

Chapter 11

Structural geology: From local elements to regional synthesis

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“Northern (or nuclear) Central America is divided into the Maya and Chortis blocks, separated by the Motagua suture zone of Central Guatemala. These blocks have been assigned widely different histories by various authors. I take the view that their original positions were not widely separated.” T.W. Donnelly: Geologic history of the Caribbean and Central America; In: A.W. Bally and A.R. Palmer (eds.): *The Geology of North America*, Vol.A —An Overview, pp.299–321, 1989.

1.1 INTRODUCTION

Central America links North and South America at the western end of the Caribbean Sea, separating the latter from the Pacific Ocean. In this location the area is influenced by five plates: North and South America, Cocos and Nazca and the Caribbean, with Central America itself lying on the western end of the last plate (Fig. 11.1).

The area is inextricably linked to the history of rift and drift between North and South America and to the evolution of the Caribbean plate. To be properly understood, its geology has to be seen as part of a complex of fragmented continental, oceanic and volcanic arc crust between the large continental masses of North and South America. Its structural geology reflects inherited lineaments (Pangean, Paleozoic/older), fragmentation and offset during separation of the Americas and convergence with Pacific oceanic elements.

At the same time, Central American geology has important implications for the understanding of regional evolution. Literature popularly derives the Caribbean plate from a Pacific origin via complex histories involving major rotations of large continental blocks (> 50°, Maya and Chortis) from the Gulf of Mexico and southwest Mexico, of volcanic arcs (Greater and Netherlands-Venezuelan Antilles) and of the plate itself. This chapter suggests an understanding of the structure and origins of Central America in a simple plate-tectonic evolution that involves no major rotations or plate migrations.

The chapter summarizes the reported structural geology of Central America, moving from north to south, considering the major recognized tectonic blocks, their subaerial areas and their submarine extensions, their internal structures and their boundaries, main unconformities and volcanology (Fig. 11.1). These are related to

neighboring parts of the Pacific and the Caribbean and to the regional setting. The integrated geology suggests a new vision of the area and its tectonic evolution. Each section includes chronologically arranged literature extracts that show evolution of thought, while an extensive bibliography allows the reader to make further references.

The main published structural elements, compiled from many sources (IFP-Beicip [1], Exxon [2], GSA [3] and references therein), appear in Figure 11.1. Figure 11.2a shows the locations of subsequent illustrations. Satellite topography (Fig. 11.2a) and drainage patterns (Fig. 11.3) suggest further structures. Bathymetric data derived from satellite free air gravity anomaly inversion, and magnetic data provide information over oceanic areas.

Lack of detailed mapping, tropical vegetation and abundant Neogene volcanic deposits in some areas combine to make the Figure 11.1 very incomplete. Disappointing hydrocarbon exploration results in general also result in the area's being much less well known than the oil-rich Gulf of Mexico and northern South America. Consequently, there is wide variation in understanding of the origins and distribution of major blocks in the area and of the age, offset, style and role of major faults. The area is often discussed in isolation and adherence to popular models influences interpretation of data, introducing needless complication.

Lastly, the structural/tectonic understanding developed in this chapter requires the Yucatán Peninsula/Maya block of southeastern Mexico and Belize to be included in discussion.

11.2 HISTORICAL DEVELOPMENT OF RECOGNIZED MAIN TECTONIC COMPONENTS

Schuchert [4] called the northern part of Central America “Nuclear Central America” and the southeastern portion the “Isthmian Link”. In 1969 Dengo [5] defined Central America as the land (and “continental shelf”) between the Mexican isthmus of Tehuantepec and the Atrato lowlands of Colombia, and he subdivided Nuclear Central America into the Maya and Chortis blocks (Fig. 11.1), highlighting differences in basement metamorphic grade. Dengo [6] saw southern Central America as part of the Antillean foldbelt—oceanic rather than continental. In 1985, Dengo [7] subdivided the Isthmian Link into the Chorotega and Chocó blocks on the basis of gravity data. Berrangé *et al.* [8] referred to Chorotega and Chocó as the Southern Central America Orogen. Fisher *et al.* [9] recognized a Panamanian microplate; a fragment of volcanic arc separated from the Caribbean plate, defined by active fold and thrust belts.

Maya (in this chapter, Yucatán refers to the peninsula) and Chortis are recognized as continental blocks with Precambrian and Paleozoic crystalline sialic basement overlain by Mesozoic–Cenozoic red beds, carbonates, clastics, volcanic and volcanoclastic rocks. Accreted/obducted oceanic/volcanic arc rocks are also present. The blocks meet onshore along the curved Motagua fault zone (Fig. 11.1), a complex of sinistral faults and north- and south-verging thrusts regarded as a suture. The N–S trending, sinistral Salina Cruz fault that crosses the Tehuantepec isthmus of southern Mexico limits Maya to the west [10], while the E–W sinistral Santa Elena fault (or Gatún fault zone, [8]) separates Chortis from the area further south. For some authors [8, 11, 12], this fault also is a suture.

The Chorotega and Chocó blocks (Fig. 11.1) are characterized by troughs of marine Cenozoic deposits, with volcanic and plutonic igneous rocks, above Mesozoic oceanic

