaire_Curacao_from_fault_kinematic_analysis. Retrieved January 2017

poor water retention of the topsoil on the islands, rainfall quickly runs off into these bays creating permanent or temporarily flooded "saliñas" (hypersaline lakes) (Roos 1971). While the saliñas are hypersaline, they are far from abiotic, supporting significant flora and fauna populations, and serving as a key stopover habitat for many migratory birds. Because of their important ecosystem function, three of Bonaire's saliñas (Saliña Gotomeer, Saliña Slagbaai, and Pekelmeer) are internationally protected as RAMSAR sites by the Convention on Wetlands of International Importance.

In addition to the saliñas, a few of the inland bays function as intertidal estuary systems which contain the majority of the seagrass and mangrove communities on the islands. Lac Bay, located on the southeastern windward shore of Bonaire, supports the island's only significant mangrove and seagrass communities (Nagelkerkena et al. 2000). Lac Bay is the largest inland bay in the ABCs with an area of 7.5 km^2 and maximum water depth of 4.5 m. The ecological presence of mangroves within the bay is relatively rare as there is no significant riverine input into the system,

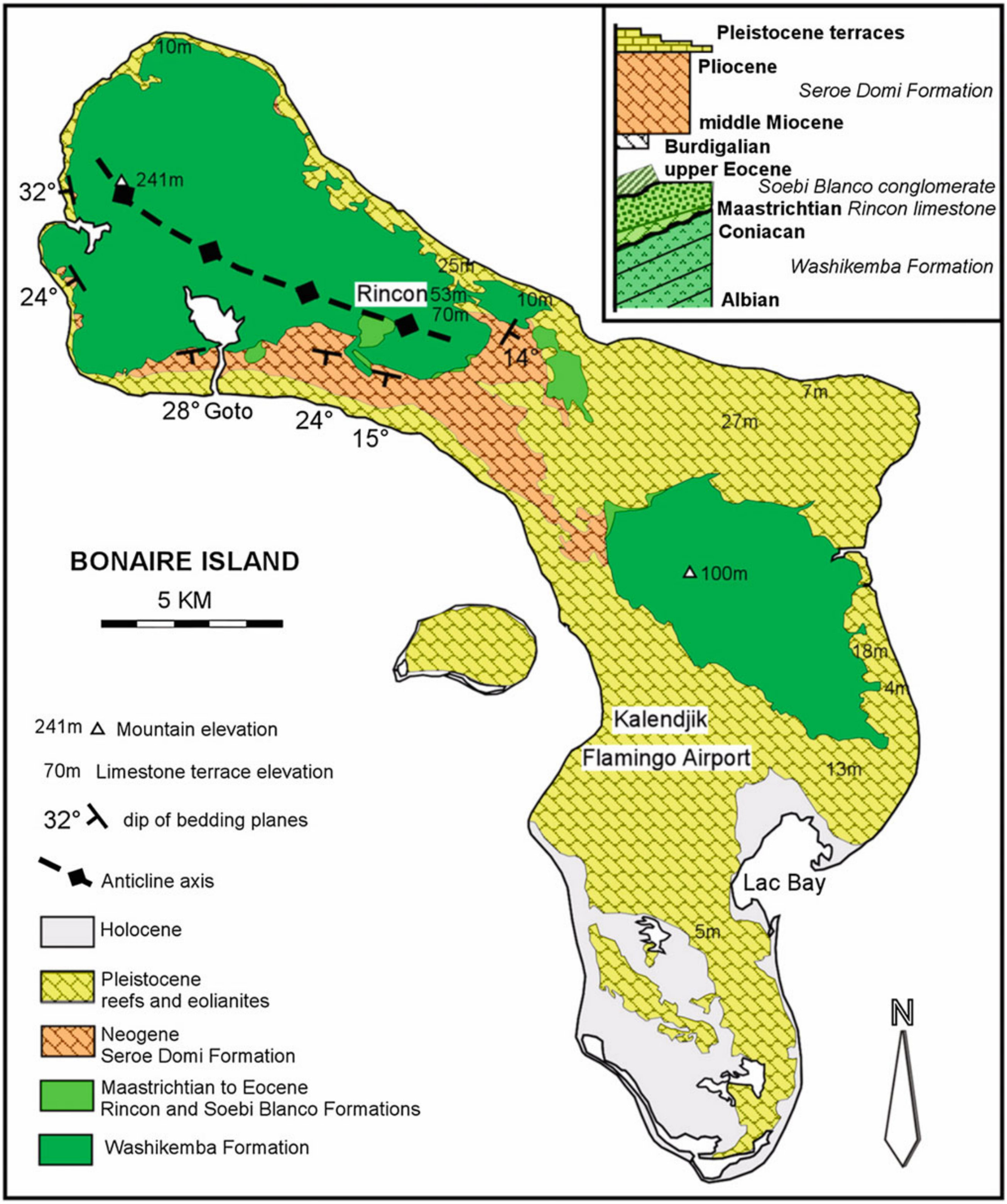

Fig. 18.8 Geologic Map of Bonaire with relative rock ages, faulting and folding, and a basic stratigraphic column. Notice the Cretaceous formations (*dark green color*) surrounded by Pleistocene deposits (*yellow*), and only one major folding event. Compare with geology of Aruba (Fig. 18.5). Map from Hippolyte and Mann (2011, 266), available online for download at https://www.researchgate.net/publication/222888734_Neogene-Quaternary_tectonic_evolution_of_the_Leeward_Antilles_islands_Aruba_Bonaire_Curacao_from_fault_kinematic_analysis. Retrieved January 2017

