Chapter 3
The Geomorphology and Physiographic Provinces of Central America

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“We have been sailing placidly along the coast...all day - a broad, low land, densely clad in a green, tropical vegetation.... In full view are three noble mountains - tall, symmetrical cones, with sides furrowed with wrinkle-like valleys veiled in a dreamy, purple mist that is charming to the eye, and summits swathed in a grand turban of rolling clouds. They say these are volcanoes, but we cannot see any smoke. No matter - it is a fairy landscape that is very pleasant to look upon.” Mark Twain, December 1866, letter written aboard the steamer Columbia offshore of Guatemala, published in the San Francisco Alta California, March 15, 1867

3.1 INTRODUCTION

Central America encompasses an intricate mosaic of dynamic landscapes shaped by a wide range of Earth surface processes. Few other regions worldwide exhibit a comparable magnitude of geomorphic diversity. Along the length of the Central American isthmus, highly variable tectonic, lithologic, and climatic domains (Figs. 3.1-3.3) are superimposed across a small land area (0.4 % of Earth’s total land surface). The resulting physiography is characterized by a heterogeneous array of geomorphic provinces (Fig. 3.4), each featuring a distinctive landform assemblage that preserves a unique history of landscape evolution.

Over 1500 km in length, Central America reaches from the rugged Maya highlands of Guatemala in the north, to the humid coast ranges of Panama’s Darién isthmus in the south. This narrow land bridge links the two American continents and forms a critical divide between the Pacific and Atlantic ocean basins, varying in width from less than 100 km at the Panama Canal, to over 400 km across the interior highlands of Nicaragua and Honduras. From towering volcanic peaks (>4000 m elevation) to jungle-shrouded alluvial lowlands, and from rugged tectonic shorelines to passive-margin lagoons, Central America embodies a geomorphic microcosm of remarkable diversity.

The physiographic architecture of Central America (Fig. 3.4) is defined primarily by the northwest-trend of the Middle America Trench and Central American Volcanic Front (Fig. 3.1). These major morphotectonic features were formed by Cenozoic subduction of the Cocos oceanic plate, and its predecessor, the Farallon plate, beneath
the western margin of the Caribbean plate [1-10]. While the northern volcanic front developed over Paleozoic continental basement of North American origin (Maya and Chortis blocks), the southern volcanic front formed on the Mesozoic oceanic basement of the Caribbean plate (Chorotega and Chocó blocks) (Fig. 3.1). Throughout the Cenozoic, this first-order contrast in basement lithology has been overprinted with a diverse suite of rock formations (Fig. 3.2) generated in a variety of tectonic settings, including volcanic cordilleras, fore-arc and trench-slope basins, alluvial plains and deltas, intra-arc rift valleys, fold-and-thrust belts, highland plateaus, and carbonate platforms.

Figure 3.1. Tectonic map of Central America, showing the regional geometry of tectonic plates and basement blocks. Plate names are in white boxes (North American, Caribbean, Cocos, Nazca, and Panama). Large arrows show plate motions relative to Caribbean plate. Active plate boundaries are shown as solid lines (with teeth on upper plate of convergent margins, and opposing arrows indicating transform motion). Shaded areas show basement blocks (Maya, Chortis, Chorotega, and Chocó). Dashed lines mark major bathymetric features. EPR: East Pacific Rise; GSC: Galapagos Spreading Center; PFZ: Panama Fracture Zone; CCRDB: Central Costa Rica deformed belt; NPDB: North Panama deformed belt; SPDB: South Panama deformed belt; EPDB: East Panama deformed belt.
Active tectonic deformation continues to shape the Central American landscape along several complex plate-boundary zones (Fig. 3.1). In the north, the Motagua-Polochic fault system cuts across central Guatemala, accommodating sinistral shearing between the North American and Caribbean plates [11-13]. Along Central America’s Pacific margin, rapid convergence (7-10 cm/yr) occurs between the Cocos and Caribbean plates at the Middle America subduction zone, generating large earthquakes [14-18], active volcanism [19-23], and pronounced upper-plate deformation [24-37]. The oblique subduction of steeply dipping seafloor, produced at the East Pacific Rise, results in pervasive strike-slip faulting and rifting along the northern Central American margin [24-27]. In contrast, the flat subduction of rough, hotspot-thickened seafloor, produced at the Galapagos Spreading Center, drives rapid uplift and crustal shortening across southern Central America [28-37]. Along the margins of Panama, rapid deformation occurs in response to collision with South America to the east, and oblique subduction of the Nazca plate to the south [38-42].

![Geologic map of Central America](image)

Figure 3.2. Geologic map of Central America, showing the distribution of major rock units (based on map of R. Weyl [1]).

In addition to contrasting lithologic and tectonic domains, Central America also hosts a wide array of climatic and ecological zones (Fig. 3.3), ranging from the humid tropical rainforests of the Caribbean and southern Pacific lowlands, with >4.0 m/yr of rainfall, to the dry tropical savannas of the northern Pacific coastal plains, with <1.0
m/yr of highly seasonal precipitation [43-45]. Similarly, vegetation zones within mountainous regions range from the humid cloud forests of volcanic highlands to the dwarf scrublands of the high-altitude páramo. Dramatic climatic and topographic gradients juxtapose 4000 m peaks that were glaciated in the Pleistocene [46] in close proximity to humid lowland basins mantled by thick lateric oxisols [7]. Topographic extremes coupled with variations in slope aspect, wind direction, and orographic precipitation result in extraordinarily diverse microclimates, vegetative cover, and soil types within single mountain ranges.

Figure 3.3. Climate map of Central America, showing the regional distribution of Köppen Climatic Zones based on average temperature and precipitation (modified from [44]).

As a whole, the Central American isthmus forms a geologically tenuous land bridge that links the two American continents and creates a topographic divide between the Atlantic and Pacific Ocean basins. This narrow landmass plays a vital role in directing the ecological evolution of the Americas [47, 48], and may also profoundly influence ocean circulation and global climate [49-51]. During the Cenozoic, a diverse array of landscapes has developed along the isthmus in response to dynamic interactions between regionally variable rock types, complex plate-boundary tectonics, and an energetic tropical climate. Central America therefore serves as a unique laboratory for the study of a wide range of geomorphic processes and consequent pathways of landscape evolution.
This chapter explores the regional geomorphology of Central America and defines a system of physiographic provinces (Fig. 3.4) that characterizes the overall landscape diversity of this dynamic region. The chapter is organized into sections that provide an overview of the characteristic landforms and geomorphic processes that define each of the physiographic provinces. The first half of the chapter looks at the geomorphic provinces of northern Central America, and the second half examines those of southern Central America. Each section provides a brief review of current geomorphic research within the physiographic provinces. Due to the wide range of possible topics, it is impractical to cover every aspect of these diverse landscapes. The discussion is therefore limited to a subset of critical topics that provide a general flavor for the regional geomorphology of Central America. Several of these topics are explored in greater detail in the four chapters that follow: Volcanism and volcanic landforms (Chapter 4), Karst landscapes (Chapter 5), Glacial geology and geomorphology (Chapter 6), and Coastal morphology and coral reefs (Chapter 7).

Figure 3.4. Map of the physiographic provinces of Central America as defined in this chapter. Solid lines indicate province boundaries. Numbers on map refer to the list of physiographic provinces at right. Yucatán platform and Chortis highlands sub-regions: a, Northern pitted karst plain; b, Southern hilly karst plateau; c, Petén karst plateau and lowlands; d, Eastern block-faulted coastal plain; e, Central Chortis plateau; f, Western rifted highlands; g, Eastern dissected plateau; h, Honduran borderlands. Digital elevation model derived from NASA Shuttle Radar Topography Mission (SRTM) image PIA03364.
3.2 GEOMORPHOLOGY OF NORTHERN CENTRAL AMERICA

Northern Central America straddles the boundary between two major crustal domains (Fig. 3.1), the Maya block of southern Mexico, Belize, and northern Guatemala, and the Chortis block of southern Guatemala, Honduras, El Salvador, and Nicaragua [52-55]. These two basement terranes are juxtaposed across the Motagua-Polochic fault zone of central Guatemala, which defines the active North American-Caribbean plate boundary. The lithologic and structural contrast between the Maya and Chortis blocks (Fig. 3.2) exerts a first-order control on regional geomorphology in northern Central America. This geomorphic template is in turn affected by active plate-boundary deformation along both the east-west trending Motagua-Polochic fault zone and the northwest-trending Middle America convergent margin along the Pacific coast. Late Cenozoic volcanism, generated by subduction at the Middle America Trench imparts an additional influence on regional geomorphology.

Both the Maya and Chortis blocks (Fig. 3.1) encompass continental basement terranes of lower Paleozoic metamorphic and igneous rocks (Fig. 3.2) [52-58]. On the Maya block to the north, the basement is overlain by a thick sequence of upper Paleozoic clastic and carbonate sediments, upper Jurassic continental red beds, and Cretaceous to Eocene carbonate and evaporite rocks [59-61]. This sequence is exposed across the Maya block within the Sierra Madre of southeastern Mexico, the northern highlands of Guatemala, and the vast lowlands of the Yucatán platform. The basement of the Chortis block, to the south of the Motagua-Polochic fault zone, is overlain by Mesozoic clastic and carbonate sediments, lower Tertiary red beds, and a thick sequence of Neogene ignimbrites [59, 62-64]. These rocks are exposed throughout the Chortis highlands of southern Guatemala, Honduras, and Nicaragua.

While the Maya block has undergone only minor rotation relative to the North American craton, the allochthonous Chortis block to the south, has experienced significant southeastward displacement and rotation relative to its original position northwest of the Maya block. The regional geomorphology of northern Central America is strongly influenced by the lithologic and structural contrasts between these two adjacent tectonic blocks.

3.2.1 Maya Highlands Province

The Maya Highlands Province (Fig. 3.4) extends in a broad arc from México’s Sierra Madre de Chiapas, eastward across the northern Guatemalan Altiplano, to the Maya mountains of southern Belize. These rugged highlands consist of a series of morphologically distinct mountain ranges separated by deep fault-controlled canyons and occasional broad alluvial valleys.

The Maya highlands are developed across a Cretaceous-Paleogene age fold belt that affects the underlying crystalline basement and its sedimentary cover [1-4]. The intensity of deformation decreases toward the north, where a near-horizontal section forms the foundation of the Yucatán carbonate platform. The geomorphology of the Maya highlands is largely controlled by variations in the lithology and structural grain of deformed sedimentary rocks and metamorphic basement exposed within a series of eroding, high-altitude mountain belts [65].

In western Guatemala (Fig. 3.5), the Maya Highlands Province extends across the border from Mexico’s Sierra Madre massif, forming the northwest-trending Cuchumatanes range. These rugged mountains encompass several distinct geomorphic
sectors, including an extensive high-altitude plateau (>3800 m) that was glaciated during the Pleistocene [46]. Toward the east, the Maya highlands decrease in elevation, extending into the Chamá and Santa Cruz ranges of east-central Guatemala (Fig. 3.5). Along their northern margin, the highlands descend toward the Yucatán platform, encompassing the Lacandón range (<800 m) of northern Guatemala and the Maya mountains of southern Belize (<1200 m).

![Figure 3.5. Map of the physiographic provinces of northern Central America, showing significant geomorphic features of Guatemala, El Salvador, and portions of Mexico, Belize, Honduras, and Nicaragua. Digital elevation model derived from NASA Shuttle Radar Topography Mission (SRTM) image PIA03364.](map.png)

3.2.1.1 Cuchumatanes Range

The Cuchumatanes range in northwestern Guatemala (Fig. 3.5) consists of a deeply dissected, northwest-trending, fault-bounded mountain block. This high-altitude range (>3800 m maximum elevation) encompasses a thick (>7500 m) section of deformed upper-Paleozoic to Mesozoic sedimentary rocks overlying a lower Paleozoic
metamorphic basement [61]. The Cuchumatanes range exhibits several distinct geomorphic sub-regions, including a spectacular highland plateau (Altos de los Cuchumatanes), a rugged mountainous zone of karst topography, and a lower-elevation area of ridges and valleys developed on metamorphic basement [65].

The Altos de los Cuchumatanes plateau (3400-3800 m elevation), in the core of the Cuchumatanes range, is formed primarily on a 2500-m-thick section of Cretaceous limestone and dolomite strata near the top of the Maya highlands sedimentary sequence [61]. This plateau was glaciated during the Pleistocene, leaving a relict landscape of striated bedrock, moraines, and outwash plains [46, 66, 67] (also see Chapter 6). The abrupt margins of the Cuchumatanes plateau correspond with deep canyons developed along a series of northwest trending faults and folds. The southern edge of the plateau follows a prominent fault escarpment that separates the Maya highlands sedimentary section from crystalline basement rocks exposed within the Motagua-Polochic fault zone to the south (Fig. 3.5).

3.2.1.2 Chamá and Santa Cruz Ranges

The Chamá range of north-central Guatemala (Fig. 3.5) exhibits a complex mountainous landscape formed over east-west trending folds in the Mesozoic sedimentary section [65]. Where carbonate rocks outcrop along the fold belt, the Chamá mountains exhibit an undulating karst topography with scarce surface drainage. On intervening clastic rocks, the landscape consists of low-relief erosion surfaces traversed by meandering streams. To the east of the Chamá mountains, the Santa Cruz range (Fig. 3.5) features a strikingly different mountain landscape of steep northwest-trending ridges cut by deeply-eroded drainages [65]. The drainage divides consist of a series of orthogonal spurs that extend out from the primary ridges. This morphology is the product of differential erosion along a system of parallel fractures within the underlying ultramafic basement rocks [60].