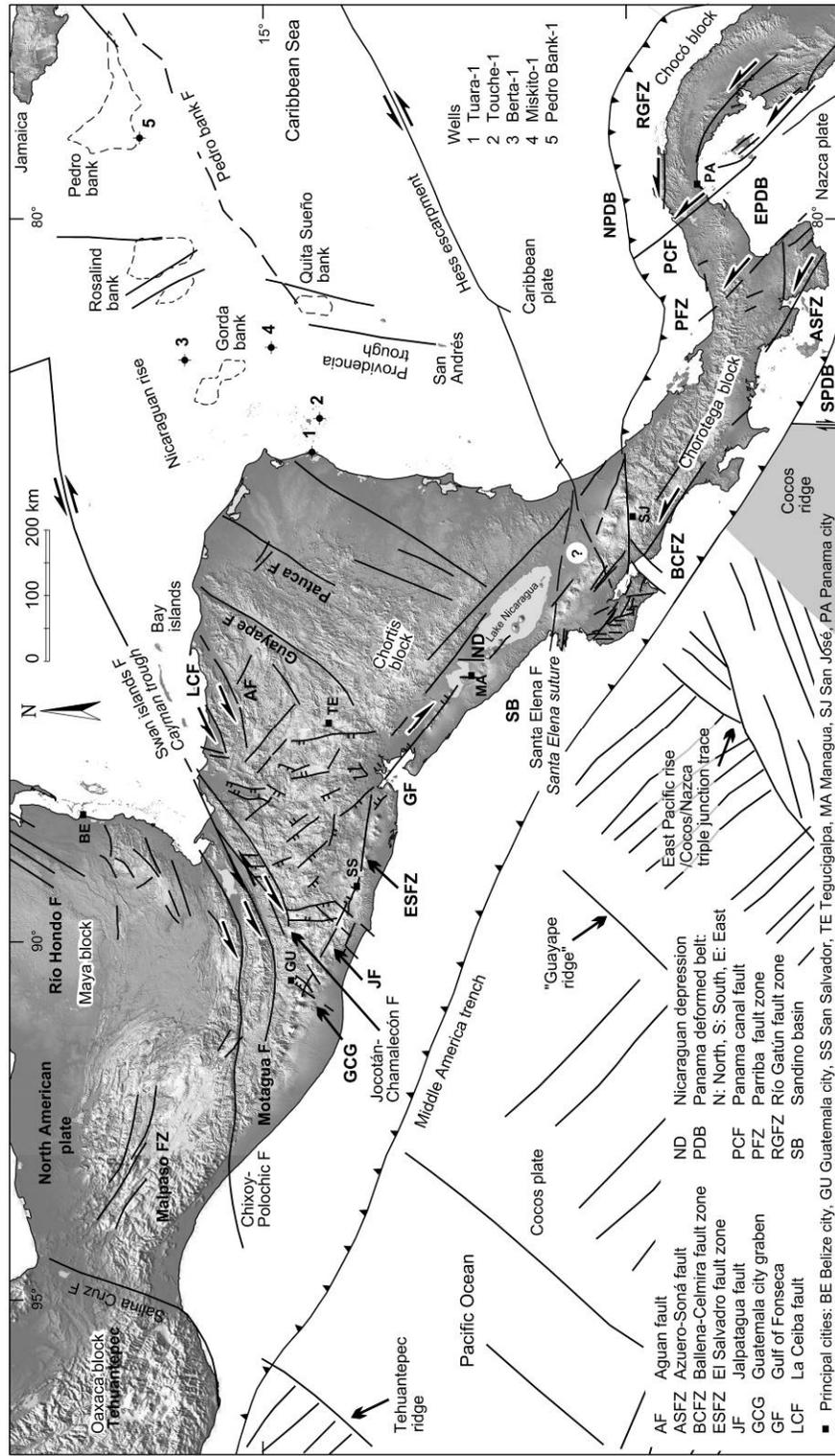


Figure 11.1. Central America —Main tectonic elements (Maya, Chortis, Chorotega, Chocó) and related plates (Cocos, Nazca, Caribbean, North and South America) and main structural elements.

rocks [8]. No continental rocks are known and the blocks are regarded as having intra-oceanic origins [8, 13]. They share composition and history but a negative Bouguer gravity anomaly along the Panama canal zone [14] is seen as a tectonic boundary. Dengo [7] noted that Neogene volcanic rocks, abundant in Chorotega, are rare in Chocó and that ophiolites on Chorotega (Nicoya complex) are generally older (Jurassic) than those on Chocó (*Complejo Basal* of Panama, Basic igneous complex of Colombia, mostly Cretaceous) [13].

The southern limit of Chocó is a major break, the Isthmina arch, in the Occidental cordillera of Colombia at 5°S [8]. The southern part of Chocó is welded to northwestern South America and plate boundary understanding here is confused.

Offshore to the west the Middle America trench runs along the margin of Chortis to Nicoya. It reflects subduction of the Cocos plate beneath Central America. South of the Cocos ridge, a narrow, sediment-filled trough flanks Costa Rica. The broad Panama basin lies south of the Panama isthmus. Its east–west southern boundary is seen by some as the Nazca-Caribbean plate boundary.

While Maya is seen as part of North America, Chortis, Chorotega and the northern part of Chocó lie on the western margin of the Caribbean plate. Dengo [8] argued that the latter two blocks lie on the South American plate. There is much discussion over the location of the southern margin of the Caribbean plate in southern Central America. Many papers state that the Caribbean plate is subducting below the North Panama ridge and the South Caribbean deformed belt. However, the Caribbean plate is moving eastwards relative to South America (e.g., [15]). The ridge and the deformed belt result from northward movement of the Panama arc and of delaminated NW South America. For this chapter, they do not define plate boundaries. Rather, both the northern and southern Caribbean plate boundaries are probably broad (several hundreds of kilometers) zones of approximately east–west distributed strike-slip [16–19].

11.3 BASIC GEOMETRIC OBSERVATIONS

The N60°W trend of the SW margin of the Central America parallels the Cuba, Bahamas, Blake Spur and Carolina fault zones (Fig. 11.2b). Thus the area between the SW Bahamian margin and the Middle America trench is bracketed by N60°W trending lineaments —the direction followed by North America as it moved away from Pangea during the late Jurassic–Early Cretaceous.

Maya and Chortis both have roughly triangular form, expanding to the north, which suggests common tectonic control. Both have considerable submarine areas. Their eastern margins trend N15°E in the south, marked by basement ridges in the offshore east of Maya and the Providencia trough east of Chortis (Fig. 11.1). Further north the eastern margins trend N35°E.

The Motagua fault zone and neighboring mountains at the junction between Maya and Chortis form a large, north concave curve or orocline. The pattern is repeated in northern Chortis, west of the Guayape fault (Sierra de Agalta), (Figs. 11.2a, b).

N35°E and N20°W trending scarps form the northwestern and northeastern margins, respectively, of the Campeche platform (Fig. 11.4a). The former parallel the Río Hondo and Guayape faults (Figs. 11.1 and 11.4b) of Yucatán and Honduras. The latter are approximately parallel to the eastern margin of southern Mexico and the western margin of the Florida platform.

