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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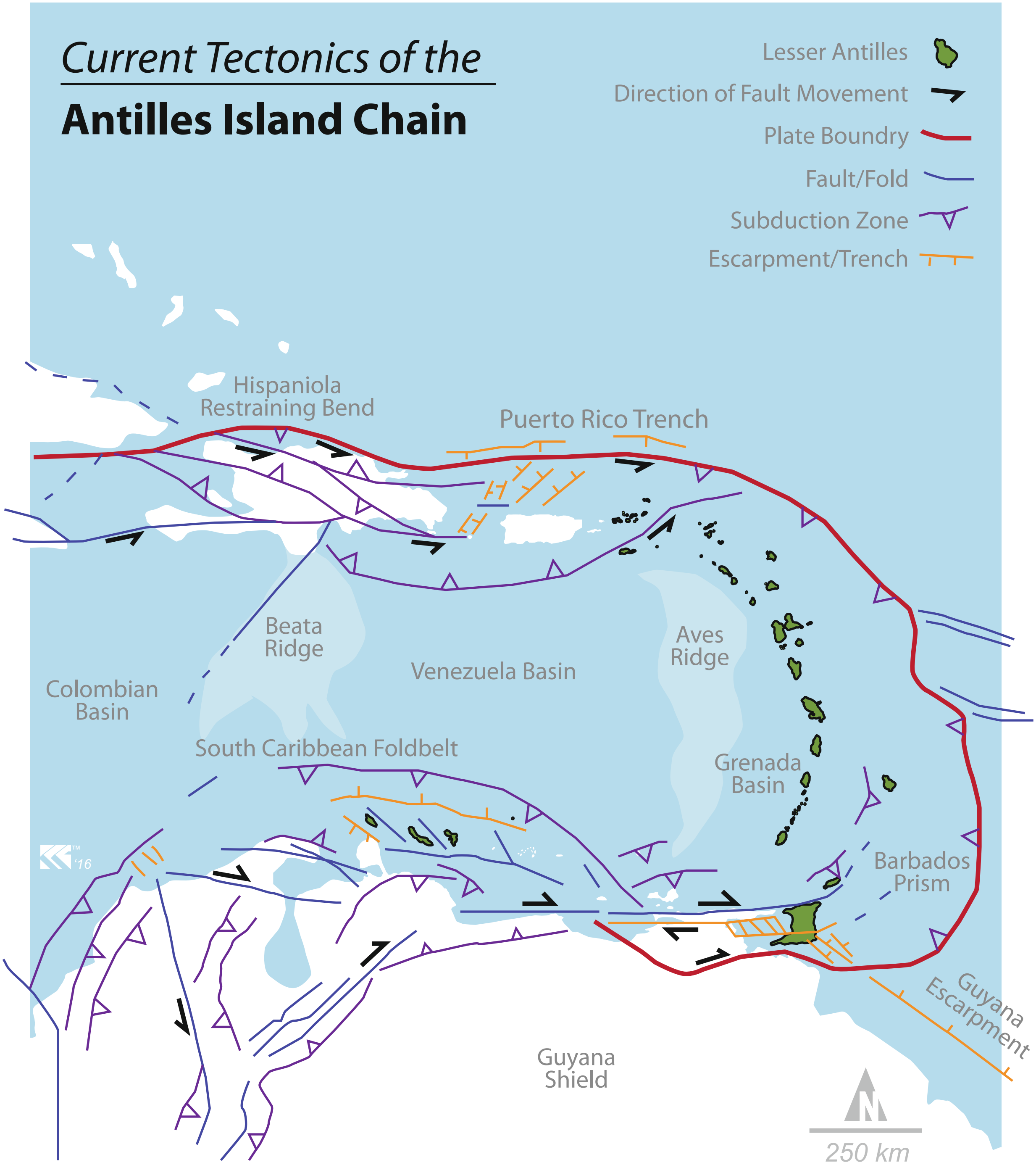

Fig. 2.1 Tectonics of the Antilles Island Chain, illustrating plate boundaries and fault zones surrounding and within the Caribbean Plate. Subduction zones along the eastern and northeastern margins have led to volcanism, which produced the Windward Islands, the inner arc of the Leeward Islands, and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