Fig. 18.9 Karst landform structures of the Middle and Lower limestone terraces on the windward coast of Curaçao. The harsh dry climate is reflected in the resilient vegetation, such as the large cactus in the foreground. Photograph by Phillip Schmutz, May 2012

making them particularly vulnerable to dieback during episodes of hypersaline conditions (van Moorsel and Meijer 1993 as cited in De Meyer 1998). The bay is internationally protected as a RAMSAR site by the Convention on Wetlands of International Importance. On Curaçao, the largest concentrations of seagrasses and mangroves can be found in Spaanse Water, located on the southeastern leeward coast of the island. Spaanse Water is the second largest inland bay on the island with an area of 3.2 km^2 and a mean depth of 5 m. It has been identified as a priority area for conservation and is part of the Curaçao Underwater Park (Debrot and de Freitas 1991). Debrot and de Freitas (1991) found that increased development in the bay has led to a dramatic decrease in species habitat to less than half of the spatial coverage of a century ago.

18.3.3 Dune

Dune fields are sparse on the islands, yet do exist along the windward coasts due to the presence of stable trade wind conditions. The largest dune fields occur on Aruba, with isolated small patches of sand dunes located at a few beaches on Bonaire and Curaçao. Research into the formation and evolution of the dunes are rare, with the work of Westermann (1932) providing the most extensive background. Westermann established that the dunes are of Holocene age consisting of limestone and quartzite sands, depending upon location. On Aruba, the largest dune field is located in the isolated northern tip of the island on the Hudishibana Plateau (Fig. 18.13). The dune field known locally as the California dunes is approximately one kilometer in length, with an area of 0.32 km^2. The dune field exhibits a quasi-parabolic shape and contains numerous vegetated nebkhas. Smaller dune fields occur within Arikok National Park on the southeastern portion of the island at Boca Prins and Dos Playa.

18.3.4 Karst

The limestone terraces along the coastal fringe of all three islands are highly permeable, and subterraneous solution of the limestone has produced numerous cave structures. The caves primarily exhibit a longitudinal shape, running perpendicular to the Quaternary coastlines, and can be found in several places along the cliff-face of the Middle, Lower, and

Fig. 18.10 View from Hooiberg (*Haystack*), Aruba. A volcanic outcrop… Photograph by D. Stanley, available online via https://commons.wikimedia.org/wiki/File:Summit_of_Hooiberg,_Aruba_(4901403229).jpg. Retrieved November 2016

Sereo Domi Formation terraces (Zonneveld et al. 1977). German geologist Karl Martin, professor of geology and director of the museum in Leiden, was the first to study the development of caves on the ABC islands in the late 1880s (Hummelinck 1979). Martin distinguishes two sets of cave formations: (1) caves that developed as a result of wave action, and (2) caves that owe their existence to openings in the cliff of the reef terrace and became enlarged via increased groundwater flow during at least two periods of more humid climatic conditions. Research by Zonneveld et al. (1977) and Hummelinck (1979) support evidence of Martin for the second set of cave formations pointing to the existence of extensive flowstone and horizontally layered dripstone structures, indicative of a more humid climate, overlain by stalactites and stalagmites, and indicative of less humid, drier climates. At present, most caves on the islands are "dead" caves as speleothem activity has completely stopped and are badly weathered (Hummelinck 1979). In addition to the cave structures, small aquifers occur below the limestone terraces across the islands, held within the layers of sedimentary sands and clays of igneous origin (De Buisonjé 1974). The aquifers consist of brackish groundwater reserves as the sources of water input primarily include sea spray and hypersaline rainwater, and the overall lack of fresh surface water (van Sambeek et al. 2000).

