Trinidad and Tobago

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Jeanette C. Arkle, Lewis A. Owen and John C. Weber

Abstract

The nation of Trinidad and Tobago comprises the two southeastern-most islands in the Caribbean. Despite being neighbors and part of the same nation, the two islands have markedly different geology, landforms and landscapes. The geologic framework of these islands is the result of protracted and complex tectonism associated with Mesozoic rifting of Pangaea, circum-Caribbean subduction, and currently, Caribbean-South American transform plate motion. Tectonism, climatic shifts, and associated sea-level fluctuations throughout the Quaternary have shaped the islands' wetlands, drainage systems, modern and ancient reefs, marine terraces, and morphology of their shallow continental shelf. The islands proximity to mainland South America resulted in unique and diverse biota of continental origin and also had a marked influence on the migration and settlement of the earliest people in the West Indies. The natural landscapes, as well as society, and policies, of Trinidad and Tobago have been affected by agriculture, mining, urban development, and the hydrocarbon industry. Continued natural and human-induced environmental change, particularly related to sea-level rise, will lead to dramatic changes of the islands' landscapes.

Keywords

Landscape evolution • Tectonics • Tropical erosion • Quaternary geology • Caribbean

17.1 Introduction

Trinidad and Tobago emerge in the southeastern-most part of the Caribbean as a pair of islands separated by <30 km on NE corner of the South American continental shelf (Fig. 17.1). Despite being neighbors and part of the same nation, the two islands have markedly different landscapes. This is a consequence of their unrelated origins in the early Mesozoic circum-Caribbean and their different and protracted geologic and tectonic histories associated with interactions between the Caribbean and South American plates. Trinidad and Tobago's diverse geologic frameworks provide the context for the islands' varied landscapes, landforms, and geomorphic evolution, which have played a critical role in the nation's socioeconomic development, particularly as the leading producer of oil and gas in the Caribbean.

The Quaternary landscape evolution of Trinidad and Tobago is a product of their positions along the southeast corner of the Caribbean plate, their shallow emergence on the South American continental shelf, and, as a result, an impressive combination of geomorphic processes. Differential vertical tectonism has uplifted coral reefs, created marine terraces, and also caused extensive subsidence (e.g., Snoke et al. 2001; Weber 2005). The Central Range transform fault

J.C. Arkle (✉) · L.A. Owen
Department of Geology, University of Cincinnati, Cincinnati, OH, USA
e-mail: arklejc@mail.uc.edu

L.A. Owen
e-mail: lewis.owen@uc.edu

J.C. Weber
Department of Geology, Grand Valley State University, Allendale, MI, USA
e-mail: weberj@gvsu.edu

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Fig. 17.1 General physiographic map of Trinidad and Tobago. Note Trinidad's low-lying plains in the south and highlands along its northern coast, as well as Tobago's more mountainous topography. Cartography by K.M. Groom

in Trinidad, which defines the Caribbean-South American plate boundary, has generated a striking topographic scar across the entire width of central Trinidad and other tectonic landforms including shutter ridges, linear drainages, and offset ridges (Prentice et al. 2001, 2010; Weber et al. 2001a, 2011).

Sea-level fluctuations, associated with climatic shifts, have exposed portions of the shallow continental shelf and resulted in the development of an extensive offshore network of paleochannels (Soto et al. 2007, 2011). These base-level changes have caused adjustments to fluvial systems and the redistribution of sedimentation and erosion throughout the islands' interior landscapes (Ramcharan 2004; Arkle et al. 2015). Periodically connected with mainland South America during sea-level low stands, Trinidad and Tobago are home to unique flora and fauna of continental origin (Kenney 2008). The severe tropical climate has caused intense weathering, ubiquitous landsliding, and flooding (ODPM 2014). Strong, sediment-rich ocean currents dominate coastal sedimentation and erosion and influence coral reef development (Darsan et al. 2012). Collectively, these dynamic geomorphic processes have sculpted a spectacular variety of landscapes and landforms throughout Trinidad and Tobago.

Since the initial arrival of humans in Trinidad at ~8 ka, the landscape has been modified by agriculture, mining, biotic resource extraction, and urban development (Harris 1973; Boomert 2000; Pagán-Jiménez et al. 2015; Siegel et al. 2015). In the twentieth–twenty-first centuries, the hydrocarbon industry and an emerging tourism sector have further transformed the landscape. Continued natural and human-induced environmental changes will result in more dramatic landscape changes. Sea-level rise associated with human-induced climate change, mass wasting, and frequent seismicity and large magnitude earthquakes are some of the greatest threats to Trinidad and Tobago (Nurse et al. 1998; ODPM 2014). The future of the islands' landscapes and their management remains in a critical balance between employment, tourism, ecological protection, and sociopolitical factors (Dillman 2015).

17.2 Setting

17.2.1 Current Setting

Trinidad and Tobago are located in the SE corner of the tectonically and geologically complex Caribbean-South American plate boundary. Currently, the plate boundary is a transform margin that strikes eastward, south of Venezuela's northern Cordillera de la Costa, steps to the right in the Gulf of Paria, and then strikes ENE through central Trinidad. The current relative Caribbean-South American plate motion is ~20 mm/yr to the east, directed ~N86°E in Trinidad (Weber et al. 2001a, 2011). The majority of the dextral shear strain, ~12–15 mm/yr, is accommodated on the Central Range fault that strikes ~N72°E through Trinidad and continues offshore where it essentially merges with faults and structures of the Barbados accretionary prism (Pérez et al. 2001; Weber et al. 2001a, 2011; DeMets et al. 1994; see Fig. 17.2). Given this configuration, the southern half of Trinidad is moving westward with the South American plate, while land north of the Central Range fault, including northern Trinidad and Tobago, travels with the east-directed Caribbean plate.

Trinidad is structurally characterized by an alternating series of roughly ENE striking mountains and basins (Fig. 17.3). The Northern Range, Trinidad's tallest mountains, that rise to 940 m above mean sea level (amsl), exposes low-grade metamorphic rocks that were derived from Mesozoic passive-margin sedimentary rocks (Fig. 17.4). Late Cretaceous to Pleistocene sedimentary rocks underlie central and southern Trinidad (Erlich et al. 1993). These sedimentary rocks are folded and faulted to form two sets of low-relief hills, the Central and Southern ranges, which are bounded to the north by the Northern and Southern basins, respectively.

Tobago is dominantly composed of Mesozoic oceanic-arc and forearc rocks that rise to 572 m amsl in the mountains called the Main Ridge (Snoke et al. 2001; Fig. 17.5). These rocks are structurally sunken and covered by a Pleistocene coralline raised reef in the lowlands of southern Tobago (Fig. 17.6). Tobago is characterized by a northern highland and southern lowland that are associated with a series of horst and graben blocks formed by Pliocene-Recent regional extension.

Trinidad and Tobago have a tropical maritime climate with wet (June–December) and dry (January–May) seasons. Mean annual temperatures range from ~21 to 31 °C and the humidity is high, ranging from ~50 to 100% and averaging >80% (WRA 2001). Mean annual rainfall is ~2000 mm with extreme events delivering over ~5000 mm in areas of the Northern Range in Trinidad and in the Main Ridge of Tobago (WRA 2001; Hijmans et al. 2005). The islands experience relatively constant and strong easterly trade winds, and sporadic wet season tropical storms (WRA 2001). Although located outside of the main Atlantic hurricane belt, hurricanes occasionally track across the islands. The most infamous hurricane was Flora in 1963, which was devastating for Tobago (ODPM 2014).

The Guiana Current is the principal ocean current that impacts Trinidad and Tobago's coastal ecology and morphology (Van Andel 1967). The Guiana Current flows northward along South America and then bifurcates to the west through the Columbus Channel along southern Trinidad, and to the north along the coastlines of eastern Trinidad