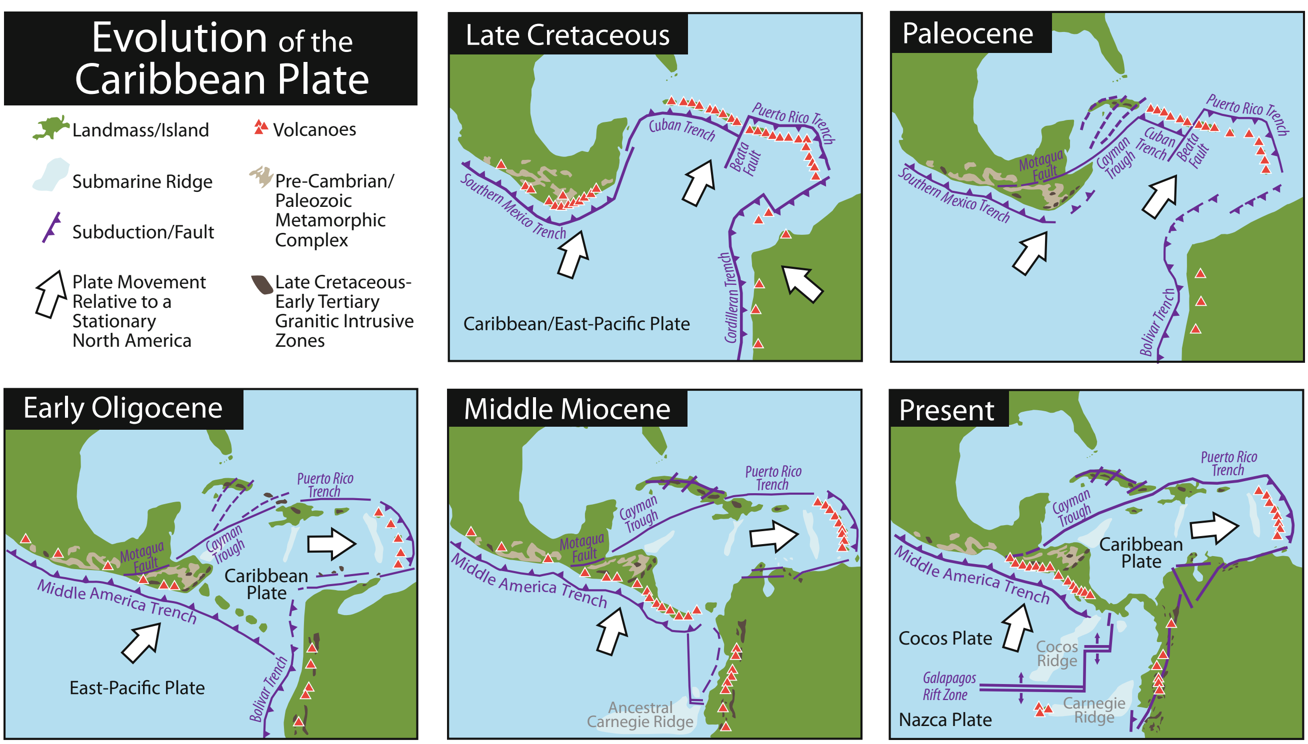

Fig. 2.2 Caribbean Plate Tectonic Evolution, including the Caribbean Plate's subduction under the South American Plate, beginning around 80 million years ago. Figure by K.M. Groom, modified from Malfait and Dinkleman 1972