18.3.5 Coral Reef

The coral reefs across the ABCs have been described extensively by Roos (1964, 1971), Bak (1975, 1977), and van Duyl (1985), who also produced detailed maps of the shallow coral reef communities along the leeward shore of Bonaire. Extreme differences in wave conditions cause the reef communities on the windward and leeward coasts of the islands to fundamentally differ in terms of reef structure and species abundance (Bak 1977; Vermeij 2012). Along the windward shore of all three islands, coral development is sparse with an abundance of crustose coralline algae found in water depths up to 12 m and the presence of dense stands

Fig. 18.11 Looking over Bonaire's Gotomeer, a saltwater lagoon on the island's northern end that hosts the Caribbean's only pink flamingo nesting sites, to Brandaris, the island's highest point. Like the lower elevation peaks surrounding it, Brandaris is a volcanic outcrop in the Washikemba Formation that straddles the northernmost section of the island's anticlinal axis. Photograph by Bgabel, available online via https://commons.wikimedia.org/wiki/File:BONAIRE-goto-meer-1.jpg. Retrieved November 2016

of *Sargassum platycarpum* (brown macroalgae) extending to depths of 40 m. The reef structure along the western leeward coasts of the ABCs, however, differs slightly between the three islands. Bonaire and Curaçao support near continuous fringing coral reefs, with a total surface of 26 km^2 (10 mi^2) on Bonaire and 20 km^2 (7.75 mi^2) on Curaçao. The islands share a general pattern in reef formation, which consists of a submarine terrace extending seaward up to 250 m gradually sloping to a drop-off at 7–12 m depth. Beyond this, the reef slopes steeply at a 20–50° angle to depths of 50–55 m where it flattens out into a shelf. A second drop-off occurs beyond this to depths of 70–80 m, ending in a sandy plain at 80–90 m (van Duyl 1985). Bak (1977) found that coral cover and diversity increase with depth across the submarine terrace with the greatest level of cover and diversity occurring near the drop-off. Beyond the drop-off, coral cover and diversity decreases rapidly as light decreases and the influence of sedimentation is high. Research on the coral reefs of Aruba is significantly less prevalent than on Bonaire and Curaçao with the work of Roos (1971) and Bak (1975) providing the most extensive, yet minimal, analysis. The limited research on Aruba's reefs occurs in part because coral growth is limited to shallow depths due to a sandy bottom at depths of 20–30 m, which obstructs the formation of coral reefs (Roos 1971; Bak 1975). There are, however, locations along the north- and southwestern portions of the island (e.g., Arashi and Baby beaches) that support extensive coral development as the sandy flat bottom changes into a shingle bottom about 1 km offshore (Roos 1971).

18.4 Landscapes

The historic and present-day residents of Aruba, Curaçao, and Bonaire have modified, utilized, and exploited their landscape in a variety of ways.[3] All three ABCs experienced waves of migration from South America, particularly from

[3]Due to the overlapping nature of heritage and its implications for landscape interactions, we have chosen to detail this information in Sect. 18.5 *Heritage and Tourism*.

Fig. 18.12 The north coast of Curaçao, host to *Shete Boka National Park* (Seven Inlets), boasts spectacular views of limestone seacoasts, and resultant coastal features like sea alcoves/caves (shown here) as well as blowholes and natural bridges. Image courtesy of J. and R. Klotz, available via https://commons.wikimedia.org/wiki/File:SHETE_BOKA_NATIONAL_PARK,_CURACAO.jpg. Retrieved November 2016

what is now Venezuela. These Amerindian peoples utilized the marine resources surrounding them for food. They also took advantage of the islands' limestone features for tools and sought shelter in the caves. The *Kueba di Hato* caves on Curaçao as well as Christoffel National Park contain petroglyphs that are at least 1500 years old (Fig. 18.14). These same caves were also a place of refuge for escaped enslaved persons from Africa taken to Curaçao during the height of the transatlantic slave trade (Fig. 18.15). Bonaire's caves also contain petroglyphs, but were unlikely used as dwellings because there is no evidence of middens or shell heaps (Klomp 1986).

The Spanish introduced livestock including "goats, sheep, dogs, donkeys, cows, and pigs" on Aruba and Bonaire[4] (Abel 2000; Dresscher 2009, p. 4) and cattle on Curaçao (Rupert 2012). As these animals were not indigenous to the islands and "[T]he presence of these small and mobile grazers and browsers meant selection for thorn forest vegetation (acacia, mesquite, many cactus species, etc.) that could defend itself from foraging animals, and that today dominates the landscape" (Abel 2000, p. 20). Additional animals were introduced as well, including dogs, cats, horses, black rats (Curaçao), brown rats and house mice, one species of agouti (Curaçao), Whitetail deer (Curaçao), and other mammals (Borroto-Páez, and Woods 2012; Watts 1987).

Large-area agriculture, as is common in other islands of the Caribbean, did not occur on the ABCs under European colonizers because of climate.[5] The Dutch, however, worked with the dry climatic constraints of the islands establishing export industries centered on aloe vera and salt production through the use of enslaved African and indigenous labor and ingenuity. The physical landscape of Bonaire is

[4]The Spanish also introduced cattle and horses to Bonaire in 1527 (Hartog 1978).

[5]This is not to imply that there were not productive plots of land on the islands. For example, Bonaire had agricultural parcels called *kunuku* where sorghum and maize were cultivated (Klomp 1986).