3.2.1.3 Lacandón Range

The Lacandón range (Fig. 3.5) marks the northern edge of the Maya Highlands Province, extending in a broad arc across Guatemala’s southern Petén region to the Maya Mountains of Belize. This relatively subdued mountain chain (<800 m elevation) is formed along an arcuate belt of tightly folded Cretaceous limestone and dolomite strata (La Libertad Arch) at the southern margin of the Yucatán platform [59]. Rising above the humid Petén lowlands, the Lacandón range consists of a series of ridges and valleys that exhibit a rugged karst landscape of abundant sinks, isolated knobs, and poorly integrated surface drainages [65]. The central Lacandón range also encompasses some broader low-relief karst uplands with occasional limestone columns and towers. Along the southern margin of the Lacandón range (Fig. 3.5), an extensive alluvial-lowland has formed where several major rivers descend out of the higher Cuchumatanes and Chamá ranges to the south [65]. This broad interior lowland consists of a network of major flood plains, developed where rapid sedimentation buried the underlying karst topography.

3.2.1.4 Maya Mountains

The Maya Mountains of Belize (Fig. 3.5) consist of a fault-bounded highland (<1200 m elevation) that exposes granitic and meta-sedimentary basement rocks within an east-
northeast trending synclinorium [57, 58]. This isolated mountain block rises abruptly above the surrounding lowlands of the Petén region and the Belize coastal plain [65]. River systems draining from the Maya Mountains experience sharp changes in channel morphology as they cross the steep mountain front that separates deformed crystalline rocks within the massif from the generally flat lying carbonate platform of the adjacent lowlands [68]. The coastline east of the Maya Mountains (Fig. 3.5) is characterized by a series of small deltas constructed of coarse clastic sediments eroded from the metamorphic and igneous interior of the mountain block [69]. This coastal morphology differs considerably from the low-relief shorelines to the north and south, characterized by broad estuaries and lagoons fed by stream networks draining carbonate terrains.

3.2.2 Yucatán Platform Province

Extending to the north of the Maya highlands, are the expansive carbonate lowlands of Petén, northern Belize, and the Yucatán peninsula (Figs. 3.5 and 5.1). Together, these regions encompass the most extensive karstlands of the North American continent, covering over 100,000 km² [70-73] (also see Chapter 5). The Yucatán Platform Province features a wide array of karst landforms, including sinkholes, cenotes, dry valleys, cockpits, towers, and elaborate cave networks. This vast carbonate platform can be subdivided into several distinct physiographic regions (Fig. 3.4), each exhibiting a characteristic topography and a unique assemblage of karst landforms. The geomorphic character of each of these areas is closely linked to regional variations in lithology, structure, and depth to the groundwater table.

3.2.2.1 Northern Pitted Karst Plain

On México’s Yucatán peninsula (Fig. 3.4), a relatively subdued karst landscape is developed across a flat-lying sequence of Cenozoic marine carbonate rocks [70, 71]. The northern third of the peninsula consists of a low relief pitted karst plain (0-30 m elevation), characterized by a dense network of sinkholes and cenotes (flooded collapse pits that access the groundwater table). Efficient subsurface drainage within the pitted karst plain results in a complete absence of surface streams [74-77]. An extensive interconnected system of flooded caverns (up to 130 km long) lies beneath the northern Yucatán lowlands. These caverns formed by aggressive karst dissolution during sea level low stands of the late Pleistocene. Much of this cave network is now flooded by stratified groundwater consisting of a lower saline layer, capped by an overlying fresh water lens.

A prominent 180-km-diameter semicircular alignment of cenotes extends across the northwestern Yucatán plain. This feature, known as the Ring of Cenotes, represents a concentric band of enhanced karst permeability that overlies the buried Cretaceous-age Chicxulub impact structure [78, 79]. Breaks within extensive coastal dune fields reveal where the buried impact structure intersects the northwestern coastline of the Yucatán peninsula. These locations coincide with zones of concentrated groundwater discharge, as manifested by a high density of springs and flooded coastal wetlands.

3.2.2.2 Southern Hilly Karst Plain

The broad lowland of the northern pitted-karst plain (Fig. 3.4) is bordered along its southern edge by the prominent northwest-trending La Sierrita de Ticul fault scarp [70]. The Ticul escarpment consists of an abrupt line of hills that rise up to 50 m above
the northern lowlands. This chain of hills forms a distinct ridge that extends for nearly 200 km across the northern Yucatán peninsula, dividing the northern pitted-karst plain from a hilly karst terrain to the south. The southern hilly-karst plain (Fig. 3.4) covers much of the Campeche region of the Yucatán peninsula, south of the Ticul escarpment. This extensive upland (60-80 m elevation) features an irregular karst terrain characterized by abundant hills with intervening flat-floored depressions (poljes). Many of these depressions host ephemeral surface streams and contain alluvial sediments. These basins occasionally flood during the rainy season due to the inefficient karst drainage in this region.

3.2.2.3 Petén Karst Plateau and Lowlands

In the Petén region of Guatemala, and adjacent portions of northwestern Belize (Figs. 3.4 and 5.1), a distinctly more rugged and heterogeneous karst terrain has formed on an older sequence of Cretaceous-Paleogene carbonate rocks [65, 80]. The diversity of karst geomorphology across this region is controlled by local variations in the lithology and structure of the carbonate bedrock. The karst plateau (<450 m elevation) of northeastern Petén exhibits a hilly landscape with local relief in excess of several hundred meters. Surface drainage across the plateau is poorly developed and abundant sinkholes feed into an extensive network of solution fractures and caverns. Along the eastern margin of the Petén karst plateau, the landscape exhibits a rugged topography controlled by underlying normal faults [65, 81]. Local relief can exceed 100 m across steep scarps formed along the fault-controlled margins of elongate depressions. A diverse suite of karst landforms occurs in this area, including dry valleys, residual limestone hills, isolated cockpits, sinkholes, solution corridors, open fissures, and elaborate cave systems. To the west of the Petén karst plateau, is a humid lowland region consisting of a vast low-relief alluvial plain covered by large swamps and numerous lakes [65]. The river network draining this region exhibits an irregular pattern, interrupted locally by subsurface karst drainage. In some areas, an undulating topography has formed by karst dissolution and alluvial filling across a series of folds within the carbonate bedrock.

3.2.2.4 Eastern Block-faulted Coastal Plain

The low-relief coastlines of the Yucatán platform (Fig. 3.4) are characterized by broad lagoons, mangrove swamps, and seasonally-flooded marshlands. Along the platform’s east-facing Caribbean coast (including northern Belize), the elongate morphology of coastal lagoons and lowlands follows a series of north-northeast-trending, fault-bounded ridges and depressions [70]. Offshore, an extensive network of fringing reefs and coral cays has also developed along this structural grain (forming the world’s second longest barrier reef). This horst and graben structure is the result of broadly distributed transtensional deformation along the North American-Caribbean transform boundary south of the Yucatán peninsula.

Groundwater discharge along the east coast of the Yucatán peninsula is concentrated along the north-northeast-trending faults [71, 75, 76]. Mixing of meteoric groundwater and saline water at the coast results in vigorous karst dissolution, producing a network of fracture-solution caverns that extend well inland [82-84]. Alignments of cenotes and large lakes occur above these fractures on the coastal plain. Where these solution fractures intersect the coast, cave collapse results in progressive enlargement of coves and lagoons. Gradual coalescence of lagoons by wave erosion
results in the formation of broad, crescent-shaped beaches along the eastern Yucatán coast.

3.2.3 Motagua Fault Zone Province

A series of major northeast-trending river valleys have developed across central Guatemala along sinistral strike-slip faults of the North American-Caribbean plate boundary (Fig. 3.4). This major fault zone separates the Maya and Chortis blocks along a broad arc extending from the Guatemalan volcanic highlands along the Pacific margin to the Gulf of Honduras on the Caribbean coast [1-6]. The two most prominent fault-controlled valleys are those of the Motagua and Polochic rivers (Fig. 3.5), which drain the interior highlands and flow eastward to the Caribbean Sea [65]. Offshore, the Motagua and Polochic fault systems merge with the Swan Islands fault, forming a transform boundary along the northern margin of the Caribbean plate [5, 6].

3.2.3.1 Motagua and Polochic valleys

The lower Motagua and Polochic valleys (Fig. 3.5) contain extensive alluvial plains that grade eastward into a broad delta on the Gulf of Honduras [65]. A major structural depression within the lower Polochic valley impounds Lake Izabal (590 km²), the largest inland body of water in northern Central America. Along both valleys, offset Quaternary river terraces, gravel fans, and tributary drainages attest to active sinistral slip along plate boundary faults [12, 13]. The damaging M 7.5 Guatemala earthquake of 1976 produced left-lateral surface rupture along 230 km of the Motagua fault with an average of 1.1 m of horizontal displacement and 0.3 m of vertical displacement [11]. Quaternary slip rates of 0.4-1.9 cm/yr have been determined from offset terrace treads in the Motagua Valley [13].

While the Motagua fault presently accommodates a significant portion of plate-boundary slip, the presence of offset late-Neogene fluvial landforms along the Polochic valley to the north (Fig. 3.5) indicates that the Polochic fault may have been the primary plate-boundary between 10 and 3 Ma [85]. Prior to this (20-10 Ma), plate-boundary deformation may have been localized further to the south along the Jocotán-Chamelcón fault zone in northwestern Honduras. This now inactive fault system has since been fragmented by east-west extension along a series of north-trending rift valleys (Fig. 3.5) along the southern margin of the plate-boundary deformation zone [86-88].

3.2.3.2 Las Minas and Chucás Ranges

From the broad alluvial valleys on the Gulf of Honduras, the Motagua and Polochic faults extend westward into the Guatemalan highlands (Fig. 3.5), where they curve to the northwest along a series of deeply incised valleys. In this region, the plate-boundary faults delimit a set of mountain-block slivers that expose lower Paleozoic metamorphic and igneous basement rocks [56]. The faulted structure of these crystalline basement rocks largely defines the morphology of sub-parallel ridges and valleys within the Las Minas and Chucás ranges (Fig. 3.5) of central Guatemala [65]. To the west, the plate boundary faults extend into Chiapas, México, where deformation becomes more diffuse within the Sierra Madre massif [89].
3.2.4 Chortis Volcanic Front Province

The active Chortis volcanic front (Figs. 3.4 and 4.1) encompasses two major, northwest-trending morphotectonic segments, the Guatemalan Cordillera, formed along the western margin of the Chortis highlands, and the Salvadoran Cordillera, developed along the southern boundary faults of the Median Trough graben [1-4, 19-23, 90-92] (also see Chapter 4). Both of these cordilleras consist of aligned clusters of stratovolcanoes and calderas localized along transverse faults that cut the Chortis volcanic front.

3.2.4.1 Guatemalan Cordillera

Central America's highest volcanoes, Tacaná and Tajumulco (>4000 m elevation), mark the northwestern end of the Chortis volcanic front just south of the Motagua fault zone (Figs. 3.5 and 4.1). In general, the Guatemalan volcanoes are aligned in clusters where north to northeast-trending faults intersect the range front of the Tertiary volcanic highlands [93]. These frontal stratovolcanoes are often flanked by large silicic calderas [94]. For example, a major volcanic complex in western Guatemala (Figs. 3.5 and 4.1) that includes Santa María, Santiaguito, Santo Tomas, and Cerro Quemado volcanoes has developed along a transverse, northeast-trending lineament that extends into the back arc [95-97]. The Quezaltenango Valley north of these stratovolcanoes may represent an extinct caldera. Similar transverse clusters of frontal stratovolcanoes flanked by back-arc calderas occur along the entire Chortis volcanic front. Other volcanic complexes along the Guatemalan cordillera (Figs. 3.5 and 4.1) include the San Pedro-Atitlán-Tolimán cluster (flanked by Atitlán caldera), the Yepocapa-Acatenango-Fuego lineament (flanked by Barahona caldera), and the Agua-Pacaya pair (flanked by Amatitlán caldera).

Near Guatemala City (Figs. 3.5 and 4.1), the twin stratovolcanoes of Acatenango and Fuego form spectacular cones that tower 2000 m above the interior highlands and over 3500 m above the adjacent Pacific coastal plain [98]. Nearby Agua volcano adds a third hulking peak to the horizon of the modern Guatemalan capital. In 1541, a major debris flow descended from Agua’s summit to obliterate the colonial capital of Ciudad Vieja [99]. Throughout the Quaternary, such debris avalanches and lahars have conspired with occasional ash flows to construct a broad landscape of debris aprons that extend outward from the Guatemalan volcanoes and on to the Pacific coastal plain below (Figs. 3.5 and 4.1). The potential for similar events in the future represents a significant geologic hazard for the people of Guatemala [100].

3.2.4.2 Salvadoran Cordillera

In El Salvador, the active volcanic front is aligned along the southern boundary faults of the Median Trough (Fig. 3.5), an elongate structural basin at the northwestern end of the Nicaraguan Depression. Similar to Guatemala, the Salvadoran volcanoes are localized where transverse faults intersect the trough [20-23].

In western El Salvador (Figs. 3.5 and 4.1), the Izalco and Santa Ana stratovolcanoes occur within a large, fault-controlled volcanic complex that also includes the Coatepeque caldera [101]. This volcanic cluster is the source of a series of Quaternary andesitic ignimbrites that extend northward into the Median Trough. Late Pleistocene edifice collapse at Santa Ana volcano unleashed a massive debris avalanche that traveled over 50 km to the south into the Pacific Ocean [102]. Like
Guatemala, the populated lowlands of El Salvador face a significant threat from debris avalanches and lahars generated by gravitational failure along the volcanic front [103-106].