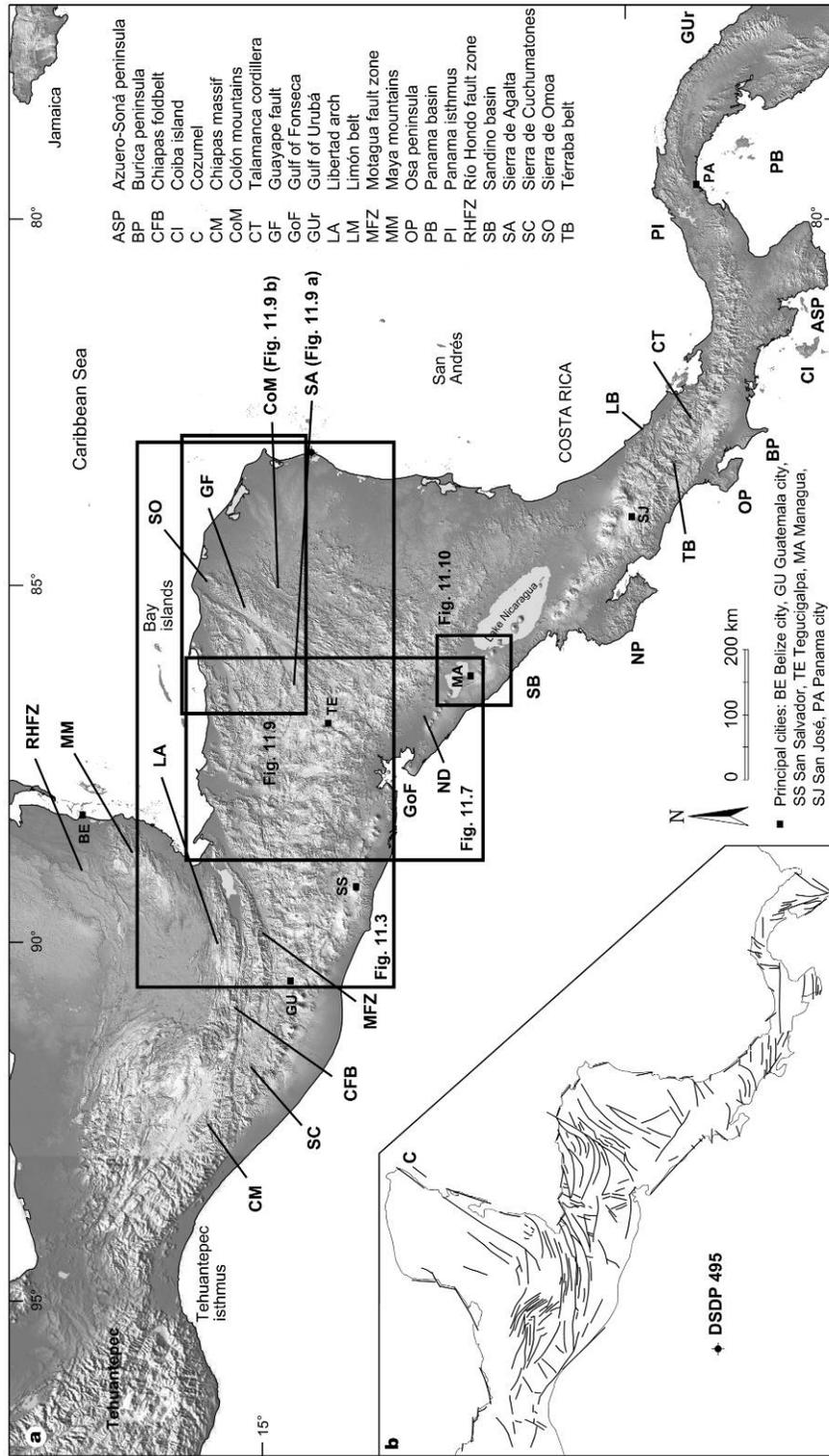


Figure 11.2. (a) Central America relief and location of following figures; (b) interpreted structural trends.

The Nicaraguan rise (Figs. 11.1 and 11.4) comprises upper and lower parts. The remarkably straight Hess escarpment trends N60°E for more than 1,000 km along the southern boundary of the lower rise. It parallels the “general” trend of the NW margin of the Campeche platform and eastern, onshore elements of the Motagua fault zone. The Upper rise tapers to the NE and becomes highly segmented into banks (Gorda, Rosalind, Pedro, Fig. 11.1) and the island of Jamaica, separated by N35°W trending channels. Its visual aspect on satellite-derived bathymetry repeats the highly extended appearance of the Bahamas platform. The Lower rise has an extremely extended/collapsed aspect.

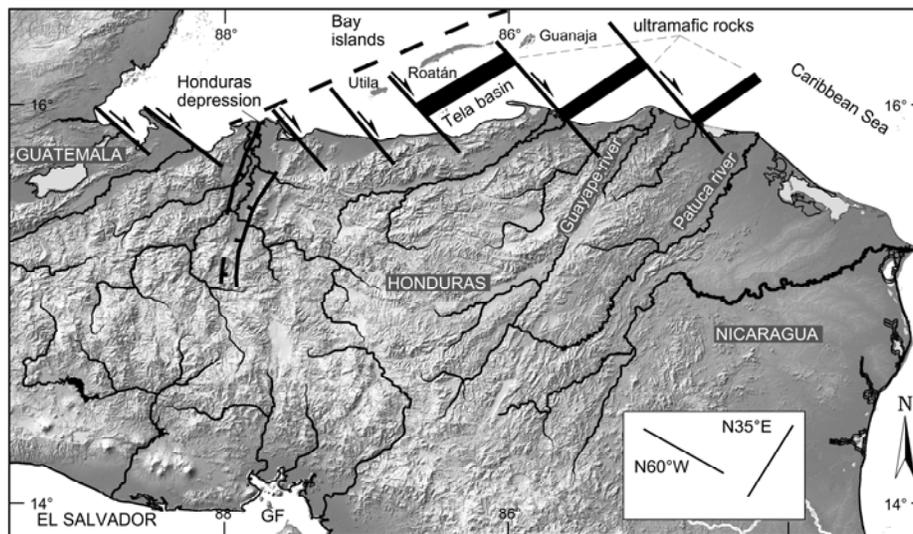


Figure 11.3. Drainage patterns of Honduras and adjoining Guatemala, El Salvador, Nicaragua (after Manton [20] reflect structure (N35°E and N60°W are common trends). NW trending dextral offsets of ultramafic rocks, defined by magnetic data, are related to the ENE trending “master” fault of the Cayman trend according to Pinet [21]. Repeated, parallel coastal segments suggest that such faults are common along the N coast of Chortis. They trend more westerly (N60°E) than shown on this figure (see Fig.11.2b), and would be synthetic to the N35°E “Guayape” trend.