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

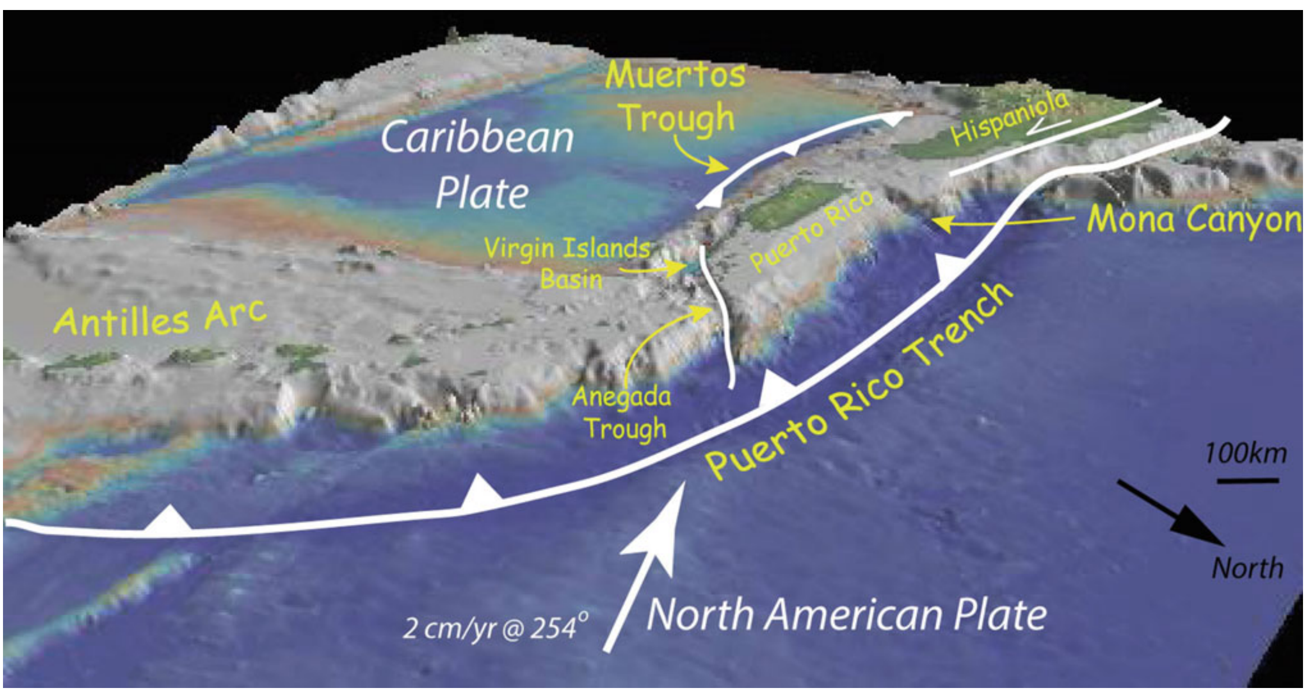

Fig. 2.3 A three-dimensional view of the Puerto Rico Trench (the Antilles Arc runs along its ridge). The northern boundary of the Caribbean Plate exhibits left-lateral strike-slip faulting along the North American Plate border to Puerto Rico, where the boundary transitions into a combination of transform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

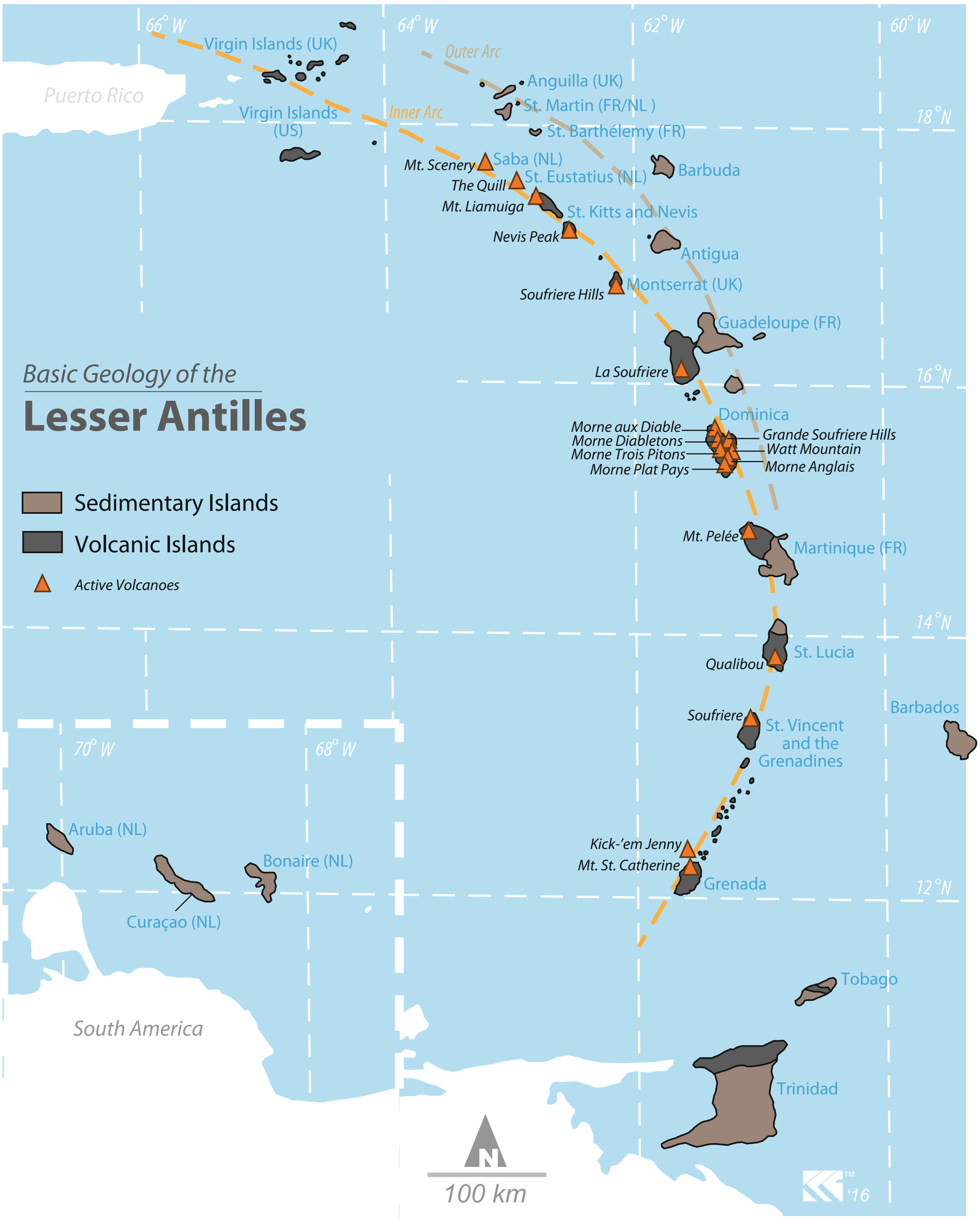

Fig. 2.4 Basic geology of the Lesser Antilles, illustrating dominant lithologies across the island chain. The outer Leeward Islands (outer arc) are the dominantly sedimentary islands of the northernmost arc, and the inner Leeward Islands (inner arc) are the dominantly igneous islands of the northernmost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