San Salvador volcano, adjacent to the country’s capital city (Figs. 3.5 and 4.1), consists of multiple remnants of Quaternary eruptive centers, including a large central crater (El Boquerón), and several surrounding peaks [105-107]. The nearby Ilopango caldera forms a large lake-filled basin created by a series ofmajor collapse events that generated widespread tephra deposits found throughout central El Salvador [108, 109]. Southeast of Ilopango caldera (Figs. 3.5 and 4.1), San Vicente volcano consists of a broad composite mass of two overlapping stratocones [103]. A late Quaternary debris avalanche and lahar deposit forms a swath of hummocky terrain that extends 25 km to the southeast of the volcano, reaching the Lempa river on the coastal plain.

Near the southern end of the Chortis volcanic front (Figs. 3.5 and 4.1), San Miguel volcano forms an imposing composite cone that rises over 2000 m above the lowland coastal plain near the Gulf of Fonseca [104, 110]. As one of the most active volcanoes in El Salvador, this prominent peak is surrounded by a youthful landscape consisting of multiple, historic lava flows. Unlike most of the Chortis volcanoes, San Miguel is composed predominantly of basalt and shows little evidence of prior explosive eruptions or debris avalanches.

### 3.2.5 Chortis Fore Arc Province

The Pacific coastal plain of Guatemala and El Salvador (Fig. 3.4) consists of a low-relief bajada of coalescing alluvial fans that extend up to 70 km seaward of the volcanic front [111] (also see Chapter 7). This broad alluvial plain is constructed of volcanic ejecta and clastic sediments delivered by a network of debris-choked rivers that drain the interior volcanic highlands. In general, coastal topography along the Chortis fore arc (Fig. 3.5) is relatively subdued, with only minor localized faulting affecting the Quaternary strata. This low-relief coastal morphology strongly contrasts with the tectonically active coastlines of the Chorotega fore arc in southern Central America (Fig. 3.4). In that region, active faulting and rapid uplift have produced abrupt coastal topography along the rugged coastlines of Costa Rica and Panama.

#### 3.2.5.1 Guatemalan Coastal Plain

The Guatemalan coastal plain (Fig. 3.5) forms a prominent bulge (>200 km long, and up to 70 km wide) along Central America’s northern Pacific coastline. This extensive alluvial lowland encompasses a series of overlapping debris fans, consisting of thick Quaternary sequences of volcaniclastic sands, gravels, pumaceous ash, and lahar deposits [111]. These materials have been deposited and reworked along a sub-parallel network of river channels that descend from the adjacent volcanic highlands. The spectacular stratovolcanoes that tower more than 3500 m above the coastal plain to the east represent sources for pyroclastic flows, long-run-out lahars, and massive debris avalanches [100]. Confined within deeply incised drainages along the volcanic front, such flows are capable of traveling great distances to inundate the coastal plain below.
3.2.5.2 Salvadoran Coastal Plain

Although narrower than the Guatemalan coastal plain, the Pacific lowlands of El Salvador (Fig. 3.5) share a similar geomorphology of coalescing alluvial fans fed by coarse detritus from the volcanic highlands. In western El Salvador, the coastline exhibits a prominent headland referred to as the Acajutla peninsula (Fig. 3.5). This small promontory extends 7 km offshore to its southern tip at Punta Remedios. The Acajutla peninsula is the product of a massive late Pleistocene debris avalanche generated by edifice collapse at Santa Ana volcano, 50 km to the north [102]. The subaerial deposit covers 390 km² with an additional estimated component of 150 km² lying offshore. A 10-km-wide swath of hummocky terrain extends from the Acajutla peninsula up to the source of the debris avalanche on Santa Ana volcano.

Southeast of the Acajutla peninsula (Fig. 3.5), the coastal plain narrows and gives way to rocky headlands and cliffs cut into resistant Pliocene volcanic rocks of the Balsamo range. This rugged volcanic range intersects the coast in a series of southwest-trending ridges separated by deeply incised linear canyons. To the east, the Salvadoran coastal plain widens again where a series of rivers that drain the volcanic front have deposited broad alluvial fans. The most prominent geomorphic feature along this coastal segment is the massive delta of the Lempa river (Fig. 3.5). This major river drains a significant portion of the interior Chortis highlands, transporting its massive sediment load across the Median Trough to the Pacific coast. The resulting, low relief, alluvial coastline is characterized by a series of elongate barrier islands and spits that enclose extensive lagoons.

3.2.6 Chortis Highlands Province

The majority of the Chortis block (Fig. 3.4) consists of a broad, dissected, highland plateau that extends from western Guatemala, across Honduras and El Salvador, to northern Nicaragua [27, 52-55, 112-114]. This mountainous topography reaches elevations >1 km and extends up to 400 km behind the active volcanic front. The Chortis highlands can be divided into four geomorphic sub-regions (Fig. 3.4) [27, 114]: a high-altitude central massif with concordant erosion surfaces; a western rifted plateau south of the Motagua-Polochic fault zone; an eastern zone of heavily dissected mountains facing the Caribbean lowlands; and an area of east-west trending, fault-bounded valleys and ridges along the northern coast. The geomorphic contrast between these subregions reflects variations in lithology, proximity to plate boundaries, and a strong east-west climatic gradient across the Chortis highlands.

3.2.6.1 Central Chortis Plateau

The core of the Chortis Highlands Province (Figs. 3.4 and 3.5) consists of a tectonically stable massif of Paleozoic metamorphic basement rocks and an overlying sequence of folded Cretaceous sediments. Concordant high-altitude erosion surfaces (700-1000 m elevation) form a relatively level plateau across this region [27]. While major rivers have incised deep canyons into bedrock, the plateau remains largely intact with only limited dissection by tributary networks (Fig. 3.5). The central Chortis plateau (Fig. 3.4) is isolated from the Caribbean Sea and Pacific Ocean, receiving less rainfall (1.0-1.5 m/yr) than the rifted highlands to the west (>2 m/yr) and the heavily dissected Caribbean slope to the east (>3 m/yr) [27].
Tomographic imaging of the subducting Cocos plate reveals a slab gap extending the length of the Chortis highlands [27]. Slab break-off during the Miocene and associated upwelling of buoyant mantle beneath the Caribbean plate may have induced epeirogenic uplift of the Chortis highlands [27]. This regional-scale uplift, beginning in the Middle to Late Miocene, led to deep entrenchment of meandering rivers throughout the region. Vertical meander incision with no lateral migration implies that uplift proceeded without local faulting or tilting, as a regional event that affected the entire Chortis highlands [27].

3.2.6.2 Western Rifted Highlands

South of the Motagua-Polochic fault zone (Figs. 3.4 and 3.5), the Chortis highlands of southern Guatemala and western Honduras are cut by a discontinuous series of small, north-trending, flat-floored rift valleys of late Miocene to Quaternary age [86]. Early workers referred to these valleys under the collective term "Honduras Depression" [19, 112]. However, instead of a single continuous feature as this term implies, these localized, independent rift basins are scattered across a broad area of the western highlands (Fig. 3.5) stretching from the Guatemala City graben in the west, to the Sula and Comayagua valleys of Honduras in the east. Rifting across the western Chortis block is attributed to regional extension in response to eastward movement of the Caribbean plate south of the arcuate Motagua-Polochic fault zone [27, 86-88, 113, 114]. In a similar fashion, anticlinal folding has occurred north of the Motagua-Polochic fault zone in response to shortening within the southern Maya block [87].

The southwestern margin of the Chortis Highlands Province (Fig. 3.5) overlies a 2 km thick sequence of pyroclastic rocks produced during the middle Miocene ignimbrite flare-up along the Central American volcanic front [63]. These materials were deposited across a pre-existing low-relief terrain formed on underlying basement rocks. This extensive ignimbrite sheet buried earlier drainage networks and reset the landscape for the development of a new system of low-gradient meandering rivers [27]. The rift basins of the western Chortis highlands cut these deposits, providing a well-constrained maximum age for rifting (middle Miocene). In many cases, the rift-bounding faults also disrupt entrenched river meanders formed during the regional uplift event that post-dates the ignimbrites.

3.2.6.3 Eastern Dissected Highlands

The eastern Chortis highlands of Honduras and Nicaragua (Fig. 3.4 and 3.6) encompass a rugged mountain landscape that faces the Caribbean lowlands of the Mosquito Coast [27]. This region is highly dissected by drainage networks and is traversed by several major trunk rivers that descend from the interior highlands onto the coastal plain. These include the high-discharge Patuca, Coco, and Matagalpa rivers (Fig. 3.6), which transport large volumes of coarse sediment eroded from the uplifted interior. Although the eastern portion of the highlands overlies the same basement rocks as the central plateau, a sharp climate gradient toward the Caribbean coast leads to significantly greater rainfall in this area (more than double the annual precipitation). Deep weathering and intense erosion have consumed the highland plateau in this region, leaving a heavily dissected, lower-elevation terrain (average of <500 m) characterized by steep ridges and deep intervening valleys.
3.2.6.4 Honduran Borderlands

The northern margin of the Chortis highlands (Figs. 3.4 and 3.6), east of the rifted plateau, consists of a zone of east-west trending fault-bounded basins and ranges, including the Aguan Valley, and the Nombre de Dios and La Esperanza ranges [114]. Five major east-northeast-trending faults traverse this region, forming the boundaries of elongate mountain blocks. Offset river channels and other geomorphic indicators suggest that these faults accommodate left-lateral transtension along the northern flank of the Chortis highlands. Transtensional fault blocks in this area may represent the onshore extension of normal fault-bounded basins within the offshore Honduran borderlands south of Swan Island fault zone. The difference in orientation and kinematics between the north-south oriented rift valleys to the west (Fig. 3.5), and the east-west oriented basins and ranges to the east (Fig. 3.6), is attributed to variations in the divergence angle between the Caribbean plate motion vector and the plate-boundary fault zone [114].

Figure 3.6. Map of the physiographic provinces of northern Central America, showing significant geomorphic features of Nicaragua, and portions of Honduras, El Salvador, and Costa Rica. Digital elevation model derived from NASA Shuttle Radar Topography Mission (SRTM) image PIA03364.
3.2.7 Mosquito Coast Lowlands Province

The Mosquito Coast Lowlands Province (Fig. 3.4) consists of a broad, thickly vegetated alluvial plain, up to 150 km wide, along the east-facing portion of Central America's Caribbean coast. With annual precipitation rates of 4-6 m/yr, these humid lowlands represent one of the wettest regions on Earth. The alluvial plains of the Mosquito Coast formed during the late Cenozoic atop a coalescing mass of deltaic sand and gravel deposits derived from the eroded interior highlands to the west [115]. These deposits may reach a thickness of up to 4500 m in some areas. Neogene uplift of the Chortis Highlands (Fig. 3.4) resulted in the deep incision of river drainages, producing a pulse of coarse, clastic sedimentation across the Caribbean lowlands [115]. Progradation of these deltaic materials across the shallow Nicaragua bank offshore has produced a low-relief, lobate shoreline (Fig. 3.6) characterized by extensive mangrove swamps, broad tidal lagoons, elongate barrier islands, and scattered coral reefs.

3.2.7.1 Northern Mosquitia

The promontory of Cabo Gracias a Dios (Fig. 3.6) at the Honduras-Nicaragua border marks the apex of a massive Pliocene-Pleistocene age delta [115]. This extensive gravel complex is composed of sediments derived from the Coco and Patuca river watersheds within the Chortis highlands. Pleistocene stream piracy within the highlands shifted deposition to the north of Cabo Gracias as the Patuca River captured flow from the paleo-Coco drainage [115]. Rising sea level during the Holocene has transferred deposition from the distal fan offshore, to a series of smaller nearshore deltas along the modern coast. The constant interplay between shifting river courses, fluctuating sea level, and migrating deltas has been instrumental throughout the late Cenozoic in shaping the broad alluvial plains of the Mosquito Coast.

3.2.7.2 Southern Mosquitia

Along the southern Mosquito Coast (Fig. 3.6), in eastern Nicaragua, a dense network of low-gradient rivers feed into a series of extensive coastal wetlands and lagoons. These lagoons are protected behind large barrier spits that generally extend southward from the mouths of major rivers. Along the southern Nicaraguan coast, the monotonous, low-relief alluvial plain is disrupted by occasional hills and coastal cliffs formed by outcrops of Paleogene to Quaternary volcanic rocks [116]. The Azul volcanic field, in the jungle-covered lowlands west of Pearl lagoon, consists of three well-defined Holocene cinder cones. Along the coast between Perlas and Monkey points (Fig. 3.6), a series of prominent cliffs expose resistant basalt flows interbedded with Tertiary volcanioclastic sediments. Tertiary lavas also form the basement of the offshore Corn Islands, where coastal cliffs up to 100 m high expose massive basalt flows.

3.2.8 Nicaraguan Depression Province

The Nicaraguan Depression (Fig. 3.4) is a ~50 km wide structural trough that extends for over 600 km along the length of the active volcanic front from El Salvador, through Nicaragua, to northern Costa Rica [25, 116]. This elongate basin is generally interpreted as a half-graben, bounded along its southwestern margin by northwest-striking transtensional faults. The basin is most pronounced in Nicaragua where it contains Central America’s two largest lakes, Lake Nicaragua (Cocibolca) and Lake
Managua (Xolotlán). Beginning in the Pliocene, the Nicaraguan volcanic front migrated toward the Middle America Trench and trench-perpendicular extension within the upper plate opened the Nicaraguan Depression. Rifting along the Nicaraguan volcanic front may reflect a late Cenozoic decrease in the plate convergence rate along the Pacific margin and hinge rollback of the subducting Cocos plate slab.