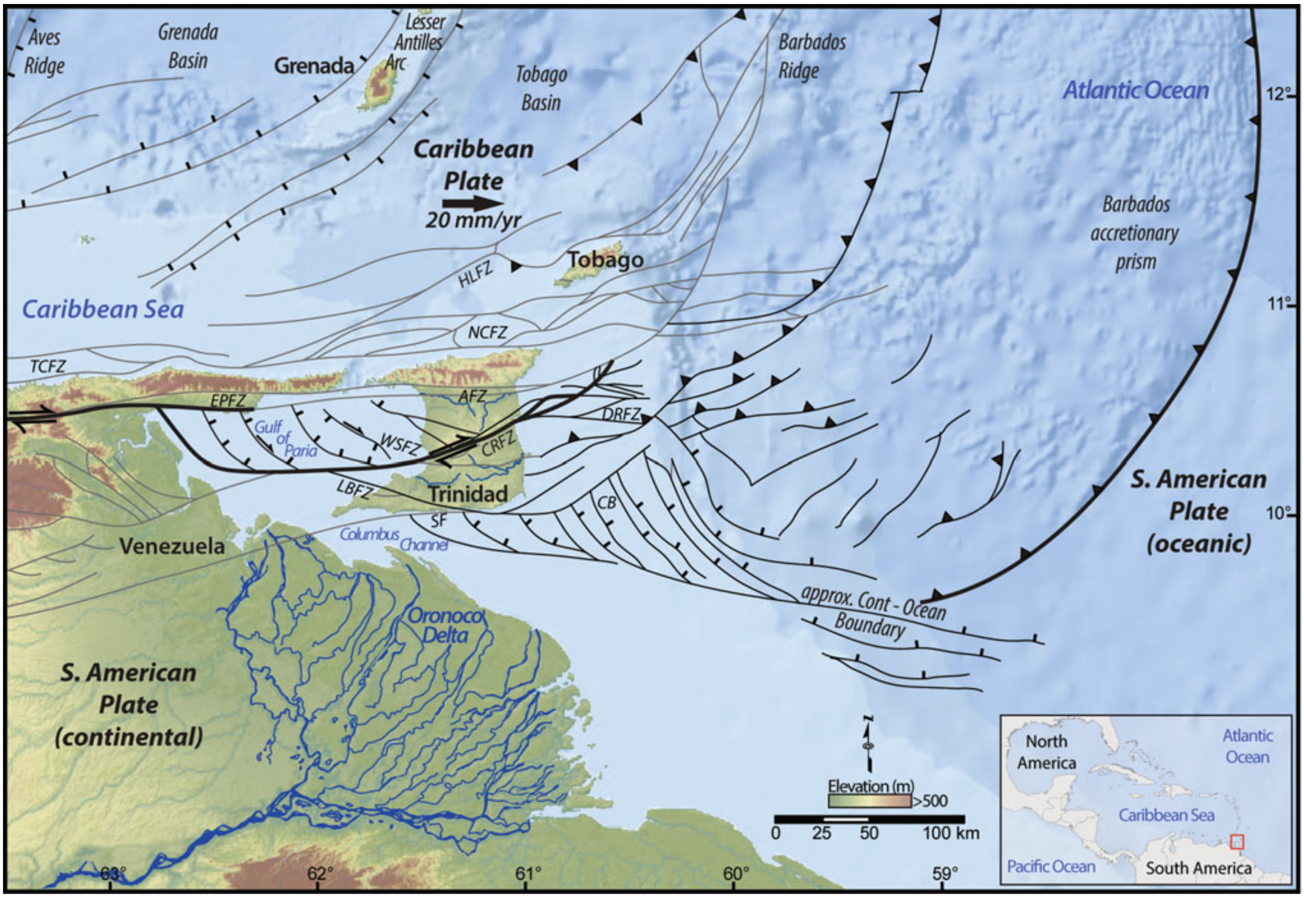

Fig. 17.2 Overview of the southeast Caribbean showing topography (0.5 km DEM from the US Geological Survey), bathymetry (from ESRI base maps and contributors therein), and major (*bold black lines*) and minor faults (*thin gray lines*) that show relative motion where known as thrust (teeth), normal (*bar*), and strike-slip (*arrows*) (after Soto et al. 2007, 2011; Prentice et al. 2010; Garciacaro et al. 2011 and references therein). Relative Caribbean-South American plate motion vector and velocity from Weber et al. (2001a, 2011), Pérez et al. (2001), and DeMets et al. (1994). *TCFZ* Tortuga Coche fault zone; *EPFZ* El Pilar fault zone; *AFZ* Arima fault zone; *CRFZ* Central Range fault zone; *WSFZ* Warm Springs fault zone; *LBFZ* Los Bajos fault; *SF* Soldado fault; *DRFZ* Darien Ridge fault zone; *CB* Columbus Basin; *NCFZ* North Coast fault zone; *STFZ* Southern Tobago fault zone; and *HLFZ* Hinge Line fault zone. Cartography by J.C. Arkle

and SE Tobago (Van Andel 1967). This current carries vast quantities of suspended sediment and plant detritus from the Orinoco and Amazon River deltas, which critically impacts coastal sedimentation and erosion, and, in large part, inhibits reef formation, particularly around Trinidad (Van Andel 1967; Laydoo 1991; Lapointe et al. 2010).

17.2.2 Geologic Setting and History

Trinidad and Tobago's geologic setting is complex and both islands have different geologic histories, structures, and rocks. Understanding the geological history is critical because it defines the context and "initial conditions" for the development of Trinidad and Tobago's landscapes and landforms.

Tobago's bedrock framework consists of three main lithologic belts that strike approximately eastward across the island and include: (i) a Cretaceous metavolcanic province, (ii) a Cretaceous intrusive igneous province, and (iii) a Plio-Pleistocene sedimentary sequence (Snoke et al. 2001; see Fig. 17.5). The Mesozoic oceanic forearc and arc rocks of Tobago formed far west of their current position and were rotated clockwise, possibly >90°, as they were translated eastward during oblique collision along the leading edge of the Caribbean plate (e.g., Erlich and Barrett 1990; Snoke et al. 2001). The intrusive igneous suites were emplaced at upper crustal levels during the late Cretaceous and experienced a protracted period of slow exhumation, through at least the Eocene (Cerveny and Snoke 1993), and then a pulse of increased exhumation during the late Neogene (Arkle et al. 2014). The metavolcanic and plutonic belts are bounded by the Central Tobago fault system (see Fig. 17.5). This normal-sense fault system and ductile shear zone strikes NE with down-to-the-south displacement and are interpreted to be related to extension that accommodated exhumation of the deep Tobago oceanic-arc rocks (Cerveny and

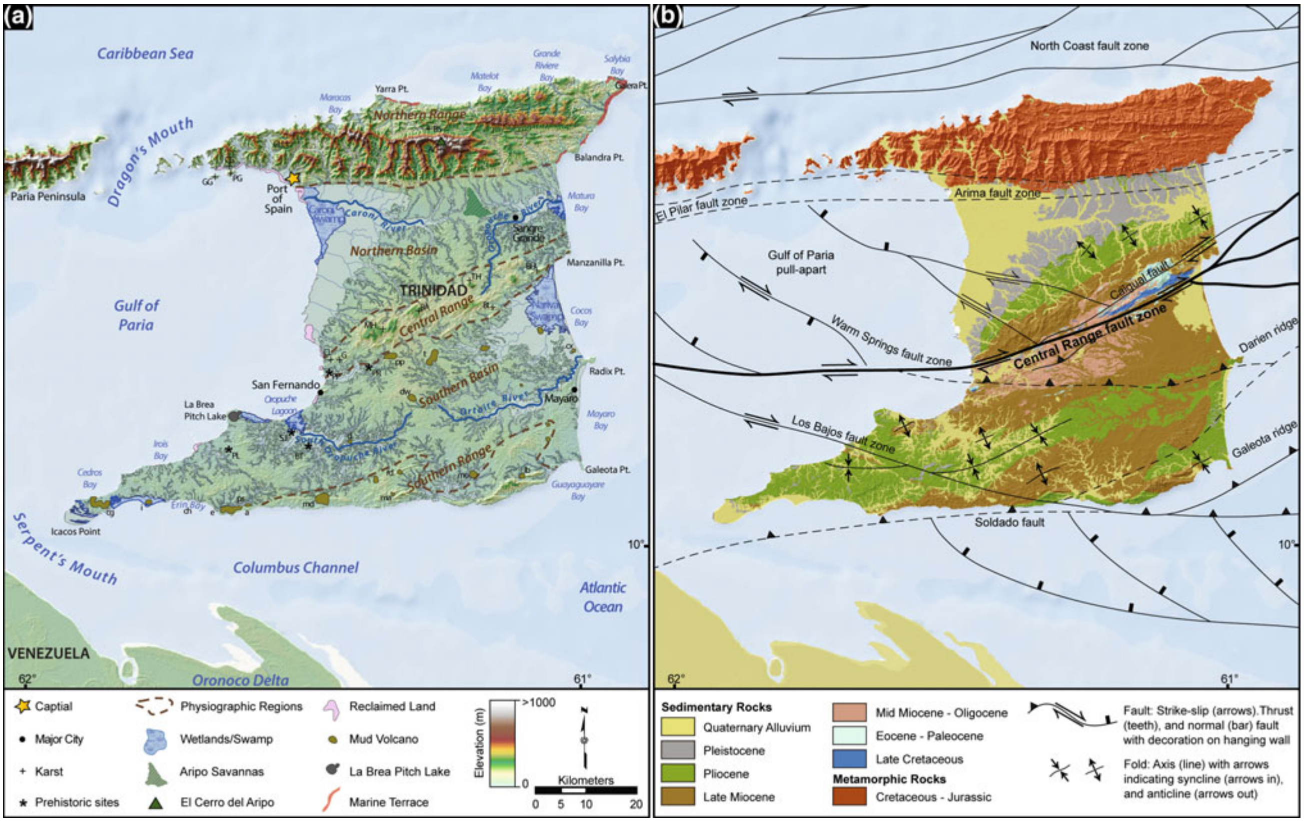

Fig. 17.3 Maps of Trinidad showing **a** the topography (30 m DEM from USGS Earth Explorer), the major highland (Northern, Central, and Southern Range) and lowland (Northern and Southern Basin) physiographic regions (*brown dashed lines*), trunk rivers (*bold blue lines*), and minor streams (*thin blue lines*), and **b** the geology. Approximate location of wetlands, swamps, lagoons, and reclaimed land are from the geologic map of de Verteuil et al. (2006). Prehistoric sites from Harris (1973): *PP* Pointe-a-Pierre; *PR* Poonah Road; *BT* Banwari Trace; *PL* Parrylands; *SJ* St. Johns. Mud volcanoes from Deville and Guerlais (2009) and Deville et al. (2003): *cg* Columbus group; *i* Islote; *ch* Chatham; *e* Erin; *ps* Palo Seco; *a* Anglais Point; *md* Morne Diablo; *ma* Marac; *rd* Rock Dome; *mo* Moruga; *lb* Lagon Bouffe; *d* Digity; *pp* Piparo; *dw* Devil's Woodyard; *t* Tabaquite; *cx* Cascadoux. Select karst outcrops from Erlich et al. (1993) and Day and Chenoweth (2004): *CL* Concord Limestone; *G* Gasparillo Limestone; *GL* Guaracara Limestone; *TL* Tabaquite Limestone; *TH* Tamana Hill; *BL* Biche Limestone; *BH* Brigand Hill; Hills; *C* Chaguaramas; *GG* Gaspar Grande; *PG* Point Gourde; *C* Cameron *AC* Aripo Cave; *BS* Brasso Seco; **b** Simplified geologic map of Trinidad modified from de Verteuil et al. (2006), Soto et al. (2007, 2011), and Prentice et al. (2010). Cartography by J.C. Arkle

Snoke 1993; Snoke et al. 2001). The Central Tobago fault system is offset by a series of younger oblique-slip faults that strike NNW (Snoke et al. 2001).

The deep meta-arc rocks of Tobago's Main Ridge are structurally sunken and covered by the Rockly Bay Formation and a coralline platform in the south (see Fig. 17.5). The clastic rocks of the Rockly Bay Formation were deposited during the middle Pliocene as a graben-fill sequence and are also likely a transgressive unit associated with concordant sea-level rise (Donovan 1989). The coralline limestone platform of southern Tobago formed during the Pleistocene and is well exposed in parts of the Tobago lowlands (Donovan and Jackson 2010). The Southern Tobago fault system and additional extensional faults cut and down-drop this limestone platform (Snoke et al. 2001; Donovan and Jackson 2010). Active extension continues today in south Tobago. The 1982 earthquake swarm and the 6.7 M_w 1997 Tobago earthquake are testaments to active extension (Weber et al. 2015a).

Trinidad's Northern Range is composed of metasedimentary rocks with Jurassic-Cretaceous protolith ages. These rocks are a continuation of the rocks exposed to the west in Venezuela's Paria Peninsula and Coasta de Cordillera. The Northern Range metasedimentary rocks were probably initially deposited along a north-facing South American passive margin during the Mesozoic (Algar and Pindell 1993). Miocene oblique collision of the Caribbean plate with the South American passive-margin, deformed, metamorphosed, and exhumed Northern Range bedrock and was synchronous with folding and thrusting in south Trinidad (Algar and Pindell 1993; Weber et al. 2001b; Cruz et al. 2007). The Caribbean-South American plate boundary

Fig. 17.4 View of the Northern Range, Trinidad from the north coast. Photograph by J.C. Arkle

stepped southward and changed to the current phase of transform plate motion at ~10 Ma (Pindell et al. 1998). The transition in plate motion from oblique collision to transform motion probably also marked the onset of low-magnitude, upper-plate collapse and extension that dominate the youngest tectonic features in and around Tobago (Snoke et al. 2001; Weber et al. 2015a).