Major N35°E trending faults (Río Hondo, Guayape, and Patuca) cross both Maya and Chortis. Chorotegua and southwest Chortis are characterized by N60°W trending faults, such as those bounding the Nicaraguan depression, parallel to the Middle America trench. Two major faults cut N30°W or N40°W across Panama. Chocó seems to continue the main structural trend of Chorotegua, offset to the north along the faults.

In the Pacific, fracture zones on the Cocos plate and the Cocos ridge trend N35°E where they meet Central America (Fig. 1.1). The Panama fracture zone (comprising the Panama, Balboa and Coiba fracture zones), east of the Cocos ridge, trends NNW–SSE. Magnetic lineaments in the Colombian basin trends E–W and probably reflect crustal structure; there is no recognized oceanic fracture pattern.

In summary, NE and NW structural trends dominate Central America. They parallel those that formed during late Jurassic–Early Cretaceous rifting and drifting of North America from Pangea. At least two major oroclines are present, associated with large-scale N35°E faults.

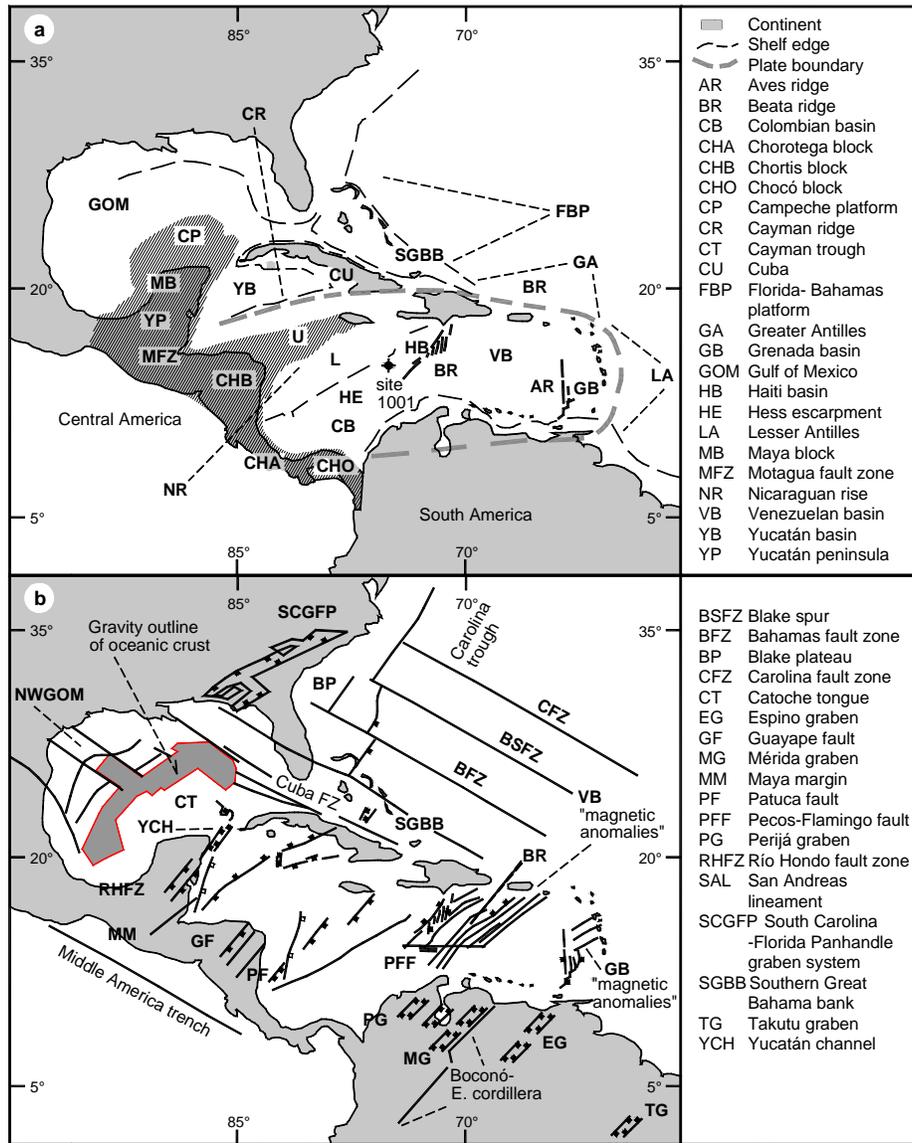


Figure 11.4. (a) Central America forms the western boundary to the Caribbean region. Its geology has to be seen in this regional context. Areas such as the Florida-Bahamas platform (FBP), the Nicaraguan rise (NR, Upper and Lower) and the margin of the Gulf of Mexico (GOM) are built of extended continental crust. The Greater (GA) and Lesser Antilles (LA), a large part of Cuba (CU) and the Chorotega (CH) and Chocó (CHO) blocks (Fig. 11.1) are generally seen to comprise volcanic arc rocks. The central Gulf of Mexico, the Cayman trough (CT) and the Yucatán (YB), Venezuelan (VB) and Colombian (CB) basins are floored by (generally undated) oceanic crust. There are no recognized spreading ridges or calibrated magnetic anomalies except for the central part of the Cayman trough (Early Miocene-recent). (b) highlights N60°W trending fractures in the western Atlantic and the Gulf of Mexico and the parallel Middle America trench. The fractures record the direction of North America's drift away from South America. Fig. 11.2b also highlights NE and NW trending faults of middle America. They formed during late Jurassic–Early Cretaceous rifting and drifting. The rifts on Maya and Chortis remain parallel to counterparts within continental North and South America and show that these units have not rotated.

11.4 MAYA

11.4.1 Onshore—the Yucatán peninsula

A thick carbonate platform conceals much of the deeper geology of the Maya block and there is little regional seismic coverage over the Yucatán peninsula [22]. Dengo [7] summarized from Bouguer gravity and seismic data that crustal thickness is 20–25 km in the north and 30–40 km in the south. Rosenfeld [22] suggested that the continental basement of Maya is stretched, since much of the block is covered by sedimentary overburden as much as 6 km thick; impossible on unstretched continental crust at isostatic equilibrium. Gravity and magnetic data indicate N35°E and N°45W deep trends that probably reflect Triassic/Jurassic rifting (Fig. 11.3; [23–25]). The most striking visible features are the Motagua fault zone and the associated large, concave-north orocline in the south, and the Río Hondo-Bacalar fault zone and related faults in the SE (Fig. 11.5).