3.2.8.1 Central Nicaraguan Depression

In central Nicaragua (Fig. 3.6), the floor of the Nicaraguan Depression lies only 50 m above sea level. Here, the Mateares fault forms a prominent 900-m-high scarp along the basin’s southwestern margin. Alluvial and volcanic fill within the basin may be up to 2000 m thick along the base of the Mateares scarp, indicating nearly 3 km of dip slip since the Pliocene [25]. The northeastern boundary of the Nicaraguan Depression is generally defined by the 500-m-high mountain front of the interior Chortis highlands formed on a thick sequence of Tertiary volcanic rocks [116, 117].

Damaging earthquakes in Managua (Fig. 3.6) in 1931 and 1972 resulted from shallow rupture on northeast-trending, left-lateral, oblique-slip faults within a pull-apart basin along the southern shore of Lake Managua [118, 119]. These faults may be part of a regional system of northeast-trending sinistral faults that accommodate dextral shear across the Nicaraguan depression between a forearc sliver at the coast and the interior highlands to the east [26]. These cross-arc transtensional faults exert a first-order control on the shoreline morphology of Lakes Managua and Nicaragua. They also may influence the spacing and orientation of volcanic centers along the Nicaraguan volcanic front [22].

3.2.8.2 Median Trough, El Salvador

From northern Nicaragua, the Nicaraguan Depression extends across the Gulf of Fonseca (Fig. 3.6), where it continues along a more westerly trend as the Median Trough of El Salvador (Fig. 3.5). In El Salvador, the topographic expression of the trough is more subdued than Nicaragua, yet its general structure and stratigraphy are quite similar. As in Nicaragua, the volcanic front of El Salvador is localized along the southwestern margin of the trough where transverse faults intersect the basin.

Focal mechanisms for shallow upper-plate earthquakes along the southern boundary faults of the Median Trough indicate that these structures are predominantly right-lateral strike-slip faults with minor components of extension [120-122]. These faults have produced multiple damaging earthquakes throughout El Salvador’s recorded history [123]. The geomorphic expression of the Median Trough dies out near the Guatemalan border (Fig. 3.5) where transtensional deformation gives way to pure dextral slip along the northwest striking Jalpatagua fault [124]. This fault forms a major topographic scarp that cuts through the southern Guatemalan volcanic front offsetting Neogene deposits [24].

3.2.8.3 Los Guatusos and San Carlos Lowlands, Costa Rica

South of Lake Nicaragua (Fig. 3.4), the Nicaraguan Depression extends into the Los Guatusos and San Carlos lowlands of the northern Costa Rican back arc (Fig. 3.7). Here, the depression is buried by a thick sequence of Quaternary alluvium and volcanic debris shed from Costa Rica’s Guanacaste and Central volcanic cordilleras. Rivers descending from the volcanic front flow northward across the basin to join the San
Juan River (Fig. 3.7). This major river, which defines the border between Nicaragua and Costa Rica, flows from Lake Nicaragua eastward to the Caribbean Sea. The southern end of the Nicaraguan Depression in this area coincides with a rapid transition from extensional to compressional tectonics within the back arc of Costa Rica’s Central volcanic cordillera [34]. This transition is related to an abrupt change in the thickness and dip of the subducting Cocos plate beneath central Costa Rica.

3.2.9 Nicaraguan Volcanic Front Province

The Quaternary volcanic front of Nicaragua (Figs. 3.4 and 4.1) has developed along the floor of the Nicaraguan depression, with most volcanic centers located along its fault-controlled southwestern margin [19-23, 116] (also see Chapter 4). Beginning at the solitary Cosigüina volcano on the Gulf of Fonseca (Figs. 3.6 and 4.1), the Nicaraguan volcanic front extends southward along the Los Marabios Cordillera to the spectacular stratocone of Momotombo on the shore of Lake Managua. The volcanic chain then continues southward, past the Apoyo caldera, to the massive Las Sierras ignimbrite shield and the calderas of Masaya and Apoyo. The Cocibolca Cordillera (Figs. 3.6 and 4.1), at the southern end of the volcanic front, extends from Mombacho volcano on the northern shore of Lake Nicaragua to the twin stratovolcanoes of Concepción and Madera on Ometepe island.

3.2.9.1 Cosigüina Peninsula

The Nicaraguan volcanic front begins at Cosigüina volcano (Figs. 3.6 and 4.1), on the southern shore of the Gulf of Fonseca [116]. This solitary volcano stands isolated on a wide promontory that extends outward into the southern gulf from Nicaragua’s northern coastal plain. Cosigüina consists of a broad, low-elevation, composite cone (872 m) with a pronounced ancient caldera rim along its northern slope, a young 300-m-high summit cone, and a 2-km-wide, prehistoric, lake-filled summit caldera. This massive composite volcano generated a powerful, explosive eruption in 1835 that sent pyroclastic flows into the Gulf of Fonseca (Fig. 3.6), and produced ash fall throughout Central America and as far away as Mexico and Jamaica [125]. This event is now recognized as one of the Western Hemisphere’s most powerful historic eruptions.

3.2.9.2 Los Marabios Cordillera

The Los Marabios range (Fig. 3.6), southeast of Cosigüina, consists of a densely spaced series of composite volcanoes that form a prominent divide between the northern Pacific coastal plain and the Nicaraguan depression [116]. This alignment of clustered volcanic vents includes the major stratovolcanoes, San Cristobal, Casita, Telica, Rota, Las Pilas, and Momotombo (Fig. 4.1). The rapidly growing cinder cone of Cerro Negro represents the newest addition to this range, having erupted a significant volume of lava and pyroclastic material since the mid-1800s [126, 127]. Momotombo volcano, at the southern end of the Los Marabios range, forms a spectacular 1300-m-high Holocene stratocone that towers above the northern shore of Lake Managua (Figs. 3.6 and 4.1).

During Hurricane Mitch in 1998, a rain-triggered landslide (1.6 million m³) from the summit of Casita volcano (Figs. 3.6 and 4.1) unleashed a devastating lahar (2-4 million m³) that inundated several villages on the volcano’s Pacific flank, killing more than 2500 people [128]. This volcano has been identified as a potential site for a future
sector collapse related to hydrothermal weakening of its summit edifice [129]. Steep topography, energetic volcanism, and an aggressive tropical climate have conspired throughout the Quaternary to induce repeated gravitational failure along the Nicaraguan cordillera. The resulting lahars in combination with pyroclastic flows have constructed a broad coastal debris apron that extends up to 30 km seaward of the volcanic front.

3.2.9.3 Apoyeque and Las Sierras Shields

Between Lake Managua and Lake Nicaragua (Figs. 3.6 and 4.1), a series of calderas and explosion pits occur along the trace of the Mateares fault zone at the southwestern edge of the Nicaraguan depression [116]. The Apoyeque caldera complex, at the northern end of this chain, sits within a broad ignimbrite shield that forms the Chiltepe peninsula on the western shore of Lake Managua (Fig. 3.6). This low-lying (500 m elevation) volcanic complex includes two large, lake-filled calderas that are the source of thick Quaternary pyroclastic deposits mantling the surrounding landscape. The Nejapa-Mirafloros alignment, west of the city of Managua (Figs. 3.6 and 4.1), features a series of explosion pits, fissure vents, and cinder cones along a north-south trend that marks a right-step along the Nicaraguan volcanic front.

Southeast of Managua, the lake-filled calderas of Masaya and Apoyo occupy a prominent upland along the escarpment of the Mateares fault (Figs. 3.6 and 4.1). These two calderas formed during highly explosive pyroclastic eruptions in the late Quaternary [130-133]. Subsequent activity along the southern margin of Masaya caldera, has constructed the twin volcanoes of Nindiri and Masaya, both sources of historic lava flows.

The Masaya and Apoyo calderas (Figs. 3.6 and 4.1) both belong to the massive Neogene-Quaternary Las Sierras volcanic shield (180 km³), located between Lakes Nicaragua and Managua [130-133]. The Las Sierras shield (Figs. 3.6 and 4.1) forms an anomalous, crescent-shaped highland (>900 m elevation) along the central Nicaraguan volcanic front. This elongate massif consists of a broad, seaward-facing apron of ignimbrite deposits of Plio-Pleistocene age, produced primarily by unusually explosive eruptions of mafic magma from the Masaya caldera.

3.2.9.4 Cocibolca Cordillera

The Cocibolca Cordillera (Fig. 3.6) of southern Nicaragua extends southeastward from the Las Sierras Shield to Ometepe island in Lake Nicaragua. This cordillera consists of a widely spaced chain of four major volcanoes that form a series of promontories and islands within Lake Nicaragua. Standing on the northwestern shore of the lake, Mombacho volcano (Figs. 3.6 and 4.1) is a large stratocone with a jagged profile, scarred by multiple episodes of edifice collapse during the late Quaternary. These events unleashed debris avalanches and lahars that form extensive hummocky deposits in the lowlands surrounding the mountain [134]. These deposits include an adjacent promontory and group of small islands that extend out into the lake.

Zapatera volcano, southeast of Mombacho, consists of a low-lying volcanic shield that forms a broad island near the northwestern shore of Lake Nicaragua (Figs. 3.6 and 4.1). This volcano features a 2-km-wide summit caldera with a 300-m-high central lava dome. To the southeast of Zapatera, the spectacular twin stratovolcanoes of Concepción and Madera form Ometepe island, located in central Lake Nicaragua (Figs. 3.6 and 4.1). Towering >1600 m above the lake, Concepción is one of Nicaragua’s
most active volcanoes, with 25 eruptions recorded in the last 120 years [135]. Recent lava flows and lahars continue to expand the shoreline of Ometepe island.

3.2.10 Sandino Fore Arc Province

The Sandino fore arc province (Fig. 3.4) extends along the entire Pacific coast of Nicaragua, from Punta Cosigüina on the Gulf of Fonseca, to Costa Rica's Punta Descartes just north of the Santa Elena peninsula. This narrow coastal strip lies west of the Nicaraguan depression and volcanic front. It includes a northern low-relief coastal plain constructed of volcanic debris shed from the Los Marabios Cordillera (Fig. 3.6), and a southern cliff-lined coast where Cretaceous-Neogene marine sedimentary rocks of the Sandino fore-arc basin extend on land in a series of margin-parallel folds [25, 136-139] (also see Chapter 7).

3.2.10.1 Northern Nicaraguan Coast

Nicaragua's northern Pacific coast, between the Gulf of Fonseca and Puerto Sandino (Fig. 3.6) consists of a low-relief alluvial plain developed on volcaniclastic debris shed from active volcanoes of the Los Marabios Cordillera. The 1998 Hurricane Mitch debris flow from Casita volcano ran out on to the coastal plain for nearly 10 km, producing sediment laden flooding that extended even further along local stream channels. Similar to the broad volcanic debris aprons of the Chortis fore arc to the north, the northern Nicaraguan coastal plain faces a significant hazard from highly mobile volcanic debris flows. The stream networks draining the Los Marabios range, deliver an abundant supply of volcaniclastic sediment to the coast. This material has been reworked along this low-relief coastline, forming a system of large estuaries, delta plains, and barrier beaches.

3.2.10.2 Southern Nicaraguan Coast

In sharp contrast to the northern coastline, Nicaragua's southern Pacific coast (south of Puerto Sandino) is characterized by a rugged morphology of rocky headlands, sea cliffs, and pocket bays (Fig. 3.6). The resistant grain of this coastline is controlled by structures within Cretaceous-Paleogene marine sedimentary rocks of the Sandino Basin [25, 136-139]. These units outcrop within a series of margin-parallel folds, which intersect the coastline at oblique angles, resulting in variable resistance to marine erosion. Along the central Nicaraguan coast, where these folds expose the Neogene units within the upper section of the Sandino Basin, a basin-and-range topography has developed along the coastal plain.

A notable geomorphic feature along this coastline is a 10-km-long Middle Miocene basaltic dike [138] that armors the coastal bluff near the town of El Transito (Fig. 3.6). This feature extends offshore at El Transito Bay, forming a rock curtain that constricts the bay entrance. This resistant barrier contributed to unusually high wave run-up and a large death toll at this site during the 1992 Nicaraguan tsunami.

3.2.10.3 Las Sierras Shield

Between Puerto Sandino and Las Salinas (Fig. 3.6), Quaternary pyroclastic rocks of the Las Sierras volcanic complex extend seaward to the Pacific coast forming a prominent convex bulge in the Nicaraguan coastline. A network of deeply incised barrancas is
developing on the Pacific slope of the range due to the rapid headward erosion of steep drainages into these weak volcanic rocks. At the coast, a late Pleistocene marine terrace, referred to as the La Boquita surface [140], is cut across the Las Sierras ash flow tuffs and the steeply dipping Cretaceous-Neogene marine sediments of the Sandino basin.

The Las Sierras tuffs have been correlated with a distinctive ash horizon in offshore drill cores dated stratigraphically at 135 ka [133]. This age suggests that the La Boquita marine terrace may have formed during the last interstadial sea level high stand at 125 ka [140]. This terrace occurs along the coast at elevations of 17-22 m attesting to active uplift at rates near 0.1 m/k.y. The La Boquita terrace occurs only along the coastal segment adjacent to the Las Sierras massif (Fig. 3.6), suggesting that coastal uplift may be related to thermal expansion or erosion-driven isostatic rebound of the Las Sierras shield.

3.2.10.4 Punta Descartes, Costa Rica

At the southern end of the Sandino fore arc province (Fig. 3.6), offshore folds intersect the coastline of northwestern Costa Rica forming the Punta Descartes (an anticline) and adjacent bays (synclines). On Punta Descartes, the west-northwest grain of the ridges and valleys is controlled by a system of parasitic folds on a broader anticline. Elevated Holocene shore platforms, beach ridges, and stream terraces record active coastal emergence on the Descartes headland [141]. Valley-fill terraces within coastal embayments extend several kilometers inland reaching 15-20 m elevation. Streams draining to the Bahía de Salinas are incised into these deposits exposing uplifted shallow bay to intertidal muds overlain by beach ridge sands and fluvial gravels. Radiocarbon ages for Holocene deposits indicate uplift rates of 2.0-3.5 m/k.y. [141].