Fig. 18.13 Dune field on the northern tip of Aruba, known locally as the California dunes for the offshore wreck of the famous ship "California." Photograph by Phillip Schmutz, May 2012

dominated still today by salt production located at Pekelmeer on the southern portion of the island, and the cultural landscape of Aruba bears the mark of a gold rush that persisted throughout the nineteenth century.

The discovery of oil in the Lake Maracaibo region of Venezuela in the twentieth century affected the landscape of each of the ABCs, although in different ways. Landscape modification included the construction of refineries and the dredging of harbors to allow for transhipment of oil (Fig. 18.16). Oil pollution from spills within the region has been documented on both Curaçao and Bonaire's beaches (Debrot et al. 1995, 2013).

Beach erosion is another consequence of human modifications stemming from development. In 1950, for example, Aruba deepened its harbor entrance, which had the unintended consequence of cutting off the natural sediment flow that nourished the island's beaches (Kohsiek et al. 1987). Hotels constructed during the 1960s and 1970s faced beach retreat by the late 1980s (Kohsiek et al. 1987:52).

18.5 Heritage and Tourism

The ABCs share a similar heritage that includes the influence of Amerindians from mainland South America, European Spaniards, Dutch, and enslaved Africans. All three islands have felt the impacts of Venezuelan oil in some capacity and the turn to tourism in the latter part of the twentieth century. While they are indeed similar in some respects, this section will focus independently on each of the three islands drawing out the nuances of their heritage particularly how each island developed into a tourist destination in the region. We will begin with Curaçao, as it was historically the dominant of the three.

18.5.1 Curaçao

The early indigenous inhabitants for all the ABCs were from mainland South America. About 30 sites investigated

Fig. 18.14 The entrance gate to the Hato caves, a popular tourist attraction located near the airport on Curaçao. The caves were an important hiding place for escaped enslaved persons and also contain Amerindian petroglyphs that are 1500 years old. Photograph by Amy Potter, May 2012

on Curaçao are from the Archaic Period (2540 BC–1840 CE), and these hunter-gatherer groups that ate turtle and crabs and used the limestone and shale to make tools lightly populated the island with one major permanent settlement (Saunders 2005). Half of the other sites belong to a later group from the Ceramic period (450 CE to the arrival of Europeans), dominated by the Dabajuroid culture diaspora from Venezuela near Lake Maracaibo (Saunders 2005).

Among Europeans, the first "discoverers" of Curaçao was the trio of Alonso de Ojeda, Amerigo Vespucci, and Juan de la Coas in May 1499, though a population has yet to be established for this time period (Rupert 2012).[6] In 1513, Viceroy Diego Colón, son of Christopher Columbus, declared Curaçao and its neighbors (Aruba and Bonaire) "useless islands" because they did not contain precious metals that he perceived to be marketable.[7] In doing this, Colón opened the door for the deportation from these islands' of all native people, most of whom ended up in Hispaniola to work at the gold mines (Rupert 2012; Watts 1987; Sauer 1966). The Spanish largely ignored the ABCs until 1526, when Juan de Ampíes was granted the right to repopulate the islands and brought 25 Native Americans to Curaçao (Rupert 2012, p. 21).

In 1633, when the Dutch were initially expelled from St. Martin, they turned their attention to Curaçao with its salt pans and attractive harbor. A year later in 1634, the Spanish governor of Curaçao surrendered and retreated. In 1636, the Dutch conquered Bonaire and Aruba, both of which were considered dependencies of Curaçao. The Dutch presence in the Caribbean was driven by a need for salt to supply the expanding herring industry, as well as cheese and butter (Römer 1984). The West India Company encouraged the settlement of colonists (the most notable being the Sephardic Jews). The Dutch were also interested in acquiring Curaçao

[6]Linda Rupert estimates that the population of Caquetios on Curaçao was 2000, while David Watts (1987, p. 109) and Carl Sauer (1966, 194) put the population much higher at 100,000, a number that today seems quite high. Rupert does not indicate whether this number was pre- or post-European contact, which could have had significant impact on the island's population due to the introduction of European diseases.

[7]As noted later in this section, gold was not discovered in Aruba until the nineteenth century.

Fig. 18.15 Inside Hato caves, Curaçao. Caves such as these host Amerindian carvings (petroglyphs) that have been dated to around 500 CE. Photograph by J. and R. Klotz, available via https://commons.wikimedia.org/wiki/File:HATO_CAVES_,_CURACAO.jpg. Retrieved November 2016

for its close proximity to Brazil as well as the West India company's involvement in the slave trade (Dresscher 2009). From 1634 to 1675, the island served as a naval base centered at the port of Willemstad. In 1675, the Dutch opened the islands to free trade, transforming the once small naval landholding by the Dutch into a major maritime commercial center and the hub of the Dutch Atlantic system (Rupert 2012). Between 1674 and 1689, Curaçao served as a slave depot for enslaved person arriving from Africa and "was the destination for 59% of all Dutch slave exports" with the majority then being re-exported to South America (Rupert 2012, p. 77).[8] Outside the port of Willemstad, merchants constructed large rural estates known as *landhuis* as a symbol of their growing wealth. Their primary function was relaxation rather than significant agricultural production with the main house emulating the large Caribbean sugar plantations but with a Dutch architectural style (Rupert 2012, 135). In 1863, slavery was abolished.