The remarkably straight Río Hondo and related faults, herein referred to as the Río Hondo fault zone, trend N35°E (note that precisely parallel faults (Guayape, Patuca, Figs. 11.1 and 11.4) occur on the Chortis block and throughout Middle America). Structural contours at top Cretaceous evaporite level and isopachs of the unit also reflect this N35°E trend (Fig. 11.5) [23]. De Cserna [24] suggested that the Río Hondo fault was the onland continuation of the Yucatán channel. Wells [1, 23], encountered little or no Jurassic strata NW of the Río Hondo fault (Fig. 11.5; Yucatán-1, -2 and -4 penetrated red beds between Cretaceous evaporites and basement [23]). In contrast, Jurassic strata are common southeast of the fault.

The main structural trends of SW Maya are N60°W. Blair [26] reported that Jurassic units in western Guatemala and along the north flank of the Chiapas massif in Mexico (Fig. 11.2a) record sedimentation over horsts and grabens (abrupt variations in thickness and facies) associated with rifting in the Gulf of Mexico (see also [27, 28]). These trends are parallel to and on strike with late Triassic–Early Jurassic highs and grabens further north in Guayachil, Mexico [29].

The structural trends undoubtedly reactivate older lineaments. Kesler *et al.* (1970) concluded that the NW trend of metamorphosed Palaeozoic rocks of western Guatemala reflects the original sedimentary trend and Bartok (1993) emphasized that late Precambrian and early Palaeozoic orogenies as well as Pangean suturing controlled early Palaeozoic, Triassic and Jurassic rift systems.

11.4.2 Offshore—east Maya

The narrow shelf east of the Yucatán peninsula (Fig. 11.4a) is the faulted margin of the continental Maya block, probably formed during Jurassic rifting and drifting.

Baie [31] described the prominent NE–SW trending bathymetric high defined by Banco Arrowsmith-Cozumel island (Figs. 11.5 and 11.6) at the northeastern point of the Yucatán peninsula. Seaward of this lies a 1200 m deep linear depression, flanked to the east by an elongate series of isolated bathymetric highs. They form a linear ridge (the outer Ridge) that continues to the western end of Cuba. They connect the two areas both structurally and geologically. Phyllite and marble dredged from the lower part of the continental slope between Yucatán and Cuba indicate basement of continental crust [32].

Dillon and Vedder [33] described five sea-floor ridges further south, offshore

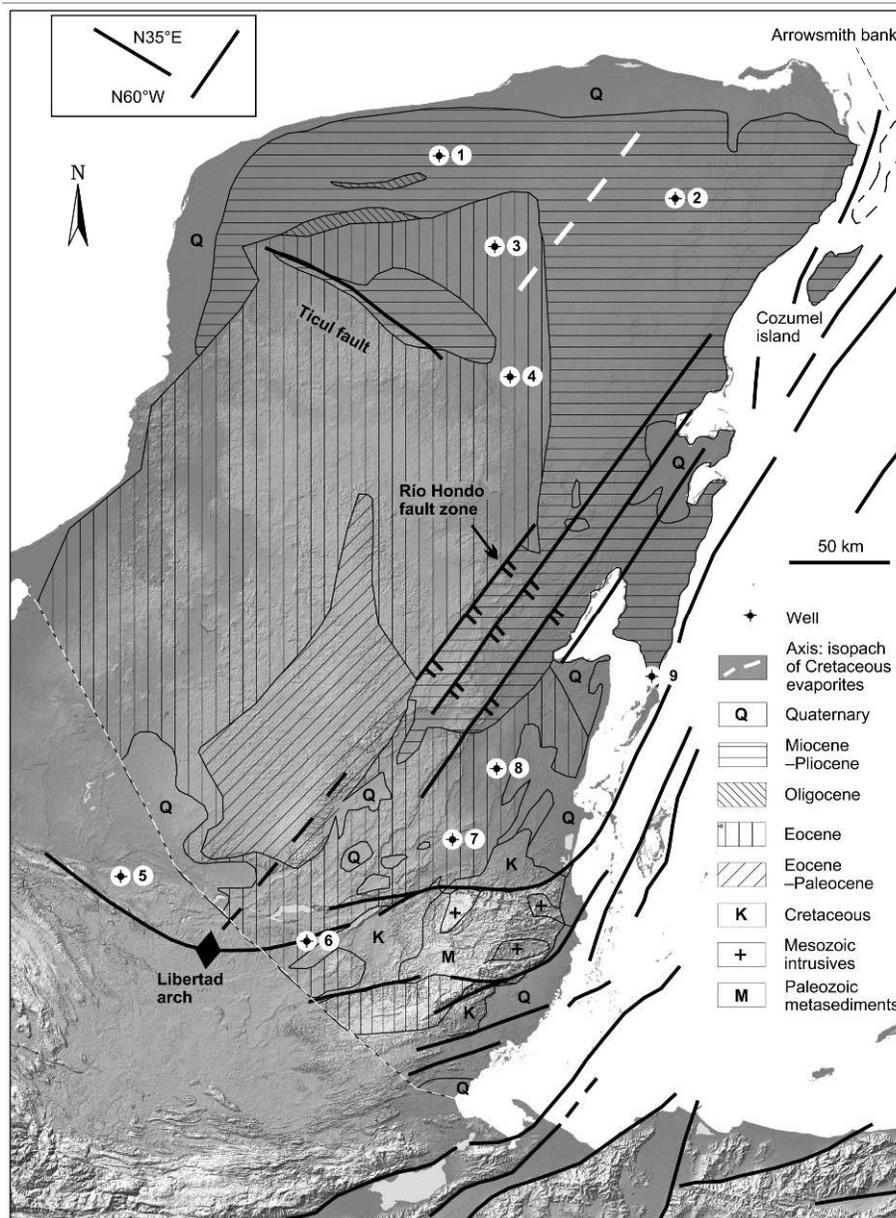


Figure 11.5. Simple geology of the Yucatán peninsula, after López-Ramos [23]. The Río Hondo and nearby faults trend precisely at N35°E and are parallel to faults in the Yucatán channel and to the Guayape-Patuca faults of Honduras. Wells 1–5 did not leave the Cretaceous or went from Cretaceous to Paleozoic rocks; wells 6–9 penetrated Jurassic sections. Faults in the southeast from Purdy *et al.* [30].