3.3 GEOMORPHOLOGY OF SOUTHERN CENTRAL AMERICA

In contrast to the continental Chortis block to the north (Fig. 3.1), most of southern Central America consists of a Neogene-Quaternary volcanic belt that overlies Mesozoic oceanic basement of Caribbean plate origin [1-10, 142]. This region, referred to as the Chorotega block (Fig. 3.1), includes all of Costa Rica and western Panama. The boundary between the Chorotega block and the Chortis block to the north is defined by a major fault lineament extending from Costa Rica's Santa Elena peninsula (Fig. 3.7), eastward to the Hess Escarpment in the Caribbean Sea (Fig. 3.1). The geomorphology of the Chorotega block reflects a dynamic history of Cenozoic volcanism and upper-plate deformation influenced by complex tectonics along the southern Middle America Trench [7-10]. The eastern limit of the Chorotega block is defined by a basement suture at the Panama Canal Zone that separates it from the Chocó block beneath eastern Panama [4-6, 142]. The Chocó block (Fig. 3.1) consists primarily of Mesozoic igneous basement and overlying Tertiary sediments that extend along Panama’s Darién isthmus and into the northwestern Colombian cordillera.

The Chorotega and Chocó blocks are situated within a region of complex tectonics between four major converging plates: Caribbean, South America, Cocos, and Nazca (Fig. 3.1) [4-6]. Active collision between these plates has fragmented their margins into a system of fault-bounded microplates that accommodate diffuse regional deformation [142-145] The Panama microplate (or Panama block) extends from the margin of South America to central Costa Rica and includes portions of the Chocó and Chorotega
basement terranes. This rapidly deforming fragment of Caribbean crust is thrusting over the back arc in response to flat subduction of thickened seafloor (Cocos Ridge) in the west, and collision with the South American craton to the east [34, 38-40].

Fold and thrust belts offshore of both northern and southern Panama (North and South Panama deformed belts) accommodate active convergence with the Caribbean and Nazca plates (Fig. 3.1) [39-41, 146, 147]. Thrust faults in western Colombia (Atrato-Urubá suture zone) [148] and a broad zone of strike-slip faulting in eastern Panama (East Panama deformed belt) [42] absorb the collision between the Panama block and South America. The western boundary of the Panama block consists of a diffuse transpressional fault zone (Central Costa Rica deformed belt) that traverses Costa Rica from the Caribbean to the Pacific margin [34].

Central Costa Rica has long been recognized as a tectonic segment boundary along the Middle America convergent margin [20, 149]. An abrupt transition from the steep subduction of smooth Cocos plate seafloor in the northwest (East Pacific Rise origin), to the flat subduction of rough, hotspot-thickened seafloor in the southeast (Galapagos Spreading Center origin) occurs along the Middle America Trench offshore of central Costa Rica [150-154]. This transition coincides with pronounced changes in subduction zone seismicity [149, 150], arc volcanism [20-23, 36], and upper-plate morphotectonics [28-37].

The thickened seafloor offshore of southern Costa Rica includes the Cocos Ridge and adjacent seamount domain (Fig. 3.1), products of hotspot volcanism along the Galapagos Spreading Center [151-158]. As this rough, sediment-poor seafloor enters the subduction zone, the overriding plate margin experiences pronounced subduction erosion [159-161]. Flat subduction of this hotspot-thickened crust also drives transpressional faulting along a broad deformation front (Central Costa Rica deformed belt) that is propagating from the fore arc into the interior of the upper plate [34]. Late Cenozoic slab flattening led to retreat of the magmatic front away from the Middle America Trench in central Costa Rica [36], and total extinction of volcanism directly inboard of the Cocos Ridge in southern Costa Rica [162, 163]. Collision of the Cocos Ridge with the southern Costa Rican margin generates pronounced uplift and upper-plate shortening from the fore arc into the back-arc basin [28-37]. Along the central Costa Rican margin, subducting seamounts on the northwest ridge flank erode the outer trench slope [151, 152] and produce corregated uplift of fore-arc fault blocks at the coast [33-35].

### 3.3.1 Chorotega Volcanic Front Province

The volcanic front of southern Central America (Figs. 3.4 and 4.1) is segmented into a series of distinct cordilleras that have evolved in response to variations in the geometry, tectonics and geochemistry of subduction along the Middle America Trench [19-23, 36, 162-170] (also see Chapter 4). In Costa Rica, a dynamic history of Cenozoic tectonics generated a complex volcanic belt that includes the Guanacaste, Tilarán, Aguacate, Central, and Talamanca cordilleras (Figs. 3.7 and 4.1). In Panama, Quaternary volcanism has been limited to the Central Cordillera west of the Canal Zone (Figs. 3.7 and 4.1). Spatial and temporal variations in the subduction system have led to sharp contrasts in magma chemistry and eruption style along the length of the Chorotega volcanic front [21-23]. Changes in slab thickness and dip have instigated episodes of volcanic front migration and rotation, resulting in a complex morphology of overlapping cordilleras and intervening basins [36, 170]. Each of the volcanic
The geomorphology and physiographic provinces of Central America exhibit a unique geomorphology and geologic history [171-177].

3.3.1.1 Guanacaste Cordillera

The northern segment of the Chorotega volcanic front (Figs. 3.7 and 4.1) consists of a Quaternary chain of shield-like stratovolcanos known as the Guanacaste Cordillera [169]. The four primary volcanoes of this chain, Orosi-Cacao, Rincón de la Vieja, Miravalles, and Tenorio, are constructed of coalescing lava flows and pyroclastic material emitted from multiple vents. Unlike the Central Cordillera to the south, the Guanacaste volcanoes each form distinct mountains that rise sharply above a surrounding low-relief landscape. The gaps between these volcanoes allow for easy passage of the Trade Winds between the Caribbean and Pacific basins, resulting in an exceptionally dry climate along Guanacaste's Pacific coast.
Two remnant calderas occur along the Guanacaste Cordillera, and a broad ignimbrite plateau (2000 km²) extends seaward from the base of the chain. Constructed of silicic tuffs emitted from pre-cordillera vents, the Guanacaste ignimbrites form a gently undulating plain (Fig. 3.7) that ends in an abrupt 100-150 m high escarpment near the modern Pacific coast. Rivers draining the cordillera have incised deep barrancas into the plateau.

The southern outcrop of the Guanacaste cordillera is Arenal volcano, a relatively small (15 km³) and highly active Holocene strato-cone [178-180]. Located behind the eroded massif of the extinct Tilarán Cordillera (Figs. 3.7 and 4.1), this steep-sided cone (>1200 m high) rises abruptly above a structural trough in which it has formed. A deadly pyroclastic blast in 1968 decimated 15-km³ of rainforest on the volcano’s western flank. Since this event, Arenal has remained in constant activity, unleashing occasional ash and lava flows that continue to alter the surrounding landscape.

3.3.1.2 Tilarán and Aguacate Cordilleras

The extinct Tilarán and Aguacate ranges (Fig. 3.7) consist of heavily dissected remnants of stratovolcanoes and calderas composed of Neogene-Quaternary basaltic to andesitic lavas, breccias, tuffs, and lahar deposits [169, 181, 182]. Hydrothermal alteration and deep tropical weathering have destabilized the steep slopes of these ranges, resulting in pervasive landsliding.

Throughout the central Aguacate range (Fig. 3.7), deeply incised linear canyons have developed along active, northwest-and-northeast-trending faults of the Central Costa Rica deformed belt [34-36]. The Río Grande de Tárcoles cuts a deep gorge through the central Aguacate range, connecting rivers of the Central Valley basin (Fig. 3.7) with the Pacific coastal plain to the southwest. Along the Tárcoles gorge and many of its tributary canyons, resistant ignimbrite deposits form level benches and isolated hilltops 50-100 m above the valley floor. Bedrock incision rates based on late Quaternary isotopic ages for the ignimbrites [40], range from 0.1 to 0.5 mm/yr. Several extinct, bowl-shaped calderas (e.g., Palmares and Atenas) centered along the northern flank of the Aguacate range may have generated silicic ignimbrites [36, 182].

3.3.1.3 Central Cordillera

The composite shield volcanoes of Costa Rica’s Central Cordillera, Platanar, Poás, Barva, Irazú, and Turrialba (Figs. 3.7 and 4.1), form an imposing northwest-trending mountain range, located northeast of the extinct Aguacate Cordillera [169, 181]. With peak elevations ranging from 2000-3400 m, these massive, broad-shouldered volcanoes tower above the adjacent low-relief landscape of Costa Rica’s densely populated Central Valley (Fig. 3.7). These are the largest volcanoes, in both area and volume, of the entire Central American volcanic front. Their summits exhibit wide calderas with multiple craters and transverse alignments of parasitic cones [169]. A strong climatic gradient across the range results in greater weathering and erosion, deeper stream incision, and more frequent landsliding on the humid Caribbean slope.

Along both flanks of the Central Cordillera (Fig. 3.7), gravitational spreading of the volcanic massif generates prominent fault-propagation-fold scarp along the base of the mountains [183]. These structures offset a sequence of Quaternary lava flows, ash flow tuffs, lahar deposits, and tephra that drape across the volcanic slopes. Streams that drain the steep slopes of the Central Cordillera have cut a radial network of deeply incised barrancas into the Quaternary volcanic sequence [36]. These canyons serve as
conduits that feed pyroclastic flows, lavas, and lahars toward the adjacent lowlands of both the Central Valley and Caribbean coastal plain.

3.3.1.4 Central Valley

The elongate Central Valley of Costa Rica (Fig. 3.7) consists of an east-west trending basin (600-1200 m elevation) situated between the active volcanoes of the Central Cordillera and the eroding volcanic remnants of the Aguacate range. Throughout the Quaternary, this highland basin filled with a thick accumulation (>1 km) of andesitic to dacitic lavas, pyroclastic rocks, lahars deposits, and lacustrine sediments [36, 181, 182].

The floor of the Central Valley (Fig. 3.7) consists of a low-relief upland surface with deeply incised river canyons cut into the underlying Quaternary volcanic sequence [35, 36]. These abrupt canyons outline a pervasive network of seismically active, northeast and northwest trending transcurrent faults that offset Neogene-Quaternary rock units throughout the Central Valley and adjacent volcanic ranges [34-36, 184-186]. In addition to controlling regional drainage patterns, these structures exhibit abundant geomorphic features associated with active faulting, including abrupt scarps, compression ridges, sag ponds, and perennial springs.

The active faults of the Central Valley mark the leading edge of the Central Costa Rica deformed belt [34], a diffuse deformation front that is propagating into the upper plate in response to shallow subduction of hotspot-thickened seafloor beneath central Costa Rica. This broad fault zone extends across the central Costa Rican volcanic front (Fig. 3.1), linking the North Panama deformed belt on the Caribbean coast, with the Middle America Trench on the Pacific margin. Throughout Costa Rican history, these faults have produced damaging, shallow-focus earthquakes, including the 1910 event that destroyed the colonial capital Cartago [187, 188]. Periods of heightened seismic activity along the Central Costa Rica deformed belt have been documented in association with large thrust earthquakes centered on both the Pacific and Caribbean margins [189-192]. This active deformation zone marks the western boundary of the Panama microplate [30, 34].

The fault-controlled drainage networks of the Central Valley feed into the Tárcoles gorge, a prominent canyon cut through the eroded highlands of the Aguacate Cordillera [35, 36]. This precipitous gorge provides a link between Central Valley rivers and the Pacific coastal plain below. During the Middle-Late Quaternary, the Tárcoles river breached the Aguacate drainage divide, leading to progressive capture and rerouting of Central Valley drainage networks toward the Pacific slope [35, 36].

The geomorphic evolution of Costa Rica’s Central Valley and surrounding volcanic cordilleras (Fig. 3.7) was profoundly affected by changes in Cocos plate subduction during the late Cenozoic. The propagation of irregular, hotspot-thickened seafloor down the subduction zone led to a shallowing of the subducting slab and a progressive retreat of the volcanic front from the Aguacate Cordillera to the Central Cordillera [36]. This northeastward expansion of the volcanic front resulted in the formation of the Central Valley basin and a shift in the location of the Pacific-Caribbean drainage divide. Linkage of the Central Valley drainage with the Pacific slope established a pathway for spillover of Quaternary pyroclastic flows and lahars onto the Orotina debris fan at the coast. Retreat of the volcanic front occurred only onshore of moderately thickened crust of the Cocos plate seamount domain, leading to formation of the Central Cordillera. Directly inboard of the subducting Cocos Ridge
(Fig. 3.1) to the south, volcanism shut off and rapid uplift maintains the drainage divide along the crest of the Talamanca Cordillera [36].

3.3.1.5 Talamanca Cordillera

Southeast of the Central Valley, the extinct Talamanca Cordillera (Fig. 3.7) corresponds with a 175 km volcanic gap that extends into western Panama [20-23]. These rugged mountains represent the only area of southern Central America above 4000 m in elevation. Similar in age to the Aguacate Cordillera (Fig. 3.7), the Talamanca range is composed of a suite of Neogene-Quaternary intrusive (principally granodiorites) and extrusive rocks (andesites) [162, 163, 166-170]. In contrast to the Aguacate range however, rapid Quaternary uplift and unroofing caused by Cocos Ridge subduction has stripped off large volumes of extrusive rock from the Talamanca range exposing the intrusive core. The highest peaks of this range were glaciated during the Pleistocene, leaving striking examples of moraines, tarns, and striated bedrock on mountaintops overlooking thickly vegetated tropical lowlands [46, 193-198] (also see Chapter 6).