In central and south Trinidad, the bedrock is sedimentary. The oldest exposed units are composed of Late Cretaceous passive-margin organic-rich marlstone (Erlich et al. 1993). The Paleogene-Early Neogene section was deposited in a distal foreland basin in front of the advancing Caribbean plate. Late Pliocene to Pleistocene sedimentary rocks in Trinidad were mostly deposited in the paleo-Orinoco delta system (Erlich et al. 1993). On the north flank of the Central Range, the Late Neogene-Pleistocene rocks were deposited after intense folding and thrusting of pre-Middle Miocene strata. This succession of rocks was then tilted to the north. In south Trinidad, folding and faulting, probably related to bends and steps in the transform system, continued into the Pleistocene.

Paleoclimate records from the Cariaco Basin in Venezuela show climatic shifts, most broadly, from a cold and dry period at the end of late Pleistocene into the Holocene (~11.5 ka) that transitions to a protracted warm and wet period until the middle Holocene (10.5–5.4 ka), and then a gradual shift to cooler and arid conditions throughout the late Holocene (~5.4–2.8 ka; Peterson et al. 2000; Haug et al. 2001). Quaternary temperature records for tropical South America are limited and regionally variable, but most studies indicate that temperatures were ~5 °C cooler than present in low-latitude areas of South America during global glacial stages (van der Hammen and Hooghiemstra 2000; Baker and Fritz 2015). Climatic transitions into cooler and arid periods likely caused rapid shifts between arid grassland and wet forest and shifts montane vegetation downslope (van der Hammen and Hooghiemstra 2000; Hughen et al. 2004).

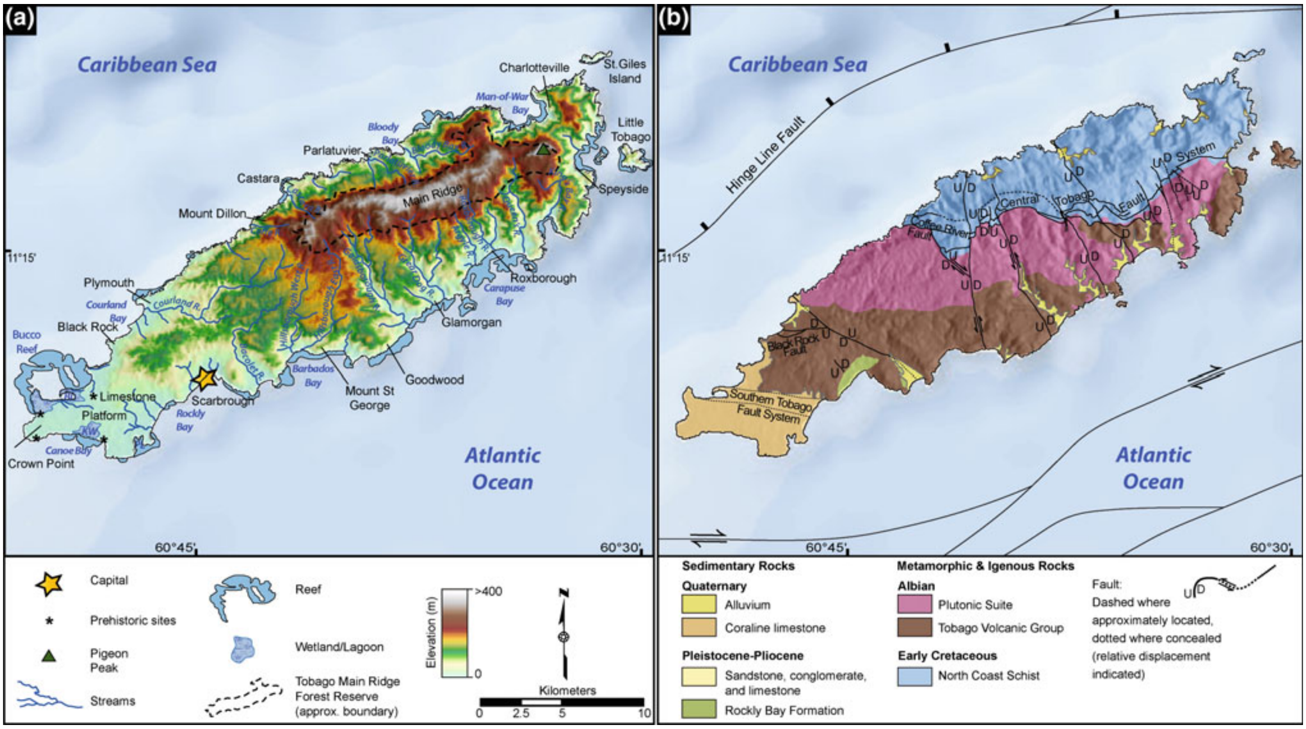

Fig. 17.5 Maps of Tobago showing **a** the topography (30 m DEM from USGS Earth Explorer), the Main Ridge Mountain highlands, the coralline limestone lowland, and major streams (*blue lines*), and **b** geology simplified from Snoke et al. (2001) and offshore faults from Garciacaro et al. (2011 and references therein). Reefs are from Hassanali (2013) and prehistoric sites from Steadman and Stokes (2002). Cartography by J.C. Arkle

Differential tectonic uplift in the region makes it extremely difficult to determine the absolute magnitudes of local sea-level fluctuations and the timing of when the islands were connected to mainland South America. However, if consistent with eustatic sea-level changes, the Caribbean may have been ~120 m lower than at present during the global last glacial maximum (e.g., Muhs et al. 2011, 2012). Trinidad, positioned aside the shallow (<30 m depth) Gulf of Paria, was likely connected to South America as recently as the Holocene, and Tobago was likely connected with the mainland during the Pleistocene (e.g., Boomert 2000).

17.3 Landforms

17.3.1 Tectonic Landforms

The large-scale (>10 km^2) landforms of Trinidad and Tobago reflect their complex tectonic and paleoclimatic history. The framework of Tobago's large-scale geomorphology is largely controlled by horst and graben structures. The island emerges as a structural high, as part of a series of regional extensional horst and graben blocks, positioned on the slightly stretched and extended southern edge of the Caribbean plate. The southern Tobago lowland lies over a down-dropped half-graben south of the South Tobago fault system, which also brings up the elevated horst block of the Main Ridge to the north. The Pleistocene limestone platform that forms the southern lowland is one of Tobago's most prominent sunken tectonic landforms. The seismically defined Southern Tobago fault system strikes eastwards across the platform, but is mostly buried and generally lacks surface expression (Snoke et al. 2001). Sea-level fluctuations and tectonic motion in southern Tobago have also generated numerous modern fringing reefs, which are more abundant and developed on the leeward side of the island, protected from severe weather tracks and sediment-laid ocean currents.

Past oblique-collision and active dextral Caribbean-South American plate deformation has created a suite of ENE striking bedrock structures that form the fundamental framework of Trinidad's large-scale geomorphology. This is highlighted by the occurrence of the alternating series of small topographic highs and low basins on the island (Fig. 17.1).

The geomorphology of Trinidad's Northern Range is dominantly controlled by neotectonic subsidence in the west and surface uplift in the east, in combination with a steep east-to-west gradient in rainfall (Weber 2005; Ritter and Weber 2007; Arkle et al. 2015). Eastern and western "blocks" of the Northern Range "split" at Yarra Point and are defined by an *en echelon* dextral break in the main

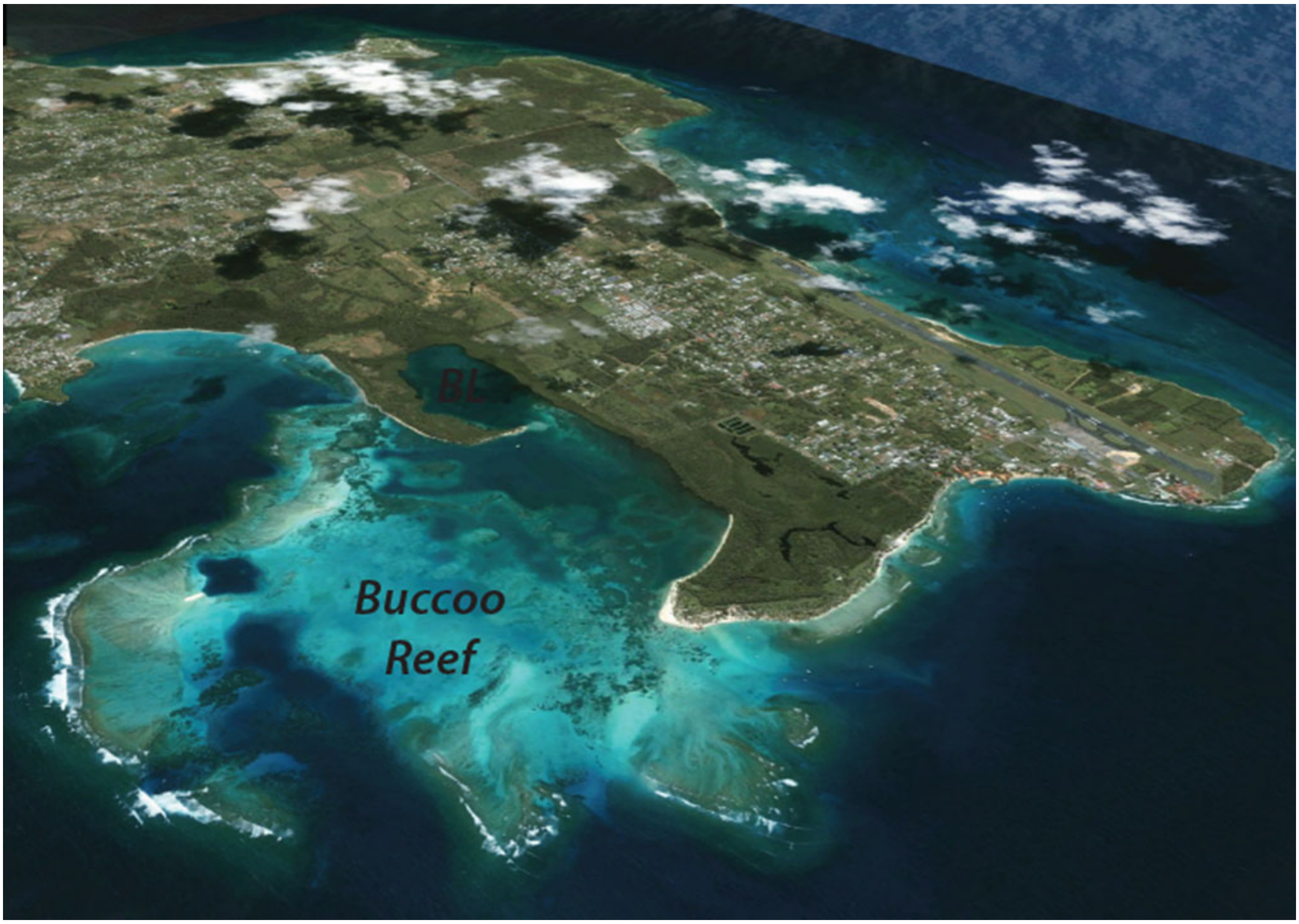

Fig. 17.6 Oblique areal view to the southeast of the coralline limestone raised reef and the relatively flat, low-lying topography of Tobago's southern lowlands. The foreground shows Buccoo Reef and the Bon Accord Lagoon (BL), Tobago's largest modern reef system and wetland. Photograph from Google Earth ca. December, 2004

ridgeline (N–S drainage divide; see Fig. 17.3). Geomorphic transitions include a relatively straight coastline punctuated by marine terraces in the east, to a highly scalloped and embayed coastline in the west, drowned island topography in the Gulf of Paria, and westward decreases of mountain front sinuosity and catchment outlet elevations. Alluvial fans bound the eastern mountain front, yet the correlative alluvial units in the west have subsided to depths over 100 m and are concealed by the Caroni Swamp (Weber 2005; Ritter and Weber 2007; Arkle et al. 2015). Quaternary erosion rates for catchments that drain the Northern Range are ~ 8 times greater in the east compared to those of the western catchments, reflecting both tectonic eastside-up tilting and high precipitation in the east (Arkle et al. 2015).

