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

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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.

Small Islands, Intriguing Landscapes

1

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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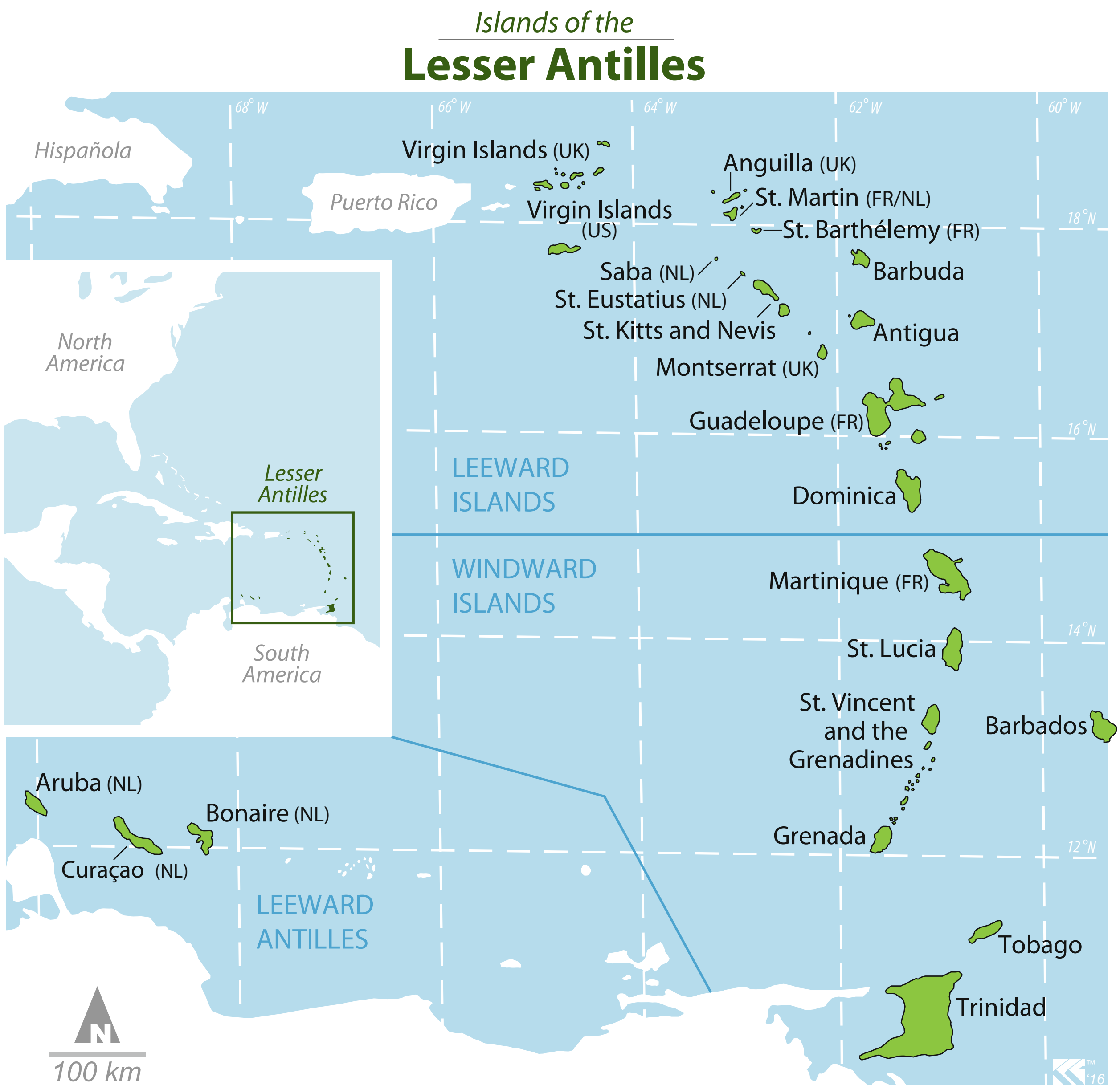

Fig. 1.1 General map of the Lesser Antilles identifying the three subregions—Leeward Islands, Windward Islands, and Leeward Antilles—as well as the primary islands/island groups that will be highlighted in this volume. Cartography by K.M. Groom