3.3.1.6 Central Cordillera, Panama

The Talamanca volcanic gap of southern Costa Rica ends at the dormant Barú volcano (Fig. 3.7) at the western end of Panama's Central Cordillera [163-166]. This imposing stratovolcano towers above the Pacific coastal plain of western Panama. It features a 6-km-wide summit caldera that was breached on its western margin by a major Quaternary debris-avalanche. Lava flows and lahar deposits on the southwestern flank of Barú volcano are affected by incipient faults of the Terraba thrust belt, which is propagating southeastward along the margin in the wake of the migrating Panama triple junction [199-200]. In addition to Barú, the Panamanian cordillera also features several other Quaternary volcanoes, including La Yeguada and El Valle [164-166]. Isotopic ages on lava flows, in conjunction with youthful geomorphic features provide evidence for recent activity at these volcanoes.

3.3.2 Chorotega Fore Arc Province

The Chorotega fore arc (Fig. 3.4) extends along the Pacific coast from Costa Rica's Santa Elena peninsula in the north (Fig. 3.7), to the Gulf of Panama in the south (Fig. 3.8). This rapidly deforming convergent margin coast is characterized by abrupt topography [201] and a series of peninsulas and headlands that expose late Mesozoic oceanic basement rocks [202-205] and overlying pelagic to shallow marine sediments of Paleogene-Quaternary age [206-208]. These peninsulas and promontories, located in both Costa Rica and Panama, include Santa Elena, Nicoya, Herradura, Quepos, Osa, Burica, Soná, and Azuero (Figs. 3.7 and 3.8). Like the adjacent volcanic front, the Chorotega fore arc is highly segmented with sharp contrasts in structure and coastal morphology linked to variations in the subducting Cocos and Nazca plates offshore [28-37] (also see Chapter 7).

Along the Chorotega fore arc (Fig. 3.4), the subducting Cocos and Nazca plates exhibit dramatic variations in thickness, roughness, dip, and convergence angle that coincide with sharp contrasts in the style of upper plate deformation. Overall, the subducting seafloor has minimal sediment cover and, in many areas (e.g., offshore southern Costa Rica), is anomalously thick with substantial morphologic roughness
As a result, subduction erosion produces scarring and subsidence along much of the offshore fore-arc [159-161]. In contrast, however, the subaerial inner fore arc along the coast has experienced uplift in many areas, consistent with out-of-sequence thrusting or underplating beneath the margin [33, 35, 37].

The overall Quaternary deformation pattern along the Costa Rican coast strongly reflects the offshore bathymetry associated with the subducting Cocos Ridge (Fig. 3.1) and seamount domain [29, 33, 35]. In general, Quaternary uplift rates derived from radiometrically-dated marine and fluvial terraces decrease parallel to the margin, moving northwestward away from the subducting Cocos Ridge. These rates range from a maximum of 6-7 m/k.y. astride the ridge in the south, to background rates of <1 m/k.y. above smooth subducting crust in the north. This overall long-wavelength trend reflects a decrease in upward flexure of the overriding crust as the thickness of the subducting plate diminishes away from the Cocos Ridge axis.

Shorter-wavelength roughness related to seamounts superimposes local variability on this background uplift pattern [33]. Along the central Costa Rican Pacific coast (Fig. 3.7), uplift rates vary sharply across a series of margin-perpendicular faults that segment the coastal fore arc into discrete fault blocks [33-35]. While the central Costa Rican fore arc exhibits strong segmentation across fault-bounded blocks, the fore arc region south of Quepos (Fig. 3.7) deforms more uniformly by rapid shortening across the Fila Costeña fold and thrust belt [37, 109, 200].

3.3.2.1 Santa Elena Peninsula and Papagayo Gulf

The northern Chorotega fore arc (Fig. 3.7) meets the Sandino fore arc of the Chortis block along an abrupt boundary defined by the Murcielago fault zone on the Santa Elena peninsula [141, 209]. This structure follows a linear E-W trending valley that bisects the peninsula along its northern coast forming several prominent bays. The Murcielago fault zone marks a sharp change in geology and geomorphology from the northwest-dipping hogback ridges formed on late Cretaceous Sandino Basin marine sediments in the north, to the peninsula’s rugged interior highlands in the south formed on the Jurassic-Cretaceous ultra-mafic basement of the Santa Elena nappe [162, 202].

The morphology of the rugged shoreline extending southward from the Santa Elena peninsula to the northern Nicoya peninsula (Fig. 3.7) is determined primarily by resistant fault-bounded basement outcrops and steep cliffs formed of the overlying Guanacaste ignimbrites. At Punta Mala along the Bahía Culebra (Fig. 3.7), a surviving fragment of the ignimbrite mesa maintains steep columnar-jointed cliffs rising from a foundation of basement rocks. Coastal embayments here preserve a Quaternary fill wedge of shallow marine sediments that record active uplift [141].

3.3.2.2 Nicoya Peninsula

The Nicoya peninsula (Fig. 3.7) lies along an emergent segment of the Chorotega fore arc south of the Santa Elena peninsula. Separated from the Costa Rican mainland by the broad Gulf of Nicoya and Tempisque river basin, this large, rectangular peninsula covers over 4800 km$^2$ of the outer forearc [171-172]. The Nicoya peninsula’s rugged Pacific coastline features abundant pocket bays and sandy beaches, bounded by steep, rocky headlands. Uplifted marine terraces and paleo-beach deposits indicate active emergence throughout the late Quaternary [210-215]. In contrast, the peninsula’s gulf coast follows a low-relief alluvial plain with extensive mangrove estuaries. The coastal
piedmont along all sides of the Nicoya peninsula rises steeply into a mountainous interior highland that reaches over 900 m in elevation.

Basement rocks exposed on the Nicoya peninsula consist of the Cretaceous-early Tertiary Nicoya Complex, an intensely deformed oceanic sequence of pillow basalts, mafic intrusive rocks, and pelagic sediments [162, 202-205]. Along the margins of the peninsula, a sequence of upper Cretaceous to Quaternary marine sediments drapes unconformably across the Nicoya Complex basement [206-208]. These sediments include Cretaceous-Paleocene turbidites, Eocene deep-water carbonates, Miocene shelf clastics and a shallowing upward sequence of Plio-Pleistocene shelf sandstones and conglomerates.

Located only 60 km inboard of the Middle America Trench (Fig. 3.1), the Nicoya peninsula lies directly above the seismogenic zone [211, 213-215]. This unique location results in pronounced seismic cycle deformation, which is readily observed along the peninsula’s shorelines. Coseismic uplift of >1m affected the Nicoya peninsula’s central Pacific coastline during the M 7.7 subduction earthquake of 1950 [211]. Since that event, interseismic strain has led to notable subsidence along this same shoreline. Seismicity and GPS data indicate that the peninsula occupies a high-potential seismic gap that is accumulating strain in advance of the next event [216, 217].

A sequence of Quaternary marine and fluvial terraces on the Nicoya peninsula (Fig. 3.7) provide a record of continuing uplift along this segment of the Chorotega fore arc [35, 210-215]. High-elevation remnants of a Pliocene-Pleistocene marine erosion surface (Cerro Azul surface) are preserved within the peninsula’s interior mountain block [210]. Deformation of this surface records differential uplift across a series of mountain block faults. A lower elevation alluvial terrace (La Mansión surface) occupies interior river valleys at 4-10 m above local base level [210].

Near Cabo Blanco at the southern tip of the Nicoya peninsula (Fig. 3.7), a prominent late Pleistocene marine erosion surface (Cobano surface) is cut across Pliocene-Pleistocene shallow-water sediments and late Cretaceous oceanic basalts [35, 210-215]. This uplifted erosion surface forms a broad dissected mesa between the interior mountains and abandoned sea cliffs near the coast. The Cobano surface encompasses at least four distinct Pleistocene marine terrace treads ranging in elevation from 15 m to 220 m above sea level. Age correlation with late Pleistocene sea level high stands at 60-215 ka (marine oxygen isotope stages 3-7) indicate net uplift rates of 1.0-2.0 m/k.y. [213-215]. Radiogenic ages (Optically Stimulated Luminescence) for terrace deposits on the lowest three treads are consistent with sea level correlations, indicating ages of 65-120 ka (marine oxygen isotope stages 3-5). The Cobano terraces exhibit a measurable decrease in tread elevation toward the northeast, away from the Middle America Trench. Uplift and tilting, beginning in the middle to late Pleistocene, led to emergence of the Nicoya peninsula's southern tip and erosion of the Cobano terraces during sea level highstands of the late Pleistocene.

An adjacent set of narrow (<1 km), low-lying (<20 m elevation) Holocene terraces (Cabuya surface) occur between the active shoreline and the abandoned sea cliffs along the seaward edge of the Pleistocene Cobano surface [211]. These wavecut platforms have emerged where uplift rates exceed the rate of late Holocene sea level rise. Radiocarbon dating of 35 samples from fossiliferous, intertidal sand and beach rock deposits yielded late Holocene ages ranging between 0.3-7.4 ka [35, 211, 212]. Uplift rates decrease from a maximum of 6.0 m/ky near Cabo Blanco, to <1.0 m/ky along a 20 km length of both the margin-perpendicular and margin-parallel coastlines of the
peninsula's southern tip. This trend indicates active rotation of Holocene paleo-shorelines toward the north, consistent with the tilt observed on the adjacent Pleistocene Cobano terraces. Rapid uplift and northward tilting of the Nicoya Peninsula's southern tip has been attributed to seamount subduction offshore of the Cabo Blanco headland [35, 211, 212].

Along the northern coast of the Nicoya peninsula (Fig. 3.7), an additional late Pleistocene marine erosion surface (Iguanazul surface) is cut across late Cretaceous seafloor basalts [213-215]. The Iguanazul surface consists of at least three separate wave-cut treads that preserve paleo-shorelines from 10-32 m in elevation. Age correlation with late Pleistocene sea level high stands at 80-215 ka (marine oxygen isotope stages 5-7) indicate net uplift rates of 0.1-0.3 m/k.y. Radiocarbon-dated beach rock horizons along the active beach yield Holocene ages consistent with recent uplift at <0.5 m/k.y. [213-215].

While the northern Nicoya peninsula lies onshore of the Cocos plate "smooth domain", the southern peninsula sits inboard of subducting seamounts of the "rough domain" (Fig. 3.1). The order-of-magnitude difference in Quaternary uplift rates between the northern Nicoya peninsula (Iguanazul surface) and the southern peninsula (Cobano surface) may be linked to sharp contrasts in the roughness, thickness, and dip of the subducting Cocos plate offshore. Rapid uplift and block rotation of the peninsula’s southern tip is consistent with seamount subduction along the projected trend of the Fisher seamount chain [35, 211, 212]. A large subduction earthquake centered offshore of Cabo Blanco in 1990 (M 7.0) may have ruptured a seamount asperity, imaged both by aftershock locations and seismic tomography [190, 218].

3.3.2.3 Orotina-Esparza Coast

Along 150 km of coastline south of the Nicoya peninsula (Fig. 3.7), major trunk rivers draining the inner forearc flow along a system of active, coast-orthogonal faults. These steep faults segment the inner forearc coastline into seven fault-bounded blocks with sharply differing Quaternary uplift rates as determined from elevated marine and fluvial terraces [30, 33-36]. These fault blocks are named (from north to south): Esparza, Orotina, Herradura, Esterillos, Parrita, and Quepos.

The coastline between the Nicoya Peninsula and the Herradura headland (Fig. 3.7) consists of a low-relief (<250 m) coastal piedmont (750 km²) along the base of the extinct Aguacate volcanic range [35, 36, 219]. This region includes the lower drainage basins of the Barranca, Jesús María, and Tárcoles rivers, which flow southwestward into the Gulf of Nicoya. These rivers follow fault-controlled valleys incised within Neogene-Quaternary nearshore sediments, volcanioclastic debris, and pyroclastic deposits. The Barranca, Jesús María, and Tárcoles faults form the boundaries of the Esparza and Orotina fault blocks.

The low-lying Orotina fault block (Fig. 3.7) between the Jesús María and Tárcoles rivers is covered by a >100 m thick Quaternary sequence of lahar deposits, ash flows, volcanioclastic sands, and fluvial gravels [35, 36, 219]. During the early Quaternary, a series of eruption-generated lahars descended from the volcanic front onto the coastal plain, forming the framework of a 25-km-wide debris fan (Orotina fan). Rapid headward erosion across the Aguacate drainage divide led to stream capture within the Central Valley (Fig. 3.7) and deep incision of the modern drainage system funneling toward the Tárcoles gorge. This shift in the location of the Pacific-Caribbean drainage divide opened a pathway for pyroclastic flows to spill over onto the Orotina debris fan...
at the Pacific coast. Meandering paleo-channels of the Tárcoles river are preserved across the fan surface as inverted topographic ridges of welded tuff overlying river gravels [35, 36].

The interior of the Orotina fault block is cut by a series of active northeast-striking dip-slip faults resulting in horst and graben topography that exposes Miocene sediments and Plio-Pleistocene lahar deposits within isolated topographic highs [34-36]. These faults show up to 50 m of vertical displacement within a welded tuff dated at 350 ka. Earthquake focal mechanisms, historical ground ruptures, mapped Quaternary offsets, and mesoscale fault data from the Orotina debris fan are all consistent with transtensional deformation across the northeast-striking margin-perpendicular faults.