The twentieth century was marked by two dominant industries: oil refining and tourism. Shell Oil was established in Curaçao in 1918, while tourism had its beginnings in the early 1900s, though it took until the 1950s before tourism became a significant industry. Today, tourism accounts for 18.5% of the island's' economy[9] up from 10.5% in 2004 (Halcrow 2010; Croes et al. 2015). In addition, tourism spending has increased over the last 15 years by an annual average of 4% (Croes et al. 2015). A significant increase in cruise passengers occurred in 2013 as a result of increased port of call, and perhaps, because that same year, Curaçao was ranked for the first time in *Cruise Insight* magazine's "World's Top 50 Ports."

Still, oil refining poses challenges to tourism. As the Curaçao Tourism Bureau (2005, p. 30) notes, "The refinery (along with other industry) dominates the harbor area and is a source of air and water pollutants in the harbor and areas immediately west of its location. In that sense, the refinery limits the land available for tourism development and can be

[8]The Dutch, beginning in 1600, contributed to roughly 5% (half a million persons) of the transhipment of enslaved persons to the New World (Emmers 2006).

[9]2013 estimates.

Fig. 18.16 Baby Beach on the southern part of Aruba with the then Valero Refinery in the background. The installment of the refinery has heavily impacted the tourism industry in the area as it is often cited on traveler blogs and review Web sites, such as *TripAdvisor*®, as an eyesore decreasing the natural appeal of the beach. Photograph by Amy Potter, May 2012

an eyesore for visitors." In addition, larger socioeconomic issues facing the island could ultimately hamper the growth of tourism in the coming years: a weak economy, debt repayment, the uncertain future of the financial sector related to offshore financing legislation, 15% unemployment (youth unemployment is 35%), poverty incidence exceeding 15%, and "brain drain of educated Curaçaoans elsewhere" (Croes et al. 2015, p. 45). While tourism does relieve some unemployment, providing 16,503 jobs, there is still a disconnect in terms of the beneficiaries of the industry.

While coral reefs and beaches attract tourists, Curaçao also boasts a repertoire of notable architecture and historic sites that both the government and private institutions have sought to restore. Willemstad, the island's capital, has around 750 historic buildings and has been designated a UNESCO World Heritage Site (Fig. 18.17). Outside Willemstad, there are 55 examples of a *landhuis* (Gravette 2000). In terms of connecting to the island's African heritage, there are several sites of significance: *Landhuis* Knip's[10] Museo Tula, the Tula monument to the Curaçao slave revolt of 1795,[11] Museum Kurá Hulanda, an anthropological museum with a variety of exhibits which focus on civil rights and the transatlantic slave trade (Fig. 18.18), and the Kas di Pal'i Maishi Slave House and Museum (Curaçao Museum) (Fig 18.19).[12]

18.5.2 Aruba

In Aruba, the first Amerindians to arrive as early as 2500 BCE were fishers, hunters, and gatherers. Just before 1000 CE, a second wave of migrants, the Caquetios from South America, arrived and settled parts of the island and used ceramics and were agriculturalists (Rupert 2012). Waves of influence can be felt from Venezuela between 100 BCE and 1000 CE. Several sites excavated on the island reveal the influence of the people of the Dabajuroid ceramic tradition,

[10]Also called Kenepa.

[11]This was the largest slave revolt in Curaçao's history.

[12]This house is an example of house construction by descendants of enslaved persons living on the island during the seventeenth to early twentieth century.

Fig. 18.17 View of the colorful gabled townhouses in Willemstad from Santa Ana Bay. In the foreground is a boat from Venezuela on its way to the floating market. Photograph by Amy Potter, May 2012

which include Tanki Flip (950–1250 CE) and Santa Cruz (occupation dates to historic times). At Tanki Flip, "…investigations have found evidence of perhaps 100 inhabitants living in large oval-shaped and small structures, and surrounded by Dabajuroid pottery, hearths or kilns, stone tools, animal bones, and thousands of shell fragments" many of which were made of Queen Conch (Gravette 2000, p. 17). The mainland connection to Aruba continued through the Spanish and Dutch period, and until 1750, Aruba was an Amerindian reservation with close ties to mainland South America—except for a small group of residents from the West India Trading Company. During this time, the island was largely maintained as a horse ranch (Römer 1984).