The Arima fault-line scarp bounds the southern flank of the Northern Range and defines a sharp transition from Trinidad's high-relief topography of the Northern Range to the Northern Basin (Algar and Pindell 1993; Weber et al. 2001b). Fault gouge is present along the Arima fault trace, yet there is no geomorphic or geodetic evidence of recent motion along this fault (Algar and Pindell 1993; Weber et al. 2001b). This suggests that it is probably an inactive exhumed fault with differential erosion of the relatively harder schist and quartzite to the north versus the softer slate to the south. The fault-line scarp strikes eastward and is exposed from the western offshore islands near Gaspar Grande, along the foothills of Port of Spain, and near the Village of Arima (Algar and Pindell 1993).

Southern and central Trinidad are characterized by a well-defined ENE structural and topographic grain, which is also parallel to the active Central Range fault zone. The contact between the weak shale-rich rocks of the Nariva Belt and more resistant Pliocene-Pleistocene Orinoco sand-rich deltaic rocks of the Southern Basin also forms a major eastward-trending escarpment (Fig. 17.7). This escarpment traverses the entire width of the island and from Point Radix in the east, continues offshore as the Darien Ridge, and is likely a fault-bounded contractile ridge. The Southern Range consists of a series of east striking *en echelon* ridges such as the Trinity and Cat's

Fig. 17.7 Low-relief hummocky hills of the Southern Basin, Trinidad. Photograph by J.C. Arkle

Hills. Collectively these features, both ancient and active, control the distribution and nature of Quaternary sedimentation, fluvial systems, coastline geometry, and endogenic landforms (e.g., mud volcanoes and asphalt seeps) in central and southern Trinidad.

The Central Range fault, the modern transform plate boundary, creates a major topographic lineament that strikes ~072° across the entire width of central Trinidad (Prentice et al. 2001, 2010; Weber et al. 2001a; see Fig. 17.3). Linear drainages and saddles and troughs are topographically aligned along the Central Range fault. Small, steep-sloped hills mark a series of shutter ridges that block and pond streams. Linear scarps striking NNE along the fault trace appear as subtle low-relief rolling bulges. Deflected ridges and streams that drain the hills across the fault trace have right-lateral offsets (Weber et al. 2001a; Crosby et al. 2009; Prentice et al. 2010). These landforms are subtle in the Central Range hills, probably due to the intense weathering and erosion of the soft shale-rich bedrock rock in Trinidad's tropical climate, as well as substantial modifications to the landscape due to agriculture, historically, mostly sugarcane cultivation (Crosby et al. 2009; Prentice et al. 2010).

Soto et al. (2007, 2011) used 3D seismic reflection data to map the submarine continuation of the Central Range fault eastwards for another 60 km into the offshore. They also map several other faults and structures, and a complex network of paleofluvial systems that are developed in the apron of young, shallow continental shelf sediments. Offsets along these paleofluvial channels provides long-term slip rate estimates of ~17–19 mm/yr along the Central Range fault offshore (Soto el al. 2007, 2011), which is consistent with the onshore geodetic estimates (Pérez et al. 2001; Weber et al. 2001a, 2011).

17.3.2 Mud Volcanoes and Related Landforms

Trinidad's most unique and transient landforms are generated by asphalt seeps and mud volcanoes, which are concentrated in southern Trinidad (Fig. 17.8). Related active hydrocarbon features are regionally widespread and extend over several hundred kilometers, from the Barbados accretionary wedge into Venezuela (e.g., Higgins and Saunders 1974; Babb and Mann 1999; Pindell et al. 1998). Active petroleum generation occurs offshore and onshore in southern Trinidad, resulting in oil and gas accumulations in complex faulted and folded structures (Babb and Mann 1999; Pindell et al. 1998). Onshore Trinidad, most mud volcanism is located in clay- and sand-rich folded sedimentary rocks. It is driven in part by active oil and gas generation at depth, with local temperature and pressure changes likely controlling the cyclic activity and eruptive style (Dia et al. 1999; Deville and Guerlais 2009).

Eruption styles of mud volcanoes in southern Trinidad range from slow, continuous expulsion, to punctuated, effusive catastrophic eruption, which creates an assortment of landforms (e.g., Higgins and Saunders 1974; Deville and Guerlais 2009). Fields of mud (tassiks) surround small, steep-sloped (>25°) cones and domes composed of stacked mudflows that reach over 150 m in height and span from a few cm up to 2 km in diameter (Higgins and Saunders 1974; Dia et al. 1999; Deville et al. 2003; Deville and Guerlais 2009). The surfaces of tassik fields solidify and desiccate into forms that include concentric and hexagonal shapes; some are capped by polygenic breccia with clasts that include quartz and sulfide pebbles (Higgins and Saunders 1974; Dia et al. 1999; Deville et al. 2003).

Mud pools and lakes are dynamic and range from a few cm up to several hundred meters in diameter. Lagon Bouffe, for example, expels mud continuously from several vents and forms large pools (>100 m wide) of fluid and viscous mud (Dia et al. 1999; Deville and Guerlais 2009; see Fig. 17.3). Mud pools can generate very smooth-textured "stemmed glass" surfaces, and convection processes in larger pools are associated with displaced mud flanked by ribbed, ring-shaped rolls (Higgins and Saunders 1974; Dia et al. 1999; Deville et al. 2003; Deville and Guerlais 2009). Some of these landforms are short-lived. For example, in 1964 the Chatham mud island located in Erin Bay along the Columbus Channel formed an ~8 m high by an ~0.1-km^2 island in just a few days. However, the mud island only lasted ~8 months above sea level as it became compacted and was quickly eroded to below sea level (Higgins and Saunders 1967).

Pitch Lake, a popular tourist destination in Trinidad (~20,000 annual visitors), is the largest natural active asphalt deposit in the world, spanning an area of >0.5 km^2 with an estimated depth of >75 m (UNESCO 2015; see Fig. 17.8). It is located on Trinidad's southwest peninsula, ~1 km from the coast, near the village of La Brea, and is elevated to ~85 m amsl, and is on the crest of an anticline of Neogene sedimentary rocks (Kugler 1959). Pitch Lake expels a mix of heavy oil, bitumen (asphalt), and water. In aerial view, this asphalt lake forms hexagonal surface textures, concentric ribbed and ringed rolls, and small mounds composed of brecciated rock. Convection cells generate meter-sized bulges and features analogous with spreading ridges, smoothed fissures, and mini-subduction zones.

Pitch Lake is recorded in Sir Walter Raleigh's ship's log as a source of pitch that was used for patching his damaged ships. Amerindian pottery and the partial remains of a prehistoric fauna are preserved in Pitch Lake (UNESCO 2015). Several asphalt streams shown on Kugler's (1959) geological map of Trinidad indicate that Pitch Lake used to flow freely into the Gulf of Paria. However, mining of the pitch has lowered the level of the "lake" and it no longer drains externally, and only minor traces of asphalt streams can be seen in the topography today.

17.3.3 Drainage Networks and Fluvial Landforms

Drainage networks and streams developed in Trinidad and Tobago are relatively small, and many are ephemeral. Flash flooding is common, especially during the wet season (July–December), and occurs as overbank channel floods and as sheetwash flow. Landslides, slumping, and severe erosion also occur frequently during wet season floods and form serious natural hazards (ODMP 2014).

In Tobago, surface runoff is limited mainly to ephemeral streams in the lowlands, as surface water quickly infiltrates this porous limestone platform (Lapointe et al. 2010). Streams that drain the leeward (NW) flank of the Main Ridge are short, with steep gradients compared to streams on the windward (SE) flank that have developed longer, more entrenched and comprehensive watersheds. The majority of the streams in the Main Ridge, including the Coffee, Hillsborough, Goldsborough, and Queens rivers, are developed along oblique-slip faults that strike NNW. The headwater regions of streams typically have bedrock channels that transition downstream, to boulder covered, and then to coarse-to-fine-grained alluvial channels. The resistant