Up to five late Quaternary alluvial fill terraces (10-260 m elevation) occur along the lower reaches of the fault-controlled Barranca and Tárcoles rivers [35]. Vertical offsets of terrace treads and Holocene marine benches at the coast indicate active slip along these faults. The upper river terrace (El Diablo surface) forms an extensive upland along the foot of the Aguacate Cordillera [30, 35, 36, 219]. This surface caps a thick accumulation (>50 m) of highly weathered alluvial gravel that exhibits a distinctive, bright-red, clay-rich soil. This deeply weathered fill terrace resembles others found along many of the major river systems draining the Chorotega forearc.

These pervasive valley-fill deposits are interpreted as uplifted alluvial prisms formed during sea level rise toward eustatic highstands of the late Quaternary [35]. Lower, inset terraces may also reflect valley aggradation during periods of sea level rise. A regional terrace correlation framework developed for the Costa Rican Pacific margin [35] establishes constraints on the distribution and magnitude of fore arc uplift during the Quaternary. These correlations are based on terrace elevations, radiometric ages, soil and weathering rind characteristics, and stratigraphy of terrace deposits. The total number of terraces, and the vertical spacing between them, varies along the coast with respect to the magnitude of local tectonic uplift rates. This relationship suggests that terrace generation along this coastline is strongly controlled by the interaction of rock uplift and eustatic sea level fluctuation.

3.3.2.4 Herradura Headland

The Herradura headland (Fig. 3.7) exhibits the highest topographic relief within the Chorotega fore arc (>1700 m). This fault-bounded block exposes late Cretaceous oceanic basalts, which have been stripped of their sedimentary cover by rapid Quaternary uplift and erosion. The differential uplift between the Herradura block and adjacent lower-relief blocks is accommodated by dip slip along steep margin-perpendicular faults [33-35]. Holocene river terraces and wavecut benches attest to rapid uplift along the Herradura headland. The absence of Pleistocene terraces here may reflect high uplift rates and accelerated erosion along the steep mountain front. Rapid uplift of the Herradura block may be driven by seamount subduction beneath the margin, as suggested by extensive scarring of the margin wedge offshore [151, 152].

3.3.2.5 Quepos-Parrita Coast

The Quepos-Parrita coastal piedmont (Fig. 3.7) southeast of the Herradura promontory consists of a low-relief embayment in the coastal mountain front where the Fila Costeña thrust belt merges with the northern Talamanca Cordillera. This area encompasses the Esterillos, Parrita, and Quepos coastal fault blocks inboard of the
rough domain on the subducting Cocos plate [33-35]. Several major rivers descending from the interior highlands traverse the Quepos-Parrita piedmont on their way to the Pacific coast. Active faulting in this area has disrupted drainage patterns, uplifting Quaternary river deposits to form flights of fluvial terraces [220-225]. High sediment loads have formed a low-relief coastline with barrier beaches and mangrove estuaries, interrupted only by an isolated rocky headland at Quepos.

The rugged, high topography of the Herradura block (Fig. 3.7) descends abruptly to the southeast where a major dip-slip fault separates it from the lower-relief upland of the Esterillos block [33-35]. The dissected upland surface of the Esterillos block is formed on a thick accumulation of alluvial gravels deposited by the paleo-Parrita river [35, 225]. Four separate late Pleistocene terrace treads occur on these deposits, ranging from 40-185 m in elevation above river level. These terraces extend up to 15 km northwest of the Parrita river, indicating channel migration in response to late Quaternary uplift and tilting of the Esterillos block. Like other fore-arc rivers along the central Costa Rican coast, the Parrita river flows along a steep dip-slip fault oriented perpendicular to the margin [33-35]. This structure accommodates differential uplift between the Esterillos fault block and the lower-elevation Parrita block to the southeast.

The smaller Quepos fault block (Fig. 3.7) has experienced pronounced uplift relative to the surrounding Parrita lowlands. Similar to other peninsulas and promontories along the Chorotega fore arc of Costa Rica and Panama, the Quepos headland exposes Cretaceous-Paleogene oceanic basement rocks [33]. Several drainage networks on the Parrita coastal plain are deflected around the Quepos highland and exhibit at least four late Quaternary terraces that attest to active uplift [220-223].

3.3.2.6 Fila Costeña

The Fila Costeña (Fig. 3.7) is a steep-fronted, linear mountain range that runs sub-parallel to Costa Rica's southern coastline from the Herradura headland to the Panama border [37, 220-224]. This abrupt coastal topography (>1 km of local relief) formed during the late Cenozoic by rapid fore-arc shortening and crustal thickening inboard of the subducting Cocos Ridge [37]. Four major thrust faults imbricate Tertiary rocks of the Terraba basin, producing rapid uplift along the Fila Costeña range front. These faults are exposed along the Terraba river gorge (Fig. 3.7), which cuts across the range front, linking the General and Coto Brus valleys with the Pacific coast [32, 37, 224]. The Terraba river serves as the primary drainage for the Pacific slope of the Talamanca Cordillera (Fig. 3.7) which rises to the northeast of the Fila Costeña. Four Quaternary fluvial terraces occur along the Terraba gorge, with some surface elevations reaching >250 m above modern river level [224]. Irregular terrace profiles, offset gravel deposits, and sharp variations in mountain-front morphometry attest to active uplift and faulting within the Fila Costeña thrust belt [220, 221, 224]. The frontal thrust of the Fila Costeña separates a subsiding outer fore arc offshore of southern Costa Rica from the onland area of rapid uplift within the inner forearc [37]. This pattern is broken only directly inboard of the axis of the subducting Cocos Ridge, where rapid uplift in the outer forearc has formed the Osa peninsula [29].

3.3.2.7 General and Coto Brus Valleys

The General and Coto Brus valleys (Fig. 3.7) occupy an elongate structural basin that stretches for over 100 km along the Pacific slope of the Talamanca Cordillera. This
basin is separated from the Pacific coastal plain to the southwest by the Térraba thrust belt within the Fila Costeña. A series of broad alluvial fans coalesce along the foot of the Talamanca Cordillera, forming an extensive piedmont surface covering over 400 km$^2$ of the valley bottom [226-229].

Tributaries of the General and Coto Brus rivers, which drain the Talamanca highlands (Fig. 3.7), have deeply incised within this fan complex leaving a sequence of terrace remnants along canyon margins. These alluvial surfaces are distinguished from one another based on geomorphic setting, sedimentary texture, and the morphologic and chemical characteristics of soils [226, 228]. The oldest geomorphic surfaces coincide with the extensive piedmont upland in the northwestern portion of the General Valley. These well-drained upland surfaces exhibit dark-red, deeply weathered lateritic oxisols. A series of lower fan surfaces with less-developed soils yield late Pleistocene radiocarbon ages. The youngest alluvial surfaces consist of low elevation aggradational terraces inset along river canyons and abandoned braided channel bars of the General and Coto Brus rivers.

3.3.2.8 Osa Peninsula

The Osa peninsula (Fig. 3.7) within the outer Chorotega fore arc of southern Costa Rica has formed by rapid uplift and crustal shortening directly above the axis of the subducting Cocos Ridge [29]. This rugged peninsula covers over 1200 km$^2$ and exposes a highly deformed sequence of late Cretaceous-Paleogene oceanic basement rocks and accreted marine sediments [204, 205]. The Osa peninsula segment of the Middle America Trench is a known source for large (M $\geq$ 7.0) subduction earthquakes associated with underthrusting of the buoyant Cocos Ridge [191, 192].

Quaternary marine sands, beach ridges, and alluvial gravels along the Osa peninsula's shorelines record high rates of tectonic uplift (6.5-2.1 m/k.y.) that decrease along an arcward trend from the peninsula's interior, northeastward toward the Dulce Gulf [29, 224, 230]. Along the peninsula's abrupt seaward-facing coast, late Pleistocene shallow marine sands dated at 27-50 ka are preserved in fill wedges overlying basement rocks at $>75$ m above sea level [230]. Along the northeastern coastal piedmont, a sequence of uplifted beach ridges yield radiocarbon ages ranging from $<1$ ka near the modern shoreline to $>30$ ka at an elevation of 25 m [29]. Rivers draining the coastal piedmont exhibit two extensive Pleistocene gravel terraces that form a thick alluvial apron across the fault-bounded mountain front [224]. These deposits overlie nearshore marine sediments dated at $>30$ ka. Two lower terraces with late Holocene radiocarbon ages occur adjacent to active channels attesting to continued uplift.

3.3.2.9 Burica Peninsula

The elongate Burica peninsula (Fig. 3.7) juts southward into the Pacific Ocean forming a 25-km-long promontory at the Costa Rica-Panama border. This emergent fragment of the outer Chorotega fore-arc exposes a basement of Cretaceous-Paleogene oceanic basalts overlain unconformably by a Plio-Pleistocene sequence of marine sands, conglomerates, and turbidite beds [28, 231]. Facies relationships and faunal assemblages indicate that Pliocene subsidence was interrupted by rapid Pleistocene uplift [28]. The Plio-Pleistocene sediments exhibit significant folding and vertical displacement along a prominent north-trending fault valley that bisects the peninsula. Uplifted wavecut platforms along the peninsula’s coast attest to ongoing deformation.
Faulting and uplift here are attributed to subduction of the Cocos Ridge and passage of the Panama Triple Junction [28].

3.3.2.10 Soná and Azuero Peninsulas

The Soná and Azuero peninsulas (Fig. 3.8) of western Panama together form a major forearc promontory (>10,000 km²) that extends over 100 km southward into the Pacific Ocean from the Panamanian isthmus. This prominent coastal landmass forms the eastern edge of the Gulf of Chiriquí and the western shore of the Gulf of Panama (Fig. 3.8). Both peninsulas feature central mountain ranges (>500 m elevation) that are separated from the volcanic cordillera to the north by east-west trending lowlands. The two peninsulas are separated from each other by the narrow north-trending Gulf of Montijo (Fig. 3.8). Offshore to the southwest of the Soná peninsula, lies Coiba Island within the Gulf of Chiriquí.

The mountains of the Soná and Azuero peninsulas are both cut by the northwest-trending Soná-Azuero fault [38]. This major left-lateral strike-slip fault forms a prominent lineament that cuts across the peninsulas along a series of aligned river valleys. Deformation along the Soná-Azuero fault affects a 40-km-wide zone marked by steep fault scarps and prominent linear valleys [38]. This fault separates two distinct suites of basement rocks common to both peninsulas. South of the fault, the basement is comprised of homogenous Cretaceous seafloor basalts, while to the north it consists of a heterogeneous late Cretaceous-Eocene volcanic arc complex of basalts and intrusive rocks overlain by intermediate lavas. Offshore to the southwest, the Coiba fault zone runs parallel to the Soná-Azuero fault, resulting in uplift at Coiba Island [232].

3.3.3 Chorotega Back Arc Province

The Chorotega Back Arc Province (Fig. 3.4) extends from the vast Caribbean plains of the Tortuguero lowlands in northeastern Costa Rica (Fig. 3.7) to the abrupt emergent shorelines of the southern Limón and Bocas del Toro basins near the Costa Rica-Panama border. While the Tortuguero lowlands in the north feature an extensive low-relief alluvial plain with a relatively monotonous shoreline, the southern Limón and Bocas del Toro region exhibits a narrow, higher-relief coastal plain with a rugged shoreline of rocky headlands and intervening embayments [171, 172]. The sharp geomorphic contrast between these regions reflects a sudden shift along the Chorotega back arc from relatively stable tectonics in the north, to active crustal deformation within the North Panama deformed belt in the south.

3.3.3.1 Tortuguero Lowlands

The Tortuguero lowlands (Fig. 3.7) of the northern Chorotega back arc encompass an extensive alluvial plain that reaches 40-70 km seaward from the base of Costa Rica’s Central volcanic cordillera. A series of major rivers draining the volcanic cordillera traverse the alluvial lowlands, transporting a high sediment load for deposition across broad inland flood plains and a coalescing delta complex at the coast. A sequence of massive alluvial fans has developed along the foot of the volcanic cordillera where the major rivers exit the mountain front [229]. In many cases, modern rivers have incised below extensive upland fan surfaces comprised of thick accumulations of Pleistocene fluvial gravels, capped by well-developed, deep-red, clay-rich soils [233]. These soils
and associated aggradational surfaces may be age correlative with the Pleistocene alluvial terraces observed along Costa Rica's Pacific fore arc [35].

Along the Tortuguero coast (Fig. 3.7), the low-relief, sediment-laden shoreline traces a broad, continuous arc for over 120 km between the San Juan River in the north and the Limón headland in the south. This coastline consists of a 10-15 km wide band of prograding, shore-parallel, beach ridges that stretch along the margin of the vast alluvial plain. The lower reaches of rivers approaching the coastline are often deflected between the shore-parallel beach ridges, resulting in a coastal morphology of elongate lagoons and narrow barrier islands. At several locations along the Tortuguero coast, the low-relief landscape is interrupted by abrupt hills generated by Neogene-Quaternary back-arc volcanism. These volcanic hills, however, represent only a minor departure from the overall monotonous topography of the Tortuguero lowlands.

3.3.3.2 Southern Limón and Bocas del Toro Coast

The low-relief landscape of the Tortuguero region contrasts sharply with the rugged emergent morphology of the southern Limón and Bocas del Toro coastlines to the south (Fig. 3.7). Along this southern segment of the Chorotega back arc, a narrow coastal plain (<20 km) with undulating topography runs along the steep Caribbean slope of the Talamanca mountains. This stretch of rugged coastline extends for >200 km from Costa Rica's Limón headland in the northwest (Fig. 3.7), to Panama's Bocas del Toro archipelago and Gulf of Mosquitoes in the southeast (Fig. 3.8).