While other important activities centered on the agricultural production of aloe vera cultivation,[13] salt production, and phosphate mining, gold was discovered in the nineteenth century. During the height of production (between 1824 and 1899, formally closing in 1913), 1,350,000 kg of gold was extracted (Gravette 2000). G.B. Bosch, a visiting preacher from Curaçao, recalled in 1836 that people left their occupations for more lucrative prospects in gold mining (Dresscher 2009, p. 15).

The 1918 discovery of oil in the Lake Maracaibo region had tremendous impacts on Aruba. Rather than opening a refinery in Venezuela—due to the turbulent political situation there—the oil companies situated their refinery on the eastern tip of Aruba because of its geography and climate.[14] The refineries would do well, with their heyday lasting from 1928 to 1948.

Tourism took on a more prominent role with decisive government intervention after the oil refinery, the Lago Oil & Transport Company, Ltd.[15]—which contributed to about 25% of the island's GDP and employed roughly 30–40% of the population—closed in 1985 (Vanegas and Croes 2003; Ridderstaat 2007). As the refinery shut down, Aruba also underwent a political shift, establishing a separate state in the Kingdom of the Netherlands. Aruba's gradual shift to tourism, however, took several decades. In 1947, Aruba

[13] At one time, Aruba, Bonaire, and Curaçao provided more than half of all aloe production in the world.

[14] They initially considered Curaçao, but the island's ports were already in use.

[15] At the time, Aruba was the site of the largest oil refinery in the world (Gravette 2000).

Fig. 18.18 The yard of Museum Kurá Hulanda, where enslaved Africans were auctioned off to destinations throughout South America. Photograph by Amy Potter, May 2012

established the Aruban Tourism Commission to explore the prospects of developing tourism for the island, leading to the establishment of the Aruba Tourism Bureau (now the Aruba Tourism Authority) in 1953 (Vanegas and Croes 2003), though it was not until 1959 that the island constructed its first 100-room hotel (Ridderstaat et al. 2014). Aruba intensified its efforts to attract tourists through advertising, infrastructure development (hotels and shopping malls, airport), and the expansion of air-seat capacity as a way to offset its economic loss of the oil refinery (Croes and Vanegas 2005; Ridderstaat et al. 2014).

Over the last several decades, international tourist arrivals increased from 129,000 tourists in 1975 to 721,000 in 2000 (Croes and Vanegas 2005). In 2014, the island surpassed one million stopover arrivals (Caribbean Tourism Organization 2016), the number of hotel rooms tripled (Ridderstaat et al. 2014), and cruise ship arrivals increased nearly tenfold in the same period (Ridderstaat et al. 2014; Caribbean Tourism Organization 2016).

Aruba has one of the highest living standards in the Caribbean, but over 85% of their economy depends directly or indirectly on tourism, making it vulnerable to global economic downturns. Many of the hotels are foreign-owned leading to capital leakage (Dresscher 2009; IMF Country Reports 2015; Caribbean Journal 2015). In addition, investment in infrastructure is ongoing and extensive, with Aruba currently undergoing a billion-dollar island revitalization and beautification project for hotels, roads, airport, water, energy, and sanitation (Caribbean Journal 2015).[16]

18.5.3 Bonaire

Bonaire's indigenous history shows evidence of a variant of the Dabajuroid cultural tradition (1000–1400 CE) that also can be felt on Curaçao and Aruba. Archaeologists have uncovered crude pottery figures, jars, cassava griddles, and documented rock paintings, which were part of spiritual life. Other tools used to prepare maize indicate these early inhabitants had a mixed diet that would have also included marine resources of fish, shellfish, and crabs. Most of the sites are located inland because these early inhabitants lived

[16]The government recently renovated the Reina Beatrix International Airport (*Caribbean Journal* 2015).

Fig. 18.19 Salt ponds on Bonaire. Photograph by A. Sieben, available via https://commons.wikimedia.org/wiki/File:Bonaire_Salzgewinnung.jpg . Retrieved November 2016

near their fields as freshwater was only available further inland (Saunders 2003; Klomp 1986).

From 1636 to 1868, Bonaire was exploited as a single large plantation,[17] initially by the West India Company and then by the government of the Netherlands. Bonaire never developed large-scale plantation agriculture. Instead, the colonial era was dominated by stockbreeding and the export of aloe divi-divi pods, brazilwood, and salt extracted in the southern region of the island. The island's dry climate facilitates high rates of evaporation that leads to salinization of inland lakes (the most notable of which is Pekelmeer) (Hartog 1957; Klomp 1986). Enslaved Africans were initially transported to the island to work in the salt industry.[18] In 1868, after emancipation, the Dutch government sold large tracts of land on Bonaire charting a new era of privately owned landholdings on the island. This time period was extremely difficult for those who were formerly enslaved, as they suffered low wages, continuous debt (similar to sharecropping in the USA), and reduced access to grazing lands (Abel 2000, p. 24; Klomp 1986).