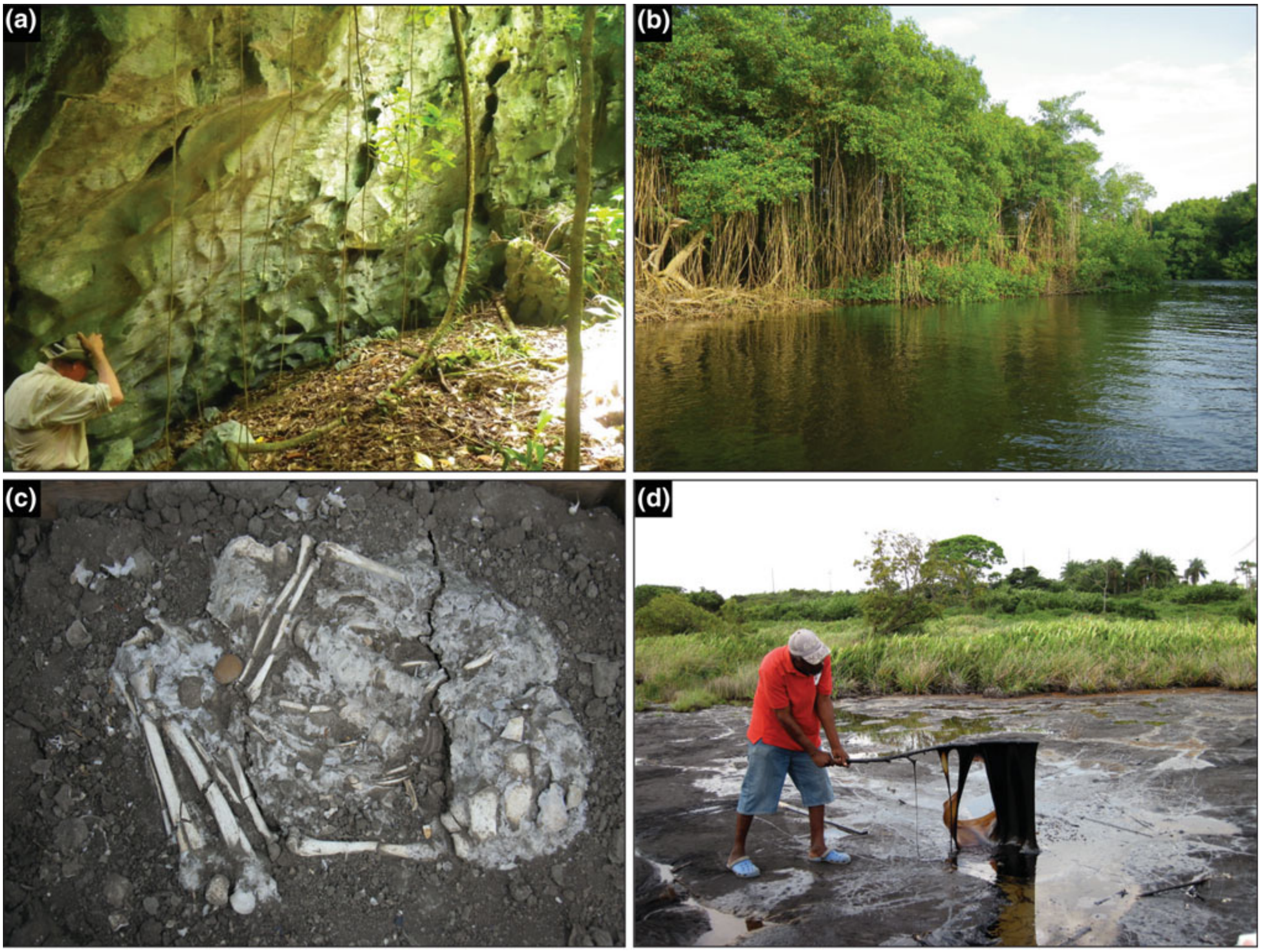

Fig. 17.8 Selected special features in Trinidad. **a** Karren dissolution developed on Cretaceous-Jurassic metalimestone bedrock exposed in a corridor of blocks (~10 m height) near the Aripo Cave in the Northern Range. Photograph by J.C. Arkle. **b** Mangrove wetlands in Caroni Swamp, the largest brackish water ecosystem in the country and habitat for the national bird, the scarlet ibis (Eudocimus ruber). Photograph by J.C. Arkle. **c** The Banwari skeleton, collected from a burial site in San Francique, southeast Trinidad, is estimated at 6000–8000 cal yr BP and is the oldest known archaeological site in the Caribbean. Photograph courtesy of the Department of Life Sciences, The University of the West Indies, St. Augustine. **d** Pitch Lake, the largest active asphalt deposit in the world, is located on Trinidad's southwest peninsula in the village of La Brea. A tour guide pulls viscous asphalt into the air with a stick to show tourists. Photograph by Dr. B. Crowley, University of Cincinnati

bedrock units form numerous stepped and hanging waterfalls and plunge pools, such as Argyle (Tobago's highest at ~55 m) and Twin Rivers (~30 m high) waterfalls (see Fig. 17.9), which commonly occur at major lithologic transitions.

Trinidad has four low-gradient truck rivers in the lowlands that generally flow along the axis of four major drainage basins; in the Southern Basin, the Ortoire and South Oropuche rivers, and the Caroni and North Oropuche rivers in the Northern Basin. These main truck rivers have broad, alluvial channels and small tightly spaced meanders. Low-gradient alluvial tributary streams drain the low-relief hills in central and southern Trinidad and dissect the soft shale-rich bedrock. Streams draining the north- and south-oriented catchments of the Northern Range are relatively evenly spaced and have numerous waterfalls and plunge pools. Stream channels on the east side of the mountains are V-shaped, and some have steep (>45°), narrow (<1 m) channels. Streams in western catchments have relatively flat, broad (>1 km) valley floors that cover the basement with over 100 m of sediment (Weber 2005; Ritter and Weber 2007; Arkle et al. 2015). Small river terraces (<20 m long) are present along several streams that drain the south flank of the Northern Range (Kugler 1959).

Holocene sea-level rise caused the islands' rivers to aggrade, and created and modified many of the coastal wetlands (Ramcharan 2004). During sea-level low stands, streams flowed through subaerial portions of the Gulf of

Fig. 17.9 Waterfall ($\sim$5 m high) in Castara River, northwest coast of Tobago, developed along NNW striking structures in the North Coast Schist. Photograph by J.C. Arkle

Paria. Trinidad's eastern coastline was $\sim$80 km east of the present shoreline during Pleistocene glacial stages (Warne et al. 2002). The morphology of the eastern offshore is characterized by a gradual eastward sloping continental shelf composed of crystalline basement with a cover of Cretaceous to Quaternary strata. The Quaternary sediment on the slope is incised by a deep and complex network of paleofluvial channels, with depths to channel bases of >100 m below modern sea level (Soto et al. 2007, 2011). East-directed paleofluvial systems there align with some of the modern drainages in eastern Trinidad (Soto et al. 2007, 2011).

The offshore paleofluvial systems may have been important conduits, in terms of the geobiological history of the modern fluvial networks in the Northern Range. Northern Range streams are habitat for the freshwater guppy (*Poecilia reticulata*), which, from an evolutionary perspective, is one of the most well-studied animal species on Earth (e.g., Alexander et al. 2006; Willing et al. 2010). Highly differentiated guppy populations in the Northern Range are concentrated on the north flank of mountains, and on the south flank in the Caroni River watershed and in the Oropuche River watershed (Alexander et al. 2006). The west-flowing Caroni and east-flowing Oropuche Rivers are separated by a major but subtle drainage divide that overlies the Guatapajaro Anticline in the Northern Basin (see Fig. 17.3). Phylogenetic and morphological analyses indicate that the Caroni network guppies are closely related to Venezuelan populations to the west of Trinidad, whereas their Oropuche neighbors share features with populations to the south of Trinidad and in eastern Venezuela and Guyana (Alexander et al. 2006; Willing et al. 2010). Weber et al. (2015b) postulated that, in addition to distal fluvial connections during sea-level low stands, range-wide eastside-up tilting during the Quaternary may have contributed to partial and progressive replacement of guppy stocks in the Northern Range streams. One possibility is that as northern Trinidad was tilted, the Guatapajaro divide may have acted like a rolling hinge, where streams were captured and added to either the Caroni network, with eastern hinge roll, or the Oropuche network, with western hinge roll, which would have then separated the two stocks of guppies (Weber et al. 2015b).

17.3.4 Alluvial Fans

Alluvial fans are not well developed on Tobago, and alluvial deposits are concentrated mainly along streams draining the Main Ridge, such as the Courland River. In contrast, impressive alluvial fan complexes are present in northern Trinidad, particularly along the southern mountain front of the Northern Range (see Fig. 17.3). The alluvial fan deposits are only exposed along the eastern mountain front and have been mapped recently as the Valencia gravels (e.g., de Verteuil et al. 2006). The Valencia gravels were initially mapped as the Pleistocene Cedros Formation on Kugler's (1959) geologic map, which is a type section in southern Trinidad of sediment that was interpreted to have been deposited by the Orinoco River. However, the vein-quartz-pebble gravels and clean quartz sands clearly indicate that the Valencia alluvium was derived from the Northern Range. In the western Northern Basin, range front alluvial fans that correlate with those in the east have subsided to depths over 100 m and are covered by the Caroni Swamp and swamp sediment. These deposits are well known as "the Northern gravels" and are a very important source of groundwater in and around Port of Spain (Weber et al. 2011).

The northern alluvial fans are highly dissected by modern streams and tributaries that flow southward out of the Northern Range. These alluvial fans consist of multiple lobes with abandoned elevated terrace surfaces. Alluvial fan deposits are broad relative to the contributing upstream catchments (see Fig. 17.3). South-flowing streams from the Northern Range deeply entrench the alluvial fans, and modern deposition is focused along the alluvial fan toes. Fan-head entrenchment likely results from a combination of dynamic climatic and tectonic interactions including a reduction of the magnitude and rate of Northern Range erosion during Holocene warming, sea-level rise, and neotectonic uplift of the eastern Northern Range (Weber 2005; Arkle et al. 2015).

17.3.5 Wetlands

Trinidad and Tobago contain a variety of coastal and inland wetlands including swamps, bogs, marshes, and lagoons (see Figs. 17.3 and 17.5). In Trinidad, the majority of wetlands occur along the coastlines, such as the Los Blanquizales Lagoon and Rousillac Swamp, whereas other small wetlands have developed along streams, such as the North and South Oropuche lagoons. The majority of wetlands in Tobago are developed along coastal outlets of streams that drain the Main Ridge such as in Bloody Bay and Lucy Vale in Speyside and are protected by ephemeral barrier beaches. Wetlands located on Tobago's southern limestone lowlands include the Kilgwyn and Little Rockly Bay wetlands, and the Petit Trou Lagoon.

Bon Accord Lagoon is the largest wetland in Tobago covering an area of ~ 1 km^2 and is bound by the Buccoo Reef along the southwest coast (Laydoo 1991; see Figs. 17.5 and 17.6). Biologically, the lagoon supports sea grass, dominantly turtle grass (*Thalassia testudinum*), and is fringed by several species of mangrove (Kenny 1976). Freshwater exchange occurs through small perennial streams and by groundwater transport through the porous limestone (Lapointe et al. 2010). Inflowing water, however, carries pollutants from the developed lowlands, including those from several sewage treatment plants, which put the water quality and ecological health of the lagoon and Buccoo Reef at risk (Lapointe et al. 2010).

The Caroni Swamp in Trinidad is the largest brackish water ecosystem in the country, covering an area of >55 km^2, and is characterized biologically as an herbaceous and mangrove forest wetland (Gibbes et al. 2009; see Fig. 17.8). The Caroni Swamp is a coastal wetland located in the western Northern Basin and is fed by the Caroni River and several streams that drain from the Northern and Central ranges. Tidal exchange occurs over the low-lying topography along the western coast, which is associated with tectonic extension and subsidence in the Gulf of Paria. Local communities harvest fish, crabs, and oysters, as well as other fauna and flora, and the swamp is a popular ecotourism destination due, in part, to its proximal location to Port of Spain. The areas around and within the swamp boundaries have been intensely modified and developed into agricultural and urban land (Gibbes et al. 2009). In addition, land along the northern edge of the swamp has been altered and polluted by Trinidad's large Beetham Landfill.