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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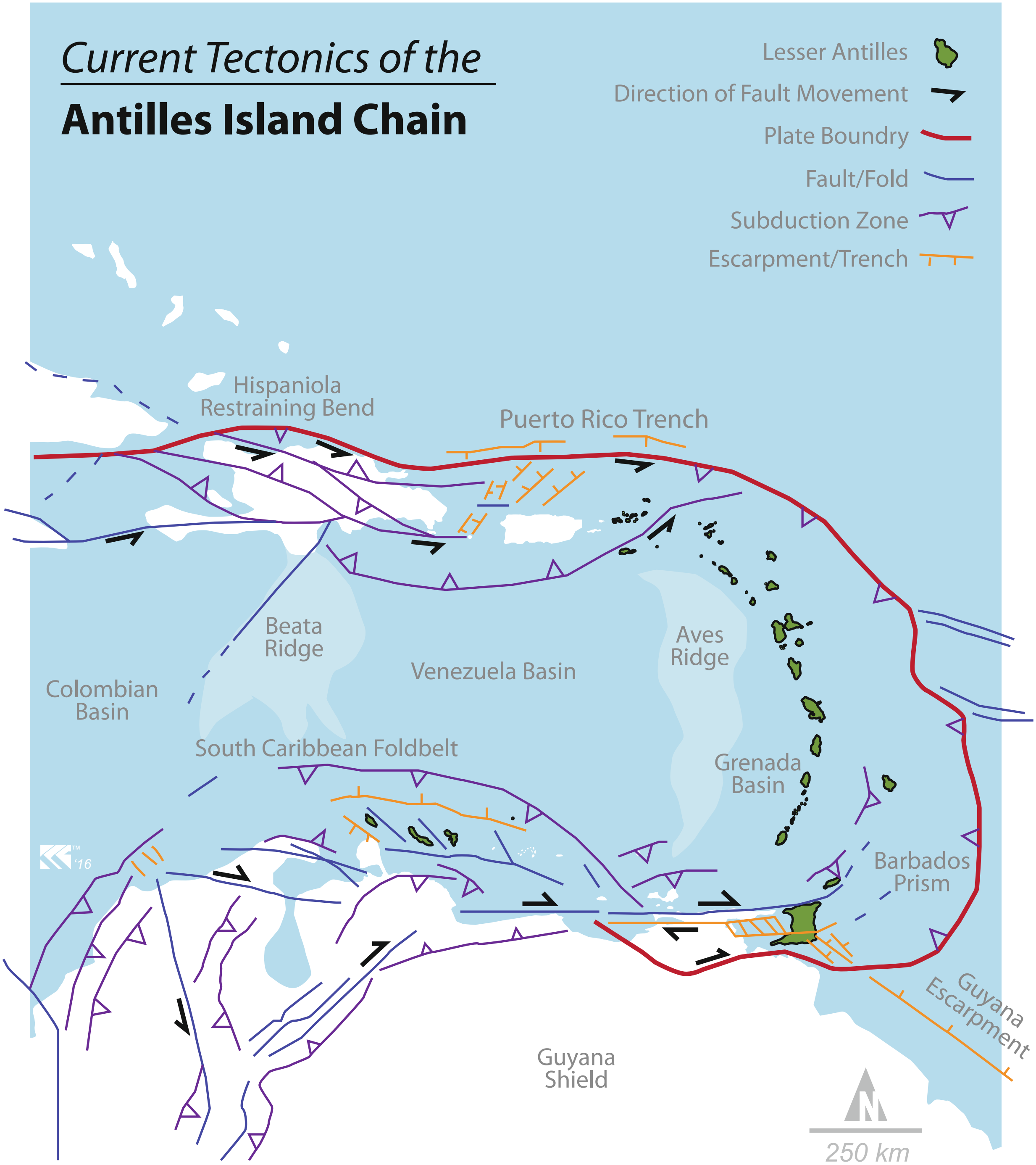

Fig. 2.1 Tectonics of the Antilles Island Chain, illustrating plate boundaries and fault zones surrounding and within the Caribbean Plate. Subduction zones along the eastern and northeastern margins have led to volcanism, which produced the Windward Islands, the inner arc of the Leeward Islands, and 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