With the establishment of Shell Oil in Curaçao in 1918 and Aruba's ESSO's LAGO in 1927, those living on Bonaire could seek out wage labor and work in the refineries or on the containers that transported oil. The Bonairean

[17]The term plantation here is not to be confused with plantations in other parts of the Caribbean. Ank Klomp describes Bonaire's plantations as similar to the Latin American hacienda. "One might picture a huge ranch on which a number of economic activities were pursued along with extensive stock raising" (p. 15).

[18]A report from 1806 documents 945 inhabitants on island: 72 white, 284 Indian, 225 freemen, 92 privately owned slaves, and 272 government-owned slaves (Hartog 1957, p. 108).

Petroleum Corporation, a fuel oil storage and transhipment terminal, was established in 1975.

In terms of tourism, the first hotel on the island opened in 1952. It was a former structure that served as an internment camp for 500 German nationals during World War II (Parker 1999). During the 1960s and 1970s, tourism on Bonaire was relatively small due to the island's limited infrastructure: four hotels (two of which had 57 rooms each) and the island's very short airport runway (Klomp 1986). In November of 1967, Bonaire received its first cruise boat visit by Norwegian American Line's *Bergensfjord* with 425 guests (Bongers 2013). In 1976, the airport added a new terminal, and in 1980, the single runway was extended. In the last several decades, Bonaire has experienced a significant increase in tourism but not on the scale of its island neighbors (Caribbean Tourism Organization 2016).

Most of the present-day tourism on Bonaire consists of "active tourism" with a particular emphasis on its marine resources (SCUBA diving). Other activities include kitesurfing, windsurfing, snorkeling, boating, and sailing. Land activities center on ecotourism, which include hiking, biking, horseback riding, caving, and birdwatching. Bonaire boasts one of the few flamingo breeding sites in the southern Caribbean with approximately 3000 breeding pairs located in the Pekelmeer flamingo sanctuary on the southern end of the island (Abel 2000; Vdauskaite 2015; Dutch Caribbean Nature Alliance 2016). Bonaire's reefs are some of the best preserved within the region and include the 2700 hectares of the National Marine Park of Bonaire, established in 1979[19] (Dutch Caribbean Nature Alliance 2016). The park includes the waters surrounding the island to a high-water mark depth of 200 feet (91 m).

In addition to Bonaire's coral reefs, the island has unique architecture. The oldest standing buildings—its slave huts—are located along the salt ponds on the southeastern side of the island. These free-standing stone structures with thatched roofs are a testament to the island's enslaved Africans and were built around 1820 (Gravette 2000). Like Curaçao, there are also planter's residences dating to the twentieth century, in addition to an ancient aloe oven at Karpata.

[19]"The early days of unregulated marine tourism on Bonaire impacted the reefs heavily with spearfishing, with anchor damage to corals and with siltation caused by onshore development. As these problems became evident, a coalition of local leaders together with The World Wildlife Fund succeeded in convincing Holland and the Antillean Government to intervene. The result was the creation of the Bonaire Marine Park (BMP) in 1979" (Parker 1999, p. 243).

18.6 Hazards

Climate change will pose a serious threat not only for the island's residents but also for the tourism industry (Debrot and Rob Bugter 2010). Scientists predict there will be increases in air and sea surface temperatures, coastal and beach erosion via sea-level rise, and an increase in the intensity and number of tropical cyclone systems (Ministry of Health and Nature 2014).

The islands formally fall outside the hurricane belt and are rarely impacted directly by tropical cyclones. On occasion, however, tropical cyclones do cause destruction through coastal erosion as refracted storm-wave swells alter, in the short run, sand movement in the littoral zone eastward (Kohsiek et al. 1987). On average, once every four years, a tropical cyclone (tropical storms up to category 5 hurricanes) occurs within a radius of 150 km, with a total of 38 tropical cyclones during the time period from 1850 to 2014 (Meteorological Department of Curaçao 2015). The most recent tropical cyclone to cause significant damage to the islands was Hurricane Lenny in 1999, resulting in considerable beach erosion and damage to the coral reefs across the islands as well as damage to historic structures at the Washington Slagbaai Park on Bonaire.

For islands such as Bonaire and Curaçao that attract tourists to their coral reefs, climate change will have a dramatic impact on these systems. Strelich (2015) analyzed data between 1982 and 2012 and observed an overall warming trend in sea surface temperatures over the past 30 years in the Caribbean, with the most significant increase occurring just north of South America. The warming ocean surface temperatures are impacting coral reef communities prompting coral bleaching events by altering ocean chemistry. It is estimated that as much as 80% of the living coral reef across the Caribbean are already gone (Economic Commission for Latin America and the Caribbean 2011, pp. 16–17) and the ABCs have not fared much better as episodes of massive coral bleaching have occurred over the past few decades (Vermeij 2012; Steneck et al. 2015). Additionally, Bak and Nieuwland (1995) found that since the 1970s, the health of the coral colonies has decreased across the shallow reef complex as a result of coastal development, sewage discharge, and artificial beach construction. A more recent report by The Ministry of Health and Nature in 2014 found that Curaçao's reefs are experiencing both human- and natural-related stresses because of overfishing, development, sewage discharge, chemical pollution, and artificial beach construction. Nevertheless, Bonaire and Curaçao support some of the healthiest coral reefs in the Caribbean, containing by far the greatest level of species diversity (Miloslavich et al. 2010; Vermeij 2012; Steneck et al. 2015).