Belize (see wells on Fig. 11.6). From east to west they are the SW Cayman ridge, the outer basement ridge system, the Glovers reef-Lighthouse reef system, the Turneffe island-Banco Chinchorro ridge system and an inferred barrier-reef-Ambergris cay-shoreline trend. In the Belize lagoon there is a series of en-echelon ridges separated by N35°E trending channels [34]. Three major half grabens lie adjacent to the Belize

coast, in the centre of the lagoon and to the east. Faulting here accommodated the Eocene Toledo formation Lara [34] recognized coast-parallel, sinistral strike-slip that occurred between the end of the Cretaceous and the Early Eocene (cf., the Guayape fault) and Pliocene or younger negative flower wrenching.

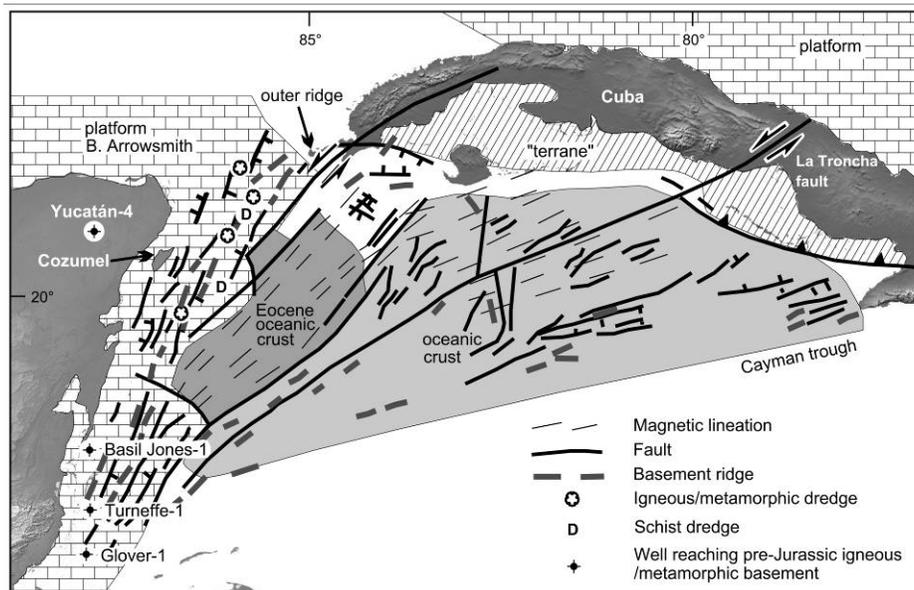


Figure 11.6. Structure and crustal types of the Yucatán basin, locations of wells and dredge sites. Compiled from Rosencrantz [35] and others.

The Yucatán basin lies east of the above structures (Fig. 11.6). The structural grain in the west parallels fracture zones on the Cocos plate next to the Middle America trench, major faults that cross Maya and Chortis (Río Hondo, Guayape, Fig. 11.1) and the structural trends of the Beata ridge and the western Venezuelan basin (Fig. 11.4b). Yucatán basin bathymetry suggests tilted fault blocks recording, rifting and extension during basin opening [36]. The age of this area is not known. Rosencrantz [35] described the west Yucatán basin as a Paleogene or Maastrichtian–Paleocene ocean floor pull-apart formed along sinistral strike-slip faults with an estimated 350 km of displacement. This agrees with the conclusions of Lara [34]. However, Lewis [37] noted that similarity of continental deposits indicate proximity of Cuba (Guaniguanico province) to Guatemala and Yucatán in the Early Jurassic. By Oxfordian time, little continental material was arriving in the Cuban area, indicating that offset, and therefore spreading, had occurred by this time. This, and the parallelism of structural grain noted above, indicates a Jurassic origin for part of the Yucatán basin.

11.5 CHORTIS

11.5.1 Onshore

The most prominent structural features of Chortis are the Motagua fault zone, which forms its northern boundary, the Nicaraguan depression (Pacific Marginal fault zone)

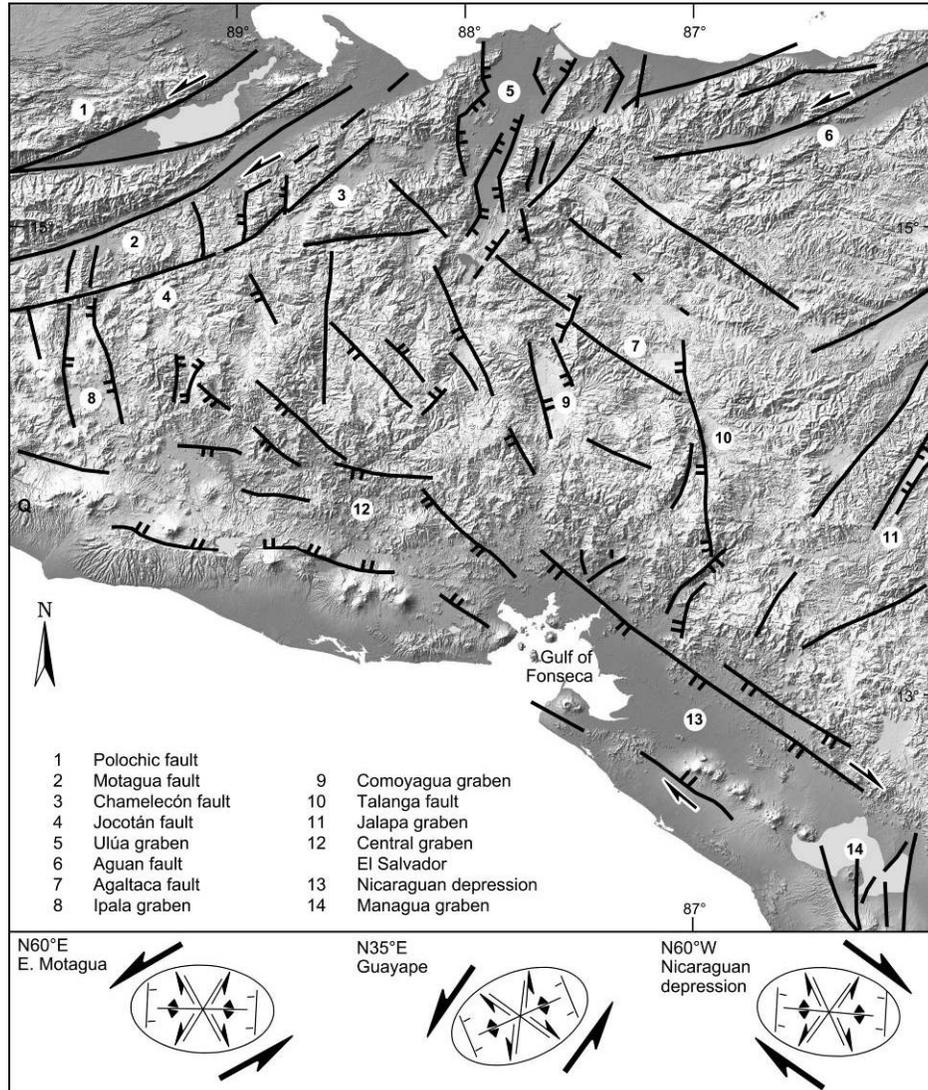


Figure 11.7. Faults of northern Chortis, after Dengo [38]. Inset strain diagram suggests that the N–S trending grabens of Honduras result from extension generated by N60°E trending sinistral stress (eastern Motagua zone). Synthetic strike-slip trends N35°E and is illustrated by the Guayape fault (Figs. 11.1, 11.3)