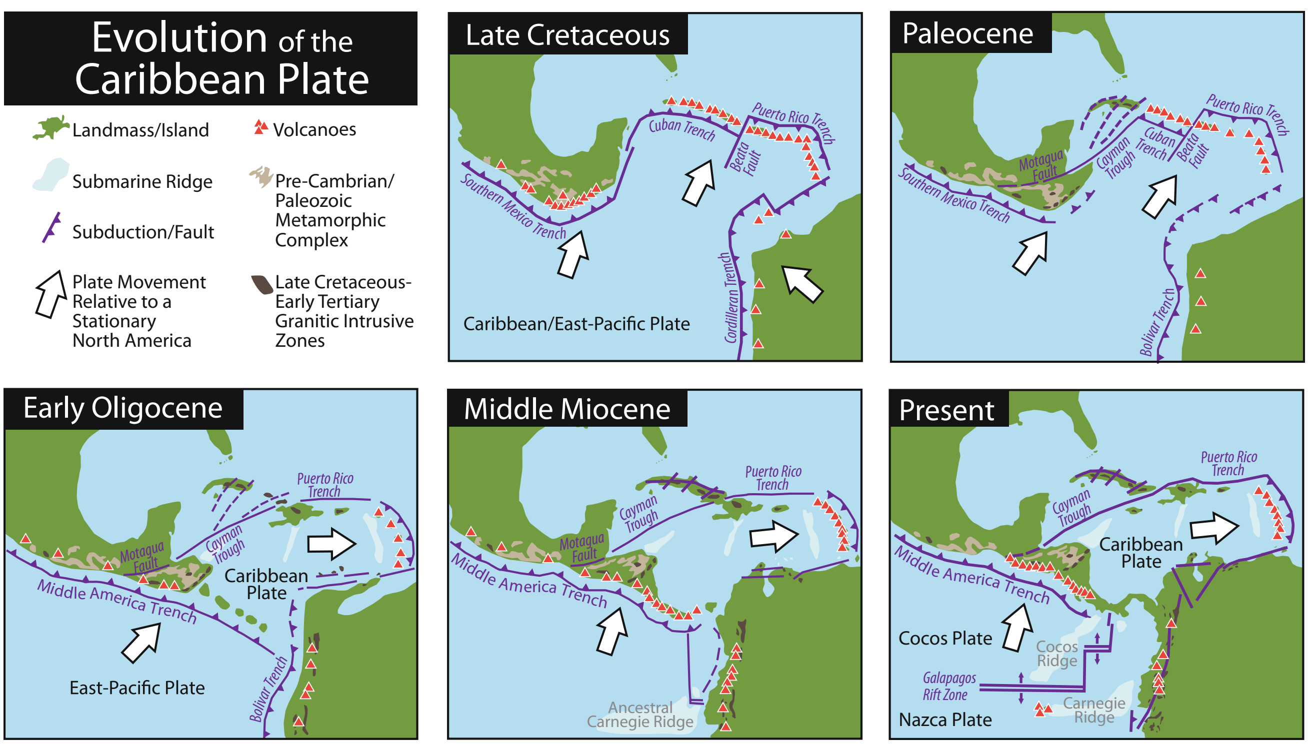

Fig. 2.2 Caribbean Plate Tectonic Evolution, including the Caribbean Plate's subduction under the South American Plate, beginning around 80 million years ago. Figure by K.M. Groom, modified from Malfait and Dinkleman 1972

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

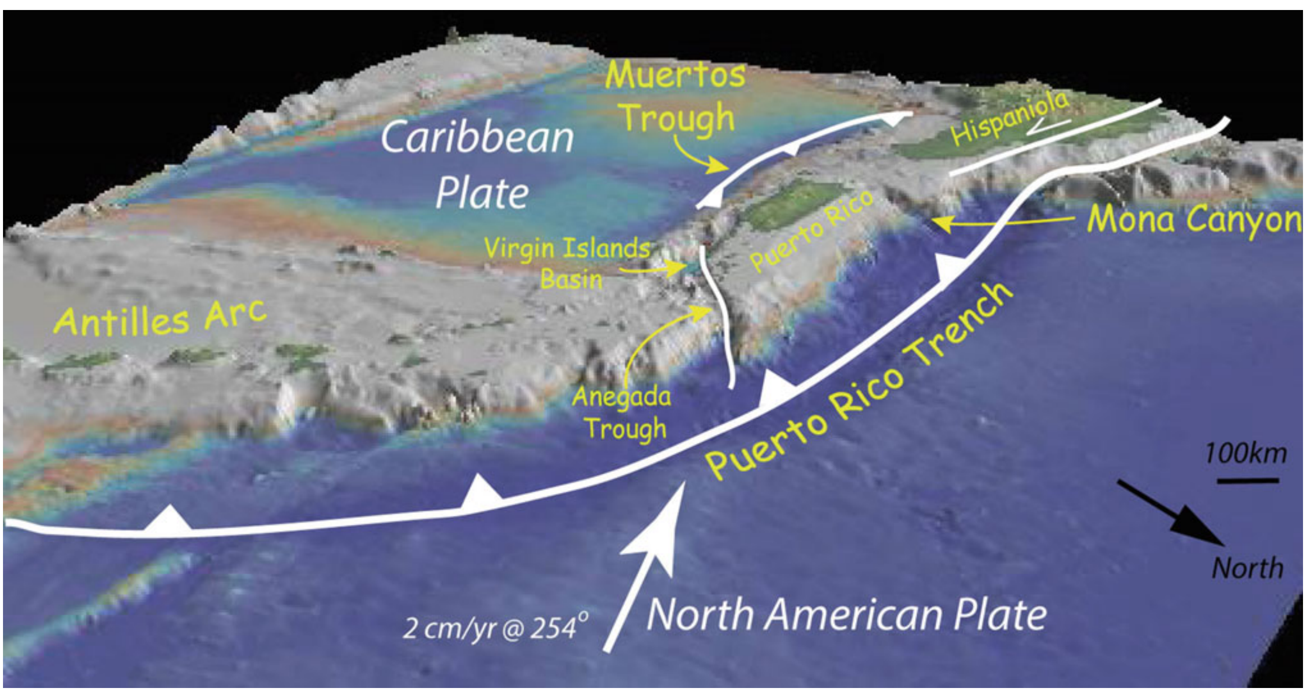

Fig. 2.3 A three-dimensional view of the Puerto Rico Trench (the Antilles Arc runs along its ridge). The northern boundary of the Caribbean Plate exhibits left-lateral strike-slip faulting along the North American Plate border to Puerto Rico, where the boundary transitions into a combination of transform 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.