Aside from the threat of climate change, there are a number of other hazards that will pose serious risks to the island's inhabitants and tourism infrastructure. Fresh groundwater resources are limited, and a large variety of natural and anthropogenic processes are influencing the groundwater quality. Sea spray, hypersaline rainwater, and lack of fresh surface water all contribute to the brackish nature of the groundwater resources, whereas anthropogenic effects introduce high concentrations of potassium, sulfate, and nitrate as a result of groundwater mixing with polluted wastewater (van Sambeek et al. 2000). The Department of Agriculture and Fisheries established a monitoring network on the islands in the late 1970s because of poor groundwater quality, though only the monitoring network on Curaçao is still operational (van Sambeek et al. 2000). These issues have prompted the production of drinking water through saltwater distillation (van Sambeek et al. 2000).

Although no written or oral sources detailing a tsunami impact exist since the occupation of the islands by the Spanish in 1527, there is historic evidence of tsunamis on the ABCs dating to only 500 years BCE (Scheffers 2002, 2004; Scheffers et al. 2005). The possibility of a new event remains plausible, and based on the location of transported debris from previous tsunami events, the height of onshore waves could have exceeded 12 m.

Beach pollution from oil spills and marine debris has been documented in a number of studies. For example, a study detailing tar pollution on Curaçao shows that over a 14-month period, January through May were the greatest months for contamination as a result of occasional oil spills. There was also evidence showing impact from more significant spills on the central-southwest coast (Debrot et al. 1995). The same authors (Debrot et al. 1999) also documented marine debris based on a study of 10 pocket beaches on Curaçao. They found higher amounts of debris on windward beaches, which included predominantly plastic and wood materials. Leeward-side beaches experienced debris from local recreational activity, while windward beaches were more likely to experience debris from the region. A study focused specifically on Bonaire found tar pollution to be less than that of Curaçao but still present (Debrot et al. 2013). In addition to oil spills, the oil refineries discharge smoke and noxious gases. While this pollution has generally been reduced, it still impacts air and water quality for areas on Curaçao, which include Willemstad, Parasasa, Piscaderabaai, and St. Michiel and serves as a visual eyesore for the tourism industry (Halcrow 2010) (Fig. 18.16).

18.7 Conclusion

Comprising the Leeward Dutch Antilles, Aruba, Bonaire, and Curaçao share a similar geology and climate. The geologic structure of the ABCs underlies the episodic evolution of the Leeward Antilles ridge since the Late Cretaceous. Although the lithology and sequence phases differ slightly between the islands, the geologic core of all three islands is composed of Late Cretaceous and Paleogene volcanic and sedimentary rocks overlain with multiple limestone terraces formed as a result of sea-level fluctuations and the tectonic rise of the Leeward Antilles ridge during the Neogene and Quaternary. Climatically, the ABCs exhibit a tropical semiarid climate with an average temperature around 28 °C.

Indigenous peoples were present on all three islands well before Europeans, and the landscape bears their imprint. Direct links to the Greater Antilles, particularly Hispaniola, started with the Spanish just after 1500 CE. Shortly afterward, the Spaniards declared the islands "useless" and attempted to depopulate them. A few enslaved Amerindians were reintroduced with their Spanish masters in the sixteenth century, but more direct links with the Lesser Antilles and Africa seem to date to the Dutch period, which began in 1634. Because of the Dutch's deep connection with the slave trade for over two centuries, these islands have an outsized role in historic slavery. The cultural imprint of the African diaspora (particularly in Curaçao and Bonaire) is deep, long-lasting, and meaningful. After the abolition of slavery, the islands became economically marginal for the Kingdom of the Netherlands. The discovery of oil in Venezuela early in the twentieth century impacted all three islands.

Tourism, which developed later in the twentieth century, is now important to the economy of all three islands. While historically Dutch activity centered on Curaçao, today Aruba dominates in the realm of tourism (cruise passenger arrivals and tourist stopover arrivals). The very characteristics that in the past gave the islands the moniker "useless" are now seen as desirable for this economic mainstay. With increasing visitors to the three ABC's, leaders will have to balance economic growth while also safeguarding resources (heritage, reefs, etc.). Bonaire's coral reef protection is some of the most impressive efforts seen globally. In addition, given Curacaos' unemployment rate, sustainable tourism development must also work to the benefit of island residents. Leaders must do all of this while also grappling with the inevitable adverse impacts of climate change.

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Index

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