The coastal morphology of the southern Limón region is characterized by a series of rocky promontories and coastal islands interspersed with pocket bays and wide crescent-shaped beaches. Coral reefs and prominent cliffs occur along some segments of coastline, while other areas feature broad estuaries, peat swamps, and barrier beaches. At Bocas del Toro in northwestern Panama, an extensive low-relief coastal embayment (70 km wide) lies inboard of an emergent string of cliff-lined islands and promontories. To the east of Bocas del Toro, the Chorotega back arc extends along the Gulf of Mosquitoes where a series of river deltas form localized bulges in the coastline.

The rugged geomorphology of the Limón and Bocas del Toro region (Fig. 3.7) is controlled by active crustal shortening within the North Panama deformed belt along the Caribbean margin of the Panama block [234]. Rapid uplift above northeast-verging thrust faults has led to the emergence of Quaternary coral terraces along the southern Limón coastline [235]. Active subsidence has also produced a low-relief trough inboard of the emergent islands of the Bocas del Toro archipelago. During the 1991 M7.6 Valle de la Estrella earthquake, coseismic uplift of 0.5-1.5 m affected the southern Limón coast [236], while subsidence of 0.5-0.7 m resulted in inundation of peat swamps along the Bocas del Toro embayment [237]. Toward the northwest, the zone of active coastal deformation ends abruptly at the Limón headland, where thrust faulting within the North Panama deformed belt gives way to oblique slip along steeply-dipping faults of the Central Costa Rica deformed belt [34, 235].

Uplift along the Limón-Bocas del Toro coast (Fig. 3.7) has exposed a Neogene sequence of marine to terrestrial sediments and volcanic rocks along coastal cliffs and islands [238-241]. These deposits are correlative with similar units mapped in the Canal Zone and Darién regions of Panama [242, 243]. As a whole, this rock sequence provides a detailed record of Neogene emergence along the Panama isthmus, resulting in closure of the oceanic strait between the Atlantic and Pacific Ocean basins [8, 9].
3.3.4 Canal Zone Lowlands Province

The Panama Canal Zone (Fig. 3.4) occupies a region of relatively low topography between the Central Volcanic Cordillera of western Panama and the mountainous Darien isthmus to the east (Fig. 3.8). This lowland encompasses a network of low-gradient river valleys that drain surrounding hills with peak elevations of less than 1200 m [244]. The Pacific-Caribbean drainage divide descends to one of its lowest elevations in Central America (~200 m) in the low saddle of the Culebra Cut along the Panama Canal (Fig. 3.8). The most pronounced expression of low topography in this region is the once-extensive swamp within the broad valley of the Chagres river, now covered by the Panama Canal’s Gatún lake [245].

The stratigraphy of the Canal Zone Lowlands includes a Cretaceous volcanic basement that is overlain unconformably by a thick sequence of Eocene-Miocene shallow marine and terrestrial sediments [242, 244-248]. These rocks are moderately folded, and were affected by late Neogene faulting and uplift that produced localized bedrock highs within fault-bounded blocks [38, 245]. Within adjacent topographic lows, these sedimentary rocks are buried unconformably by a horizontal valley-fill sequence of Pleistocene-Holocene estuarine and swamp deposits referred to as the Atlantic Muck.

3.3.4.1 Gatún Fracture Zone

The low topography of the Canal Zone (Fig. 3.8) has been attributed to pervasive faulting and fracturing that extends across the Panamanian isthmus within an 80-km-wide zone referred to as the Canal Discontinuity or the Gatún Fracture Zone [244, 245, 248]. This major crustal discontinuity has been interpreted as a Neogene-age basement fault that divides the Chorotega block to the west from the Chocó block of eastern Panama and western South America [4].
Seismic imaging along the Caribbean coast indicates that faulting in the Canal Zone post-dates late Miocene strata and may in some cases displace overlying Quaternary beds of the Atlantic Muck [245]. Prominent geomorphic lineaments, topographic breaks, and bends in river courses are all consistent with a young, fault-controlled landscape [244-246]. For example, a major northeast-trending fault lineament along the Rio Gatún (Fig. 3.8) forms the southern boundary of a basement highland at the northern end of the Canal Zone. This lineament extends eastward into the northern coastal ranges of the Darién Isthmus and is interpreted as a major left-lateral strike-slip fault [38]. Abundant north-striking and generally east-facing scars south of the Gatún fault suggest that the Canal Zone is undergoing active east-west extension across a series of normal faults [38]. These normal faults may represent the western termination of left-lateral shearing along major strike-slip faults within the Darién region of eastern Panama.

3.3.5 Darién Isthmus Province

The Darién Isthmus (Fig. 3.4) of eastern Panama is bounded by a northwest-trending set of rugged mountains along both its Caribbean and Pacific coasts (Fig. 3.8). These include the San Blas and Darién ranges along the Caribbean coast, and the Majé, Bagre, and Sapo ranges along the Pacific side. These coastal highlands flank an elongate lowland basin centered along the broad valleys of the Bayano, Chucunaque, and Tuira rivers (Fig. 3.8). On the Pacific coast, the Gulf of San Miguel (Fig. 3.8) forms a deep bight into the coastal mountains where the Tuira river estuary drains from the central lowland into the ocean. Much of the humid and rugged landscape of the Darién Isthmus remains cloaked in dense tropical vegetation, contributing to its reputation as one of Central America’s most remote regions.

The coastal massifs of the Darién Isthmus expose a Cretaceous-Eocene crystalline basement complex comprised predominantly of highly deformed mafic igneous rocks [142, 243, 248, 249]. These rocks belong to the Chocó block (Fig. 3.1), an allochthonous oceanic basement terrane that lies beneath eastern Panama and western Colombia [4]. The Chocó block is separated from the Chorotega block to the west, across Tertiary basement faults of the Panama Canal Discontinuity.

The basement rocks of the Darién region are overlain along the flanks of the coastal mountains by Eocene-Miocene pillow basalts and deep marine sediments deposited prior to Panama’s collision with South America [243]. These rocks are in turn buried by a thick, post-collisional sequence of Neogene siliciclastic sediments within the core of a complex synclinorium centered along the Bayano-Chucunaque basin.

Within Panama and southern Costa Rica, the Chocó and Chorotega basement terranes (Fig. 3.1) together form the modern Panama block, a semi-rigid microplate that is caught between the Caribbean, Cocos, Nazca, and South American plates [5, 6]. Fold and thrust belts offshore of both the northern and southern Darién isthmus (North and South Panama deformed belts) accommodate active convergence with the Caribbean and Nazca plates [39]. Active collision between the Panama block and the South American craton to the east occurs across thrust faults of the Atrato-Urubá suture zone in western Colombia [148].
3.3.5.1 East Panama deformed belt

Ongoing collision between the Panama block and South America results in clockwise rotation and left-lateral slip along several major northwest-trending faults that cut the eastern Darién Isthmus [38]. Together, these structures constitute a diffuse deformation zone referred to as the East Panama deformed belt [42]. The Sansón Hills, Sambú, Majé, and Jaqué River faults (Fig. 3.8) each follow prominent northwest-trending lineaments along the flanks of the Pacific coastal ranges.

The Sansón Hills fault forms the boundary between the Chucunaque basin (Fig. 3.8) and the coastal highlands to the southwest [38, 42]. Hilly topography northeast of the fault exposes Paleogene sediments of the Chucunaque basin within a series of breached, en-echelon anticlines. These folded strata are juxtaposed against Cretaceous oceanic basement rocks exposed southwest of the fault within the estuarine lowlands of the Tuira river.

The Sambú fault, southwest of the Tuira river (Fig. 3.8), marks the boundary between the Bagre and Sapo massifs near the coast [38, 42, 250]. A left-step in this fault bounds the Sambú pull-apart basin, which forms the entrance to the Gulf of San Miguel and a broad alluvial valley between the Bagre and Sapo ranges (Fig. 3.8). The Majé fault trends onshore to the northwest from the Gulf of San Miguel where it offsets basement rocks of the Majé massif [38, 42]. The Jaque River fault along the southwest range front of the Sapo Massif follows the Pacific coast southeastward from the Darién isthmus into western Colombia [38, 42, 250].

The northwest-trending left-lateral faults of the Darién Isthmus terminate at their southeastern ends along a zone of north-trending thrust faults within the Panama-South America suture zone [38, 42, 243]. Toward the northwest, the left-lateral faults die out as they approach north-trending extensional structures along the Canal Zone Discontinuity. The presence of undeformed Pliocene-Pleistocene sediments along fault valleys in the eastern Darién Isthmus may indicate that the left-lateral faults are no longer active [243]. If this is the case, the Panama block in this region may now be acting as a rigid plate as it collides with South America.

3.4 SUMMARY

The geomorphology of Central America is extraordinarily rich and varied (Fig. 3.4). This small fragment of land linking North and South America features a diversity of landforms and geomorphic processes usually associated with an entire continent. While accounting for only 0.4 % of the Earth's total land area, Central America encompasses a wide range of landscapes, from jungle-covered tropical lowlands to glaciated highland plateaus, from cloud-forested volcanic peaks to rolling dryland savannas, and from rocky tectonic shorelines to low-relief barrier islands and mangrove estuaries. This chapter presents a broad overview of Central American geomorphology, and defines a system of physiographic provinces (Fig. 3.4) that serves as a framework for characterizing regional landscapes and geomorphic processes.

The physiographic trend of the Central American isthmus is defined by the Middle America trench and volcanic front (Fig. 3.1), active since the initiation of subduction in the late Cretaceous. Cenozoic magmatic rocks and adjacent sedimentary basins are overprinted across four crystalline basement terranes, two of continental affinity beneath northern Central America (Maya and Chortis blocks), and two of oceanic origin (Chortis and Chocó blocks) beneath the southern isthmus. This geologic
template (Fig. 3.2) is in turn affected by active tectonics within three major plate-boundary deformation zones: the Motagua-Polochic transform faults of Guatemala, the Middle America convergent margin along the Pacific coast, and the diffuse collisional belts along the margins of Panama and Costa Rica. The delicate interplay between Central America’s highly variable climate and topography (Fig. 3.3) imparts an additional influence over regional geomorphology.

The Maya Highlands Province (Fig. 3.4) of northern Central America includes a series of high-altitude mountain ranges and plateaus that extend in a broad arc from Central Mexico, across northern Guatemala, to Belize. These highlands descend to the north onto the vast carbonate lowlands of the Yucatán Platform Province (Fig. 3.4), the most extensive karstlands of the North American continent. Along the southern margin of the Maya highlands, the Motagua Fault Zone Province (Fig. 3.4) extends across central Guatemala along a series of major fault-controlled valleys that define the active North American-Caribbean plate boundary.

The Chortis Volcanic Front Province (Fig. 3.4) parallels the Pacific margin from Guatemala to El Salvador, and consists of a series of clustered stratovolcanoes and calderas arranged along transverse fault lineaments. Along the Pacific slope, the Chortis Forearc Province (Fig. 3.4) encompasses a broad coastal plain made-up of coalescing alluvial debris fans that descend from the volcanic highlands. Behind the volcanic front, and south of the Motagua fault zone, the Chortis Highlands Province (Fig. 3.4) extends across the mountainous interior of Guatemala, Honduras, and Nicaragua. This extensive region of high topography includes a rifted plateau in the west, a stable central massif, a northern coastal borderland of fault-bounded ridges, and an eastern zone of dissected mountains facing the Caribbean coast. The Mosquito Coast Lowlands Province (Fig. 3.4), east of the Chortis highlands, encompasses the extensive alluvial plains along the Caribbean coast of Honduras and Nicaragua.

The Nicaraguan Depression Province (Fig. 3.4) consists of a fault-bounded structural basin that extends for 600 km between the coastal fore arc and the Chortis highlands. This tectonic lowland includes the Median Trough of El Salvador, the Gulf of Fonseca, and Lakes Managua and Nicaragua. The Nicaraguan Volcanic Front Province (Fig. 3.4) encompasses a chain of stratovolcanoes and calderas centered along the southwestern boundary faults of the Nicaraguan depression. The Sandino Fore Arc Province (Fig. 3.4), southwest of the Nicaraguan volcanic front, includes a low relief coastal plain composed of volcaniclastic debris in the north, and a rugged shoreline of pocket bays and rocky headlands in the south.

The Chorotega Volcanic Front Province (Fig. 3.4) of Costa Rica and Panama consists of a segmented series of distinct cordilleras that have evolved in response to highly variable tectonics along the southern Middle America margin. A major volcanic gap occurs along an uplifted segment above the subducted Cocos Ridge. The adjacent Chorotega Fore Arc Province (Fig. 3.4) encompasses a rugged tectonic coastline, characterized by prominent uplifted headlands and peninsulas, as well as an active fold and thrust belt inboard of the Cocos Ridge. The Chorotega Back Arc Province (Fig. 3.4) features a broad alluvial lowland in northern Costa Rica and a rugged coastline with uplifted coral reefs formed within an active back arc thrust belt. The Canal Zone Lowlands Province (Fig. 3.4) includes a swath of densely fractured, low relief landscape that extends across central Panama. To the east, adjacent to South America, the Darién Isthmus Province (Fig. 3.4) consists of a fault-bounded series of humid coastal mountain ranges flanking an elongate central valley.
As described throughout this chapter, the physiographic provinces of Central America (Fig. 3.4) each exhibit a characteristic assemblage of landforms that records a unique history of landscape evolution. The distinctive geomorphology of each province reflects a dynamic interplay between regionally variable rock types, active plate-boundary tectonics, and an energetic tropical climate. As a whole, the physiographic provinces of this dynamic region encompass an exceptionally diverse array of landscapes and associated landforms. Central America, therefore, serves as an outstanding geomorphic laboratory for the study of a broad range of surface processes and their imprint on the landscape.

REFERENCES


50 THE GEOMORPHOLOGY AND PHYSIOGRAPHIC PROVINCES OF CENTRAL AMERICA