The Nariva Swamp in Trinidad is the country's largest freshwater wetland, covering an area of >62 km^2 (Gibbes et al. 2009). The swamp is located along the east coast and is bound to the north by the Central Range and to the south by the Darrien Ridge escarpment. The Nariva Swamp and the majority (90%) of coastline along this stretch is, on average, <2 m amsl (Ramcharan 2004). Radiocarbon ages and fossil pollen show a varied vegetation history and that the wetland has existed since at least 6 ka (Ramcharan 2004). The Nariva River drains the swamp, which flows in a shore-parallel depression, bound by the Manzanilla barrier beach and subsidiary sandbars. The Manzanilla barrier beach protects the wetland from high-energy Atlantic waves and assists in regulating salinity levels in the swamp (Gibbes et al. 2009).

Freshwater lakes are limited to artificially constructed reservoirs, such as the Hollis, Navet, and Arena reservoirs in Trinidad, and the Hillsborough Reservoir in Tobago (WASA 2015). The nation's wetlands, both natural and constructed, serve as important ecological habitats for biota including the national bird, the scarlet ibis (*Eudocimus ruber* common to the Caroni Swamp), and the West Indian manatee (*Trichechus manatus* present in the Nariva Swamp), among many others (WASA 2015). Communities around these wetland areas are dependent on their resources.

17.3.6 Coastlines and Coastal Landforms

17.3.6.1 Shorelines and Coastlines

The coastal regions of Trinidad and Tobago vary from the high-energy, windward coasts bordering the Atlantic Ocean to the relatively protected leeward coasts bordering the Caribbean Sea and Gulf of Paria.

Tobago's windward SE coast, bordering the Atlantic, consists of numerous large bays and beaches. In the SW, the coastline along the limestone platform consists of elevated wave-cut cliffs that contain small sea caves and are punctuated by beaches composed of coarse-grained carbonate sand. The central and northern portions of the SE coast consist of large arcuate bays where the resistant oceanic-arc bedrock crops out along the shorelines. Numerous sea arches and sea stacks have formed in the rocky headlands, as well as fringing reefs (see Figs. 17.5 and 17.10).

Although wave and wind action are less intense along Tobago's leeward NW coast, the bathymetry and onshore topography steepen to the NE. Thus, the north and central stretch of this coastline is rocky with steep sea cliffs and hillslopes and consists of intermittent beaches formed in small embayments. Some barrier beaches, baymouth bars, and lagoons occur along stream outlets that drain the Main Ridge, such as those at Bloody Bay. To the south, the continental shelf is shallow and supports numerous, large fringing reefs such as the Buccoo Reef (Fig. 17.6). This segment of coastline consists of long beaches and bays with prominent headlands including Crown Point, Pigeon Point, Mt. Irvine, Black Rock, and Plymouth (from south to north).

Trinidad's Northern Range rises from the Caribbean Sea to form a rugged northern coastline, which is shaped by its bedrock geology and high-energy wave and wind action (see Fig. 17.4). Yarra Point marks a significant transition in coastal morphology, from a highly embayed, drowned coastline in the west, to a semi-linear, elevated coastline in the east; this transition is controlled by Quaternary eastside-up tilting of northern Trinidad (Weber 2005; Arkle et al. 2015). To the east of Yarra Point, steep sea cliffs, marine terraces, rocky headlands, and occasional sea stacks characterize the coastline. Subsidence to the west of Yarra Point, has led to the capture of watersheds by the sea and has left drainage divides and their flanks elevated at or near sea level, where small beaches bound by semi-circular bays have developed, such as Maracas Bay (Weber 2005). Sandbars, beach berms, and barrier beaches are present to both the west and east of Yarra Point. Back-bay areas that contain localized brackish tidal channels, isolated wetlands, and lagoons, including the Maracas Swamp and Madamas Lagoon (see Figs. 17.3 and 17.11), are critical for protection of the delicate wetland biota in the northern bays.

The eastern Atlantic coastline of Trinidad has the longest and straightest beaches on the island, namely Matura, Manzanilla, and Mayaro beaches. Manzanilla Beach is an impressive ~20-km-long barrier beach composed of fine sand and silt across which small ephemeral streams drain (Fig. 17.3). The beaches, sandbars, and shoreline along the east coast are maintained by sediment brought by the Guiana Current (Darsan et al. 2013). However, human-induced erosion from agriculture and recreation has caused severe coastal erosion. Manzanilla Beach may also likely be undergoing severe and rapid retreat due to sea-level rise (e.g., Bedell et al. 1997).

Trinidad's southern coast consists of sea cliffs, beaches, and small wetlands. This coastline is bordered in the east by the Trinity Hills of the Southern Range that rise to 325 m amsl, by low coastal plains in the west, and by the Columbus Channel to the south. The Columbus Channel is a shallow (maximum depth of ~55 m) and narrow waterway that separates Trinidad from mainland South America—by only ~14 km at Icacos Point (see Fig. 17.2). The west-directed Guiana Current flows through the Columbus Channel and has created narrow asymmetric beaches that contain abundant silt and nutrients transported from the Orinoco and Amazon rivers (Darsan et al. 2012). Beach erosion and hillslope failures are severe along the southern coastline due to strong the currents and weakly consolidated sedimentary bedrock (Darsan et al. 2012; Darsan and Alexis 2014).

Trinidad's west coast borders the Gulf of Paria, a large extensional pull-apart basin where submerged and buried normal faults connect the El Pilar and Central Range transform faults (Flinch et al. 1999; Babb and Mann 1999). Tectonic extension results in surface subsidence along the west coast. This creates drowned islands and rocky embayments in the north, mudflats and mangroves along the central-west coast, and low-lying beaches and cliffs in the south (Darsan et al. 2012). The Gulf of Paria is a major depocenter of Orinoco River-derived sediment, with very shallow water depths that, aside from the deep inlets and outlets, reaches to only ~30 m below mean sea level (Van Andel and Sachs 1964). Although the Gulf of Paria is a major depocenter, coastal erosion is a severe problem for

Fig. 17.10 Rocky headlands along the northeast Atlantic coast of Tobago south of Speyside, showing a sea arch and sea stacks. Photograph by J.C. Arkle

many of the shorelines along this stretch of coast (Darsan et al. 2012; Darsan and Alexis 2014).

17.3.6.2 Marine Terraces

Marine terraces are present in both Trinidad and Tobago. The Pleistocene coralline raised reef of southern Tobago's lowlands is exposed over an area of >27 km^2 and has an average thickness of 12 m (Wadge and Hudson 1986; see Fig. 17.6). The dominant fauna are benthic mollusks and hermatypic corals, which are nicely preserved in many areas (Trechmann 1934; Maxwell 1948). This fossil reef formed over the oceanic-arc and forearc bedrock of Tobago in a structurally low, down-dropped half-graben, likely during the last interglacial (Wadge and Hudson 1986; Snoke et al. 2001; Donovan and Jackson 2010). Subsequent uplift and tilting has exposed the reef platform to heights of up to ~10 m amsl along the SSW coast and up to ~30 m amsl in the NE (Donovan and Jackson 2010). The sharp unconformity between the underlying Mesozoic bedrock and the overlying coral limestone is apparent in coastal outcrops at Back Bay to the north of Plymouth (Donovan and Jackson 2010).

In Trinidad, marine terraces occur both as single platforms and as multiple terrace flights that punctuate the emergent NE coastline. Marine terraces are intermittently exposed between Yarra and Galera points and then southward to near Balandra Point at elevations from a few up to ~45 m amsl (Kugler 1959; Barr 1963). Most of the marine terraces consist of an eroded metamorphic strath surface with an overlying cover of unconsolidated quartz-rich, sand- to gravel-sized sediment that generally lacks any carbonate marine fossil debris. The terraces are all mapped as Pleistocene (Kugler 1959; Barr 1963), but recent OSL dating on quartz-rich sands and gravels indicates some may be as young as the late Holocene (Arkle et al. 2015). At least four flights of marine terraces are present and well preserved near

Fig. 17.11 Barrier beach berm, and lagoon of the Madamas River outlet along the north coast of Trinidad. Photograph by J.C. Arkle

the villages of Blanchisseuse and Yarra, but dense vegetation and tropical weathering have degraded and perhaps concealed the continuation of well-defined terrace flights along this coastline. In contrast, at some localities such as Tompire Bay, along the NE coast, a marine terrace is nearly continuously exposed for over 0.5 km at elevation ~20 m amsl (see Fig. 17.12).

17.3.6.3 Reefs

Reefs are abundant around Tobago, but are limited in Trinidad due to the high sediment load derived from the Orinoco and Amazon Rivers and, where present, tend to be dominated by sediment-tolerant species (Bouchon et al. 2008; Kenny 2008). Trinidad's only extensive coral reef is located along the NE coast and forms a flat, broad reef platform that extends ~100 m offshore from Salybia Beach. Reef growth in Salybia Bay is enhanced by its connection with the Caribbean Sea and its protected location (Kenny 2008). Salybia Beach is Trinidad's only white sand beach, composed of broken branching coral and other primary reef-dwelling carbonate fragments.

Tobago is flanked by numerous active patch and fringing reefs that stretch for >90 km around its coastline (nearly 50% of Tobago's coastline) (Laydoo 1991; Kenny 2008; see Fig. 17.5). Tobago's NW coastline, along the Caribbean Sea, is largely protected from the NE weather tracks and high-energy waves and has a higher diversity of coral species than on the Atlantic side of the island (Bouchon et al. 2008). Reefs on the Caribbean coasts support coral-gorgonian communities, whereas macro-algae and sponges dominate on the Atlantic coasts (Bouchon et al. 2008). Fringing reefs also occur along many of Tobago's satellite islands and are particularly abundant along Sisters Rocks, Little Tobago, and Saint Giles Islands.

Buccoo Reef is the largest modern reef system and covers an area of >7 km^2 extending seaward from between Booby

Fig. 17.12 Marine terrace, a metamorphic strath surface with an overlying cover of unconsolidated sand-gravel raised about 30 m amsl, located at Tompire Beach along the northeast coast of Trinidad. Photographs by J.C. Arkle

Point and Pigeon Point in SW Tobago (see Fig. 17.6; Laydoo 1991; Kenny 2008). Freshwater streams enter the reef at Buccoo Bay and in the Bon Accord Lagoon. Buccoo Reef is arcuate and consists of numerous emergent reef flats, which are structurally continuous but fragmented and covered by sediment in places (Laydoo 1991; Kenny 2008). Buccoo Reef Marine Park was established in 1973 as a designated protected marine area. The reef attracts tens of thousands of visitors per year, and this together with urban development and industrial activities in the southern lowlands has caused severe damage, erosion, and alteration to the reef (Laydoo 1991; Hassanali 2013).

17.3.7 Karstlands and Karst Landforms

Trinidad and Tobago have an impressive variety of karst landforms and landscapes, although these are fairly limited in area (Day and Chenoweth 2004). According to Day and Chenoweth (2004), limestone outcrops represent only $\sim$1.6% of Trinidad's and $\sim$8.1% of Tobago's land areas, with most karst located in Trinidad's Northern and Central ranges and in Tobago's southwestern lowlands.