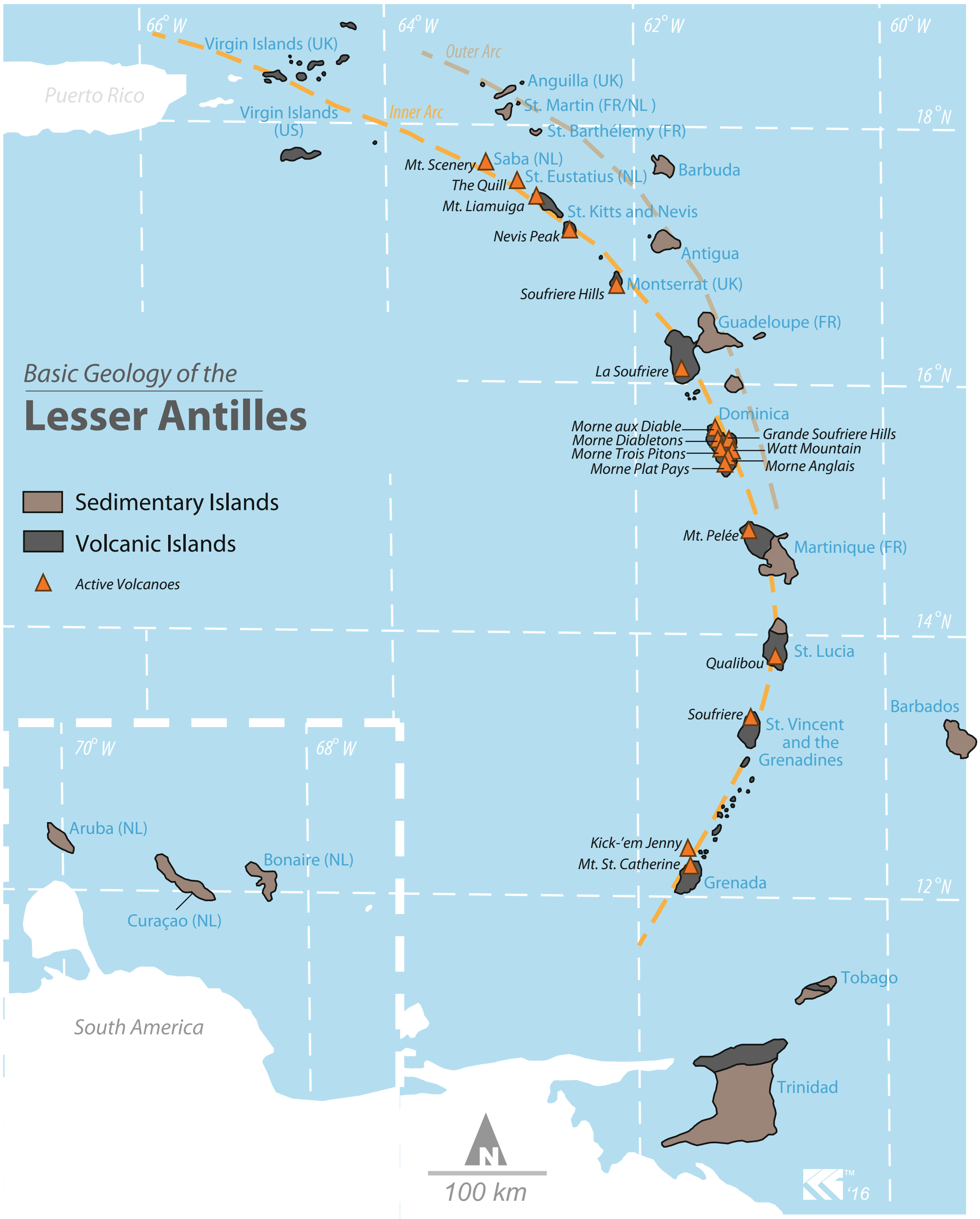

Fig. 2.4 Basic geology of the Lesser Antilles, illustrating dominant lithologies across the island chain. The outer Leeward Islands (outer arc) are the dominantly sedimentary islands of the northernmost arc, and the inner Leeward Islands (inner arc) are the dominantly igneous islands of the northernmost 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