in the southwest, N–S trending grabens near the centre and the N35°E Guayape fault that crosses the block from the Gulf of Fonseca on the southwest margin to the Caribbean. The Sierra de Agalta mimics the oroclinal bending of the Motagua fault zone and associated uplifts. Seismic refraction data indicate 45 km thick continental crust north of the Guayape fault [39]. South of the fault the crust is 30–35 km thick.

The “Honduras depression” was seen to cut across central Honduras. Dengo [7] showed this to be a series of approximately N–S aligned grabens [40] estimated that the Comoyagua valley (Fig. 11.7) is filled by sediments to 2000 m below sea level). Manton [20] denied that a rift extends from Gulf of Fonseca to the Caribbean and

wrote: “The notion of the Honduras depression, which has persisted over the last half century, stems from misinterpretation of the maps and writings of Karl Sapper” (e.g., 1905).

Gordon and Muehlberger [41] split the Chortis block into three segments (Fig. 11.8a):

1: A triangular wedge west of the Honduras depression, south of the Motagua fault zone and bounded to the south by the dextral Jalpatagua fault. It suffered east–west extension that produces N–S grabens.

2: A triangular block between the Honduras depression and the Guayape fault characterized by strike slip faults subparallel with Swan island fault. It is broken along previous NW and NE fractures with resultant opening on the Honduras depression and dextral slip on the Guayape fault. The movements reportedly reflect counterclockwise rotation (see Chapters 8 and 13).

3: The region east of the Guayape fault including the offshore Nicaraguan rise. This was a wide area, too large to fracture except at its narrow eastern end at Jamaica where Paleogene–Neogene rifts separate carbonate banks (Fig. 11.1).

Rogers *et al.* [42] used aeromagnetic data and pre Cretaceous outcrops to define five Chortis “terranes” (Fig. 11.8b). Magnetic gradients trend WNW on the central Chortis terrane where basement of schist and gneiss of Cacaguapa group. Paleozoic and Grenville orthogneiss is folded and thrust into WNW trends. The northern Chortis terrane is similar to the central Chortis terrane but is more variable. The eastern Chortis terrane, east of the Guayape fault, exhibits northeasterly magnetic trends. Northwest vergent folds and southeast dipping faults of the thin-skinned Colón mountains, built of Jurassic–Cretaceous continental margin rocks, parallel this magnetic fabric [43]. The belt, which formed in the late Cretaceous–Eocene, trends 350 km northeastwards across the Chortis block. The Siuna terrane is an oceanic arc [39] that accreted to Chortis in the Campanian [44], driving the Colón fold and thrust belt [43].

Rogers *et al.*, [45] explained curvature of the Honduran Agalta range (Fig. 11.9a) as oroclinal bending in response to 60–70 km of sinistral strike-slip along the Guayape fault. The range originated as a N60°W trending Aptian–Albian intra-arc rift zone (Agua Blanca rift, [45]) that became inverted between 70 Ma (youngest deformed rocks) and the Middle Eocene (undeformed limestones).

The NW–SE trending Nicaraguan depression is an outstanding feature of southwest Central America. Weyl [46] described it as a 50 km wide graben, 35–50 m above sea level, that extends more than 500 km from the Caribbean coast of Costa Rica (i.e., on the Chorotega block, Fig. 11.1) through southwest Nicaragua to the Gulf of Fonseca. For Mann *et al.* [47] the Nicaraguan depression is ~75 km wide and 600 km long.

The Nicaraguan depression continues in El Salvador as a series of en-echelon Plio–Pleistocene basins (Olomega, Titihuapa, Río Lempa, Metapán; not illustrated). Martinez-Diaz *et al.* [48] summarized that mapped faults in El Salvador trend NW, NNE and E and most are less than 30 km long. However, radar imagery reveals a > 100 km long El Salvador fault zone (ESFZ, Fig. 11.1), oriented N90°–100°E, extending across the country. It deforms Quaternary deposits with dextral and oblique-slip offsets. According to Corti *et al.* [49] the main active faults of El Salvador trend approximately E–W and are dextral, they are sub-parallel to and lie north of the volcanic arc. To the southeast the feature projects towards the inverted Limón belt of Costa Rica above/ahead of the subducting Cocos ridge (Fig. 11.2b, [50, 51]).