Karst is present only in the coralline limestone platform of the southern lowlands in Tobago (see Figs. 17.5 and 17.13). Rugged and pitted dissolution surfaces are present where the limestone is devoid of vegetation and soil, particularly along the southern coastline. Dry valley systems, $\leq$16 m wide, $\leq$1 km long, and $\leq$2 m deep, are present on the relatively flat carbonate platform. Dolines also occur across the platform surface and are usually $\sim$5 m in diameter and <2 m deep (Day and Chenoweth 2004). Several small caves are formed in the sea cliffs along the south coast including Robinson Crusoe Cave (Eshelman and Grady 1990). Narrow openings generally impede access to these caves, but the subterranean cave system is likely fairly

Fig. 17.13 Karst and collapse features developed in the Late Pleistocene coralline limestone near the Robinson Crusoe cave along the south coast of Tobago. Photograph by J.C. Arkle

extensive with complex networks of tunnels and subcaverns (Eshelman and Grady 1990; Day and Chenoweth 2004).

Karst features are present throughout central Trinidad and are developed mainly in the Miocene limestones, particularly in the Tamana Formation, which crops out in the Central Range (Kugler 1959; Erlich et al. 1993; Day and Chenoweth 2004; see Fig. 17.3). The limestone bedrock is exposed as resistant topographic highs, distinct from their softer bounding sedimentary rocks, in a series of northeast trending hills, e.g., the Tamana, Biche, Bassin, and Brigand hills. Ephemeral streams, springs, and dolines are present in the Tamana and Brigand hills (Day and Chenoweth 2004). An impressive cave system on the north flank of Tamana Hill consists of the Tamana Main (>130 m long) and Tamana Dry (∼50 m long) caves (Darlington 1993). The cave consists of several large walk-in chambers, throats, and chimneys, and narrow crawl shafts. The Tamana Main chamber is floored by a small northward-flowing stream that drains beyond the generally accessible passage into the "Far Deep" (Darlington 1993). A variety of depositional and dissolution speleothems occur in this wet and humid cave, including fluted stalactites and flowstone. The Tamana cave system also harbors a significant ecosystem, including ∼11 species of bats with a population that can exceed 1.5 million (Goodwin and Greenhall 1961).

The most extensive karst and cave systems in Trinidad are developed within the metacarbonate bedrock (Cretaceous to Jurassic protolith ages; Cenozoic metamorphic ages) of the Northern Range and in the western offshore islands (Shaw 1993; Day and Chenoweth 2004; see Fig. 17.8). Development of karren is abundant on uncovered surfaces and dolines, and associated ephemeral springs are common. The largest known cave system in Trinidad, the Aripo Main Cave, is >860 m long, and is located south of El Cerro del Aripo peak at an altitude of ∼800 m amsl (Shaw 1993; see Fig. 17.3). The cave walls and ceiling are lined with intricate and colorful flowstone and speleothems that are generally bulky and include coned stalagmites, large, rounded stalactites, and ribbed columns.

Small vegas, flat-floored intermountain valleys, similar to poljes in karst nomenclature (e.g., Ford and Williams 2007) are scattered throughout the Northern Range. These intermountain valleys are consistently located where metacarbonate layers have been mapped and identified in hillslopes and stream channels (see Fig. 17.3). Some of these vega regions were developed into prolific cocoa plantations during colonial times because of their rich soils and originally tall, dense forest cover and cool, damp microclimates. Segments of metacarbonate stream channels also form small gorges, some of which are lined with tufa, and many of which form several lithologically controlled knickpoints or waterfalls with associated plunge pools such as the 20-m-high Sobo Falls near Brasso Seco.

Day and Chenoweth (2004) identify an area of >6 km^2 of polygonal cockpit karst in Cameron, a block of hills at ~350 m located between Maraval and Petit valleys (see Fig. 17.3). They describe cockpit depressions that reach diameters of 100 m and are generally 15–20 m deep, bound by moderately steep hillslopes (~25°) and serrated ridges. Day and Chenoweth (2004) describe similar features on Paramin Hill, a region famous for the cultivation of culinary herbs, which is located between Maraval village and Maracas Bay. The Cameron karstscape is drained by a star-shaped centripetal drainage system formed along the hillslopes and is perhaps internally drained through concealed cave systems (Day and Chenoweth 2004).

The western offshore islands are composed of the Cretaceous Laventille limestone that contains abundant karst and caves, which are situated both below (drown caves) and above sea level, including the popular Gasparee Cave (Shaw 1993). Caves in northern Trinidad are of great ecologic importance as they harbor unique fauna such as the oilbird (*Steatornia caripensis*; Day and Mueller 2004), blind catfish (*Caecorhamdia urichi*; Shaw 1993), and numerous species of bats (Goodwin and Greenhall 1961).

17.4 Landscape

17.4.1 First Human Interactions with the Landscapes

Trinidad and Tobago have a protracted history of settlement and the longest documented human interactions with landscapes in the West Indies (e.g., Boomert 2000; Siegel et al. 2015). Trinidad has the oldest documented archaeological sites in the West Indies, Banwari Trace, and St. John, which date the earliest people (Amerindians) on the island to ~8 ka (Harris 1973; Boomert 2000; Pagán-Jiménez et al. 2015; see Fig. 17.8). (Note: archaeological ages reported have been calibrated to calendar years.) Archaeological evidence from Tobago indicates earliest occupation of Amerindians before ~5.2 ka, which currently postdates the occupation ages on other West Indies islands farther to the north such as Grenada (~5.6 ka; Siegel et al. 2015).

Trinidad is considered the "first step" on the path of initial human migration and diffusion out of mainland South America into the West Indies (Boomert 2000, 2002; Wilson 2007). This view is based on the Banwari Trace and Trinidad's proximity to the South American mainland, their intermittent connections during sea-level low stands, as well as navigational ease, and resource availability. Although the exact timing and location of a land bridge(s) between mainland South America to Trinidad and Tobago is not known, Trinidad's last mainland connection was likely during the early Holocene and Tobago's most recent connection may have been during the Pleistocene (Boomert 2000). The Gulf of Paria likely did not exist, and Trinidad was connected with the mainland during the global last glacial maximum, while Tobago was likely connected to Trinidad along the NNE coast (Boomert 2000).

Waterways were likely critical for the Amerindians (Boomert 2000, 2009). Boomert (2009) suggests that coastal routes were generally more favored than overland travel routes and interisland migration and trade routes were likely assisted along stream networks, lagoons, and wetlands. Thick tropical vegetation and the Northern Range and Cordillera de la Costa likely formed significant barriers to early human interisland migration and interaction (Boomert 2009; see Fig. 17.2). Early people in central and southern Trinidad interacted most intensely with those in bordering regions of mainland South America, whereas early people that settled along Trinidad's north coast were aligned more closely with other maritime occupants along the Venezuelan coast, Tobago, and the southern islands of the Lesser Antilles (Boomert 2000, 2002, 2009). Throughout early occupation, waterways facilitated Trinidad's development into an important center of cultural exchange and communication (Boomert 2000, 2013; Wilson 2007).

Trinidad and Tobago offered varied geologic and biotic natural resources for Amerindians. Stone artifacts recovered from Amerindian sites on the two islands include intricate ornamental artifacts carved from the islands' different lithologies, and the hard bedrock from Tobago was particularly valuable for cutting tools (Boomert 2000, 2009, 2013). Trinidad and Tobago's intermittent connections and proximity to the mainland also influenced their unique terrestrial biota, which are primarily of continental origin, similar to that of nearby South America (Kenny 2008). The species richness was likely advantageous for the initial occupants providing opportunistic foraging, collecting, fishing, and hunting, including the widespread availability of large game (Steadman and Stokes 2002; Boomert 2013; Siegel et al. 2015).

Paleoenvironmental evidence from Nariva Swamp indicates that the Amerindians used fire to manage and maintain habitats (Siegel et al. 2015). Pagán-Jiménez et al. (2015) identified numerous cultivar and wild taxa from starch grains on stone artifacts collected at the St. John Archaeology Site (see Fig. 17.3). These authors suggest that Trinidad's early occupants (~7.7 ka) perhaps transported domesticated and wild plant species from mainland South America. Collectively, these findings offer a significant insight into human interactions with the landscape, as highlighted by Siegal et al.'s (2015) submission that the earliest-known occupants of Trinidad were modifying, creating, and managing the landscape roughly 8 ka.

17.4.2 Landscapes Transformed: Colonization to the Twenty-first Century

In 1498, on his third voyage, Christopher Columbus sighted the Trinity Hills in the Southern Range, landed on Trinidad, and claimed the island as a Spanish colony. This "ownership" lasted until 1797 when Trinidad was claimed as a British colony. Tobago, a western spelling of the Amerindian word for tobacco, was fought over by the Spanish, British, French, and Dutch because of its strategic position and fertile land, until 1889 when both Trinidad and Tobago became a British territory. Upon the arrival of Europeans, the Amerindian populations of Trinidad and Tobago were very quickly reduced. The natural vegetation and landscapes of Trinidad and Tobago were transformed by agriculture and plantation-style farming throughout the sixteenth–nineteenth centuries. Trinidad and Tobago developed slave and indentured servant populations during this period. Large areas of Trinidad and Tobago's landscapes were cultivated for tobacco, cacao, and sugarcane (Newson 1976).

Development and proliferation of the country's hydrocarbon industry that quickly followed the drilling of Trinidad's first oil well in 1857 brought significant and irreversible changes to Trinidad and Tobago's landscapes (Higgins 1996). Oil extracted from Trinidad constituted ~40% of the British Empire's total oil production by 1930 (Dillman 2015). In 1962, Trinidad and Tobago gained independence from the British Empire and then became a republic in 1976. The two-island nation is now the leading producer of oil and gas in the Caribbean, which comprised ~45% of their GDP in 2012 (Ministry of Energy and Energy Industries 2015). Although, the agricultural economy has declined during the twentieth–twenty-first centuries, cultivation of Trinidad and Tobago's lands including dredging and modification of wetlands, river channels, and other ecologically sensitive areas has caused significant landscape changes. Extensive limestone quarrying has significantly modified some of the karst terrains such as in the Laventille and Montserrate hills. The diverse landscapes of Trinidad and Tobago have been a great asset and have helped directed the trajectory of people there for roughly 8000 years.