Dengo *et al.* [52] attributed the Nicaraguan depression to geanticlinal arching

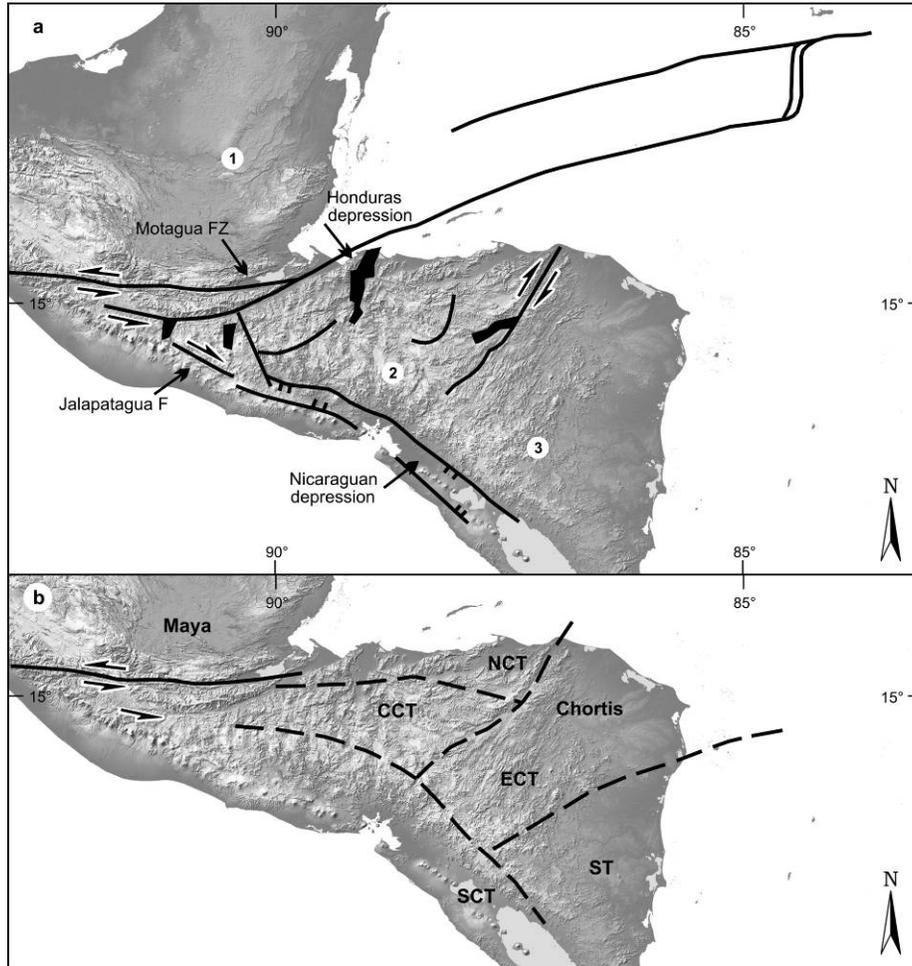


Figure 11.8. (a) Subdivision of the Chortis block into three units [41]. Unit 1 suffers N–S trending extension (“Honduras depression”) between the sinistral and dextral Motagua and Jalapategua faults. The central unit is rotating anticlockwise (along the Guayape fault) between unit 1 and the large, stable block of unit 3. (b) Subdivision of Chortis into five terranes (North, Central, East, South and Siuna, [42]).

resulting from compression between ocean and continent. Plank *et al.* [53] viewed it as a backarc basin, formed during late Neogene trenchward migration of the Central America volcanic arc and slab rollback (perhaps as a result of the break off the slab at 4–10 Ma).

Carr [54] noted that Quaternary faulting in northern Central America is dominated by transcurrency. Sinistral faults transverse to the arc could coincide with breaks in the subducting slab while dextral faulting parallels the volcanic arc.

Molnar and Sykes [55] and White and Harlow [56] interpreted earthquake focal mechanisms to indicate dextral slip today on trench-parallel faults such as those along the depression and Martinez-Diaz *et al.* [48] reported dextral drainage offsets along the N90°–100°E trending El Salvador fault zone (Fig. 11.1). Burkart and Self [57] recognized trench-parallel extension in El Salvador and Honduras bounded by the

Jalpatagua fault. Martinez-Diaz *et al.* [48] deduced that earthquakes along the dextral El Salvador fault zone could be related to normal faulting in the subducting Cocos plate.

Trench-parallel faults are not well expressed in Nicaragua (under volcanic cover?). Instead, seismically active northeast trending faults offset the northwest faults by as much as 10 km [58]. La Femina *et al.* [58] observed that if these faults are sinistral, they also conform to the (“dextral”) focal mechanisms of Molnar and Sykes [55]. They could be accommodating clockwise block rotation (“bookshelf”) in trench-parallel slip. However, illustrations (Figs. 11.1 and 11.2, [58]) show the faults trending at N35°E, exactly parallel to major faults in Honduras (Guayape, Patuca). The faults could well be sinistral, but rotation does not seem to occur.

The Central American volcanic arc follows the dextral/normal fault that forms the southwest flank of the depression. A northwest trending chain of volcanoes indicates continuation of the depression in Guatemala. At the southeastern end of Lake Nicaragua the volcanic arc takes a notable dextral sidestep and dextral slip continues along the Ballena-Celmira reverse fault (Figs. 11.1 and 11.2). This appears as the Longitudinal fault zone of Di Marco *et al.* [59] (Fig. 11.1). Kolarsky *et al.* [50] seem to suggest that the fault continues to the Azuero peninsula but here the sense of movement is sinistral. Di Marco *et al.* [59] show the Longitudinal fault zone swinging southwards towards the Panama fracture zone.

Other offsets in the volcanic front occur at some northeast trending sinistral faults. These correspond to large water bodies (Lake Nicaragua, Managua lake, Gulf of Fonseca). La Femina *et al.* [58] and Cowan *et al.* [60] showed detail of the Managua graben, where the arc is offset by 15 km. The sinistral Estadio and Tiscapa faults trend at around N35°E, while the graben boundary faults are approximately north–south. Figures 11.7 and 11.10 suggest that the latter are antithetic to the N35°E sinistral faults and that they bound pull-apart depressions. The approximately N–S trending grabens of Honduras could be related to regional (“Motagua”) and synthetic (“Guayape”) sinistral faults, while the Managua graben could be related to dextral slip along the Nicaraguan depression.

11.5.2 Offshore—north and east Chortis

The Bay islands (Guanaja, Roatán and Utila, Figs. 11.1 and 11.3a) lie off northern Honduras on a ridge (Bonacca) that parallels the Cayman ridge. They expose a variety of meta-igneous, metasedimentary and sedimentary rocks (greywacke, shale, chert, thin limestone) of pre-Cenozoic (possibly Paleozoic) rocks and serpentinites and granitic intrusions of unknown age [36]. On Roatán serpentinite intrudes fault planes. Banks, [61] and Holcombe *et al.* [36] suggested that similarity of these rocks to those of the Motagua valley (El Tambor group) indicates that fault slices of the Motagua valley area have been carried east at least as far as the islands. Gough and Heirtzler [62] explained juxtaposed magnetic and non-magnetic rocks on the walls of the Cayman trough in the same manner.

Holcombe *et al.* [36] reported that thrust faults on Roatán suggest N–S compression, with no evidence of sinistral strike-slip. According to Ave Lallement *et al.* [63] ductile structures on Roatán island formed under metamorphic conditions during late Cretaceous–Early Cenozoic left-oblique collision of the Chortis and Maya blocks. Brittle structures formed after uplift and exhumation in late Eocene or early