17.5 Heritage and Tourism

17.5.1 Heritage Tourism

Trinidad and Tobago have a diverse and rich cultural blend of people, locally called a "callaloo," that includes Amerindian, Spanish, French, English, African, Indian, Chinese, Syrian, and Lebanese influences. Heritage tourism is an emerging focus for both islands. Tourism contributes only ~4% annually to the economic output (TDC 2015) and employs only ~10.4% of the labor force. Of all Caribbean overnight visitor arrivals in 2011, Trinidad and Tobago had ~400,000 visitors representing only ~2% of Caribbean tourism (TDC 2015). The Government of Trinidad and Tobago recognize the potential and positive economic impacts that tourism could have and has an active policy of encouraging the growth of the tourism trade (Wall and Ali 1977; TDC 2015). With the hydrocarbon industry's dominance in Trinidad, tourism on the island is promoted for its heritage activities, including major annual events such as Carnival, whereas Tobago is better positioned to become a typical "sun, sea, and sand" island of leisure like many of the other Caribbean islands (TDC 2015).

Trinidad and Tobago's heritage sites and historic landmarks include the karat-roofed leepay homes of indentured servants, sugar and cocoa sheds, the barrack houses of slaves, urban chattel houses, the great houses of the Port of Spain Savannah, various estates (plantations), and historic churches, mosques, and temples (Jordan 2013). These historic landmarks, however, are overshadowed by Trinidad's annual Carnival that is celebrated before Ash Wednesday, typically in February or March. The Carnival is responsible for the largest influx of tourists, over ~40,000 annually, which come from around the world (TDC 2015). The Carnival dates to the eighteenth century and showcases the island's heritage through traditional music, dance, and food, and two major street parties—J'Ouvert ("I arise"), a "dirty" mud and cocoa butter nighttime masquerade, which is followed by the daytime "pretty" masquerade. While this event takes over nearly the whole of Port of Spain, it (particularly the "pretty" masquerade) is centered on the Queen's Park Savannah, which is the largest (>1 km^2) public space in Trinidad, and the oldest recreation ground (165 years old) in the West Indies (Jordan 2013). The large number of visitors during this roughly weeklong celebration has lead to tremendous pollution problems in the city and surrounding areas, and it is taxing on the country's natural resources. The need for infrastructure to support such an event, as well as the rapidly growing urban population, has lead to significant changes of the landscape, particularly in the form of hasty development and expansion, particularly in and around Port of Spain (Wall and Ali 1977).

17.5.2 Ecotourism

The natural landscapes of Trinidad and Tobago have the potential for becoming a major destination for ecotourism, particularly because it is one of the most unique and species-rich nations in the region (Kenny 2008; TDC 2015). Notably, the Trinidad and Tobago National Commission was successful in having three sites added to UNESCO's World Heritage Tentative Listing in 2011. These included the Banwari Trace Archaeological Site (cultural), La Brea Pitch Lake (natural), and the Tobago Main Ridge Forest Reserve (mixed) (Jordan 2013; UNESCO 2015).

Trinidad and Tobago's rainforests, habitat to unique biota of continental origin, are popular ecotourism destinations (UNESCO 2015). The Main Ridge Forest Reserve on Tobago encompasses nearly 40 km^2 of mountainous rainforest and is the oldest (since 1776) piece of protected land and forest reserve in the Western Hemisphere (UNESCO 2015). Trinidad's Northern Range includes significant biopreservation sites such as the Asa Wright Nature Reserve (www.asawright.org) that contains over 2200 flowering plant species, 97 native mammals, 400 birds, 55 reptiles, 25 amphibians, and 617 butterflies. Impacts of tourism on Trinidad and Tobago' rainforests have not been quantified. However, undisturbed rainforest in Trinidad's Northern Range has been reduced to isolated patches due to piecemeal degradation related to urbanization, agriculture, mining, and timber production (Day and Chenoweth 2004).

Snorkeling and scuba diving are popular tourist activities, concentrated mainly in Tobago along the southwest coast and around its northeastern satellite islands. The Buccoo Reef Marine Park was designated as a marine protected area in 1973; it has also been a Ramsar Site (see http://www.ramsar.org/) since 2005, and the Buccoo Reef Trust and the University of the West Indies started monitoring at Buccoo Reef Marine Park in 2007 (Laydoo 1991). However, local communities are very dependent on tourism, and thus, land on the nearby limestone platform has been developed for tourist accommodations and corals have been harvested for tourist souvenirs (Wall and Ali 1977; Hassanali 2013). Other threats to Buccoo Reef include sewage pollution, climate change and associated mass-bleaching events, and various coral diseases (Bouchon et al. 2008; Laydoo 1991; Lapointe et al. 2010).

Sandy beaches along the north and east coasts of Trinidad are home to the second largest nesting assemblage of the leatherback sea turtle (*Dermochelys coriacea*) in the Atlantic (e.g., Mycoo and Gobin 2013). Roughly 3000 turtles nest annually on the beach at Grande Riviere along the northeast coast (Mycoo and Gobin 2013). These delicate nesting sites are impacted by both natural and human influences including coastal development, illegal harvesting, climate change, coastal erosion, and thick accumulations of seaweed (*Sargassum*) on the beaches (Mycoo and Gobin 2013; Weber et al. 2015c). The village of Grande Riviere serves as an excellent model for how regions can transition from exploitation to protected ecotourism destinations.

Many other areas of ecological importance and popular ecotourism destinations are present throughout the interior of Trinidad, including the Aripo savannah, and the Caroni and Nariva swamps (see Fig. 17.3). The Aripo savannah is a unique edaphic landscape in the Northern Basin, designated an Environmentally Sensitive Area in 2007, that covers roughly 18 km^2. The area contains several localized dry savannahs with the dominant grass (*Paspalum pulchellum*) developed on clay-rich sandy soil (Richardson 1963). The Caroni and Nariva swamps were designated as protected areas in 1936 and 1968, respectively, and are both major tourist attractions. Traditional activities such as castnet fishing, small-scale rice farming, and the harvest of many of the marine and brackish species, such as oysters, are permitted in the swamps. These activities, as well as ecotourism, have in large part, driven controversial land cover shits in the Caroni and Nariva swamps (e.g., Gibbes et al. 2009). Perceptions of Trinidad and Tobago's landscapes, and thus management of them, remain perched in critical balance between employment, tourism, and conservation, among other environmental and social-political factors (Dillman 2015).

17.6 Hazards

Trinidad and Tobago have experienced several destructive natural disasters, which have been recorded since the seventeenth century. The largest historic earthquake to shake Trinidad was in 1766 and is estimated to have had a magnitude of ~8. Earthquake damage was so severe that Trinidad's people petitioned the King of Spain for resettlement to another Caribbean island. The largest recorded earthquake (M_w 6.7) occurred in 1997, ~5 km offshore south of Tobago along an unnamed fault and caused over US$25 million in damages, injured several people, and left many people homeless in Tobago (ODPM 2014; Weber et al. 2015a).

Even though Trinidad and Tobago are positioned outside of the main Atlantic hurricane belt, the islands have been damaged by several hurricanes. In 1963, Tobago was devastated by one of the deadliest Atlantic hurricanes (Category

3) in recorded history, Hurricane Flora, with winds >160 km/h. The hurricane destroyed or damaged 6250 of Tobago's 7500 houses and at least 18 lives were lost. Property and crop damage on the island amounted to US $30 million (ODPM 2014). The islands regularly experience large tropical storms often associated with distant hurricanes, particularly during the wet season, and annually cause tremendous damage to infrastructure and occasional loss of life (ODPM 2014).

Fires and droughts are among the most common natural hazards in Trinidad and Tobago (ODPM 2014). They are typically associated with the dry season, and year-round high winds. Floods and mass movements are also common. Mass movements range from landslides on steep hillslopes like those in the Northern Range to slow, but destructive creep, especially in the expanding clay soils in central and southern Trinidad. Liquefaction of unconsolidated sediment and long-term subsidence in western Trinidad collectively result in erosion and have caused dramatic changes to the landscape.

Sea-level rise, frequent seismicity, and large magnitude earthquakes pose some of the greatest threats to the islands' (Nurse et al. 1998; ODPM 2014). Low-laying coastal areas in Trinidad and Tobago, like those in other small-island nations of the Caribbean, are extremely vulnerable to sea-level rise as a consequence of human-induced global climate change (e.g., Nurse et al. 1998). This is particularly confounded in Trinidad and Tobago because the islands' major population centers and infrastructure are located along its coastlines. Trinidad's capital, Port of Spain, is built in part on reclaimed land and located along the western coast, which is tectonically subsiding. Sea-level rise and climate change are also linked to potentially devastating hazards such as the loss of agricultural land and delicate ecosystems, coastal erosion, increased pollution, coral reef destruction, changes in aquifer volume and quality, and many other complex direct and indirect environmental responses to global climate change (e.g., Nurse et al. 1998). Efforts to minimize, respond to, and recover from natural hazards are a major concern of local government, community organizations, as well as other West Indian nations and non-governmental organizations abroad (ODPM 2014).

17.7 Conclusions

Trinidad and Tobago's distinct geologic histories and their shallow emergence along the southeast corner of the Caribbean plate throughout the Quaternary provide the context for the two islands' varied landscapes, landforms, and geomorphic evolution. Dynamic geomorphic processes have sculpted a spectacular variety of landscapes and landforms in Trinidad and Tobago. Tectonism, climatic shifts, and associated sea-level fluctuations have shaped the islands' wetlands, modern and ancient reefs, marine terraces, alluvial fan development, and shallow continental shelf. Significant changes in local and regional base level have caused adjustments in fluvial systems, and the redistribution of sedimentation and erosion throughout the islands' interior landscapes (e.g., Ramcharan 2004; Weber 2005; Soto et al. 2007; Arkle et al. 2015). The severe tropical climate causes ubiquitous landsliding and flooding and contributes to intense weathering and to the development of a variety of karst and cave systems (e.g., Day and Chenoweth 2004; ODPM 2014). Strong, sediment-rich ocean currents dominate coastal sedimentation and erosion and influence coral reef development (Darsan et al. 2012).

Trinidad and Tobago's geologic and geomorphic histories have also influenced their biota, the migration and settlement of its people, colonization, and economy. Intermittently connected to mainland South America throughout the Quaternary, the two islands were populated with rich and diverse continental flora and fauna (Kenny 2008). Trinidad played a critical role as a "first step" for initial human migration out of mainland South America and then as a central hub for trade as early Amerindians dispersed into the West Indies (Boomert 2000, 2002; Wilson 2007). Geologic structures, both ancient and active, control the distribution and nature of active hydrocarbon systems, and the most transient landforms on Trinidad, mud volcanoes and asphalt seeps. As the leading hydrocarbon producer in the Caribbean, tourism is an important and emerging economic sector for Trinidad and Tobago, with its diverse culture heritage, unique biodiversity, and varied landforms.

Natural and human-induced environmental changes continue to cause dramatic modifications of the islands' landscapes. Potential natural hazards include frequent and large magnitude earthquakes, climate change and associated sea-level rise, tropical storms and associated flooding, mass wasting, wind damage, and dry-season fires. Perceptions of the landscape and its management require a delicate balance between employment and tourism, and ecological protection (Dillman 2015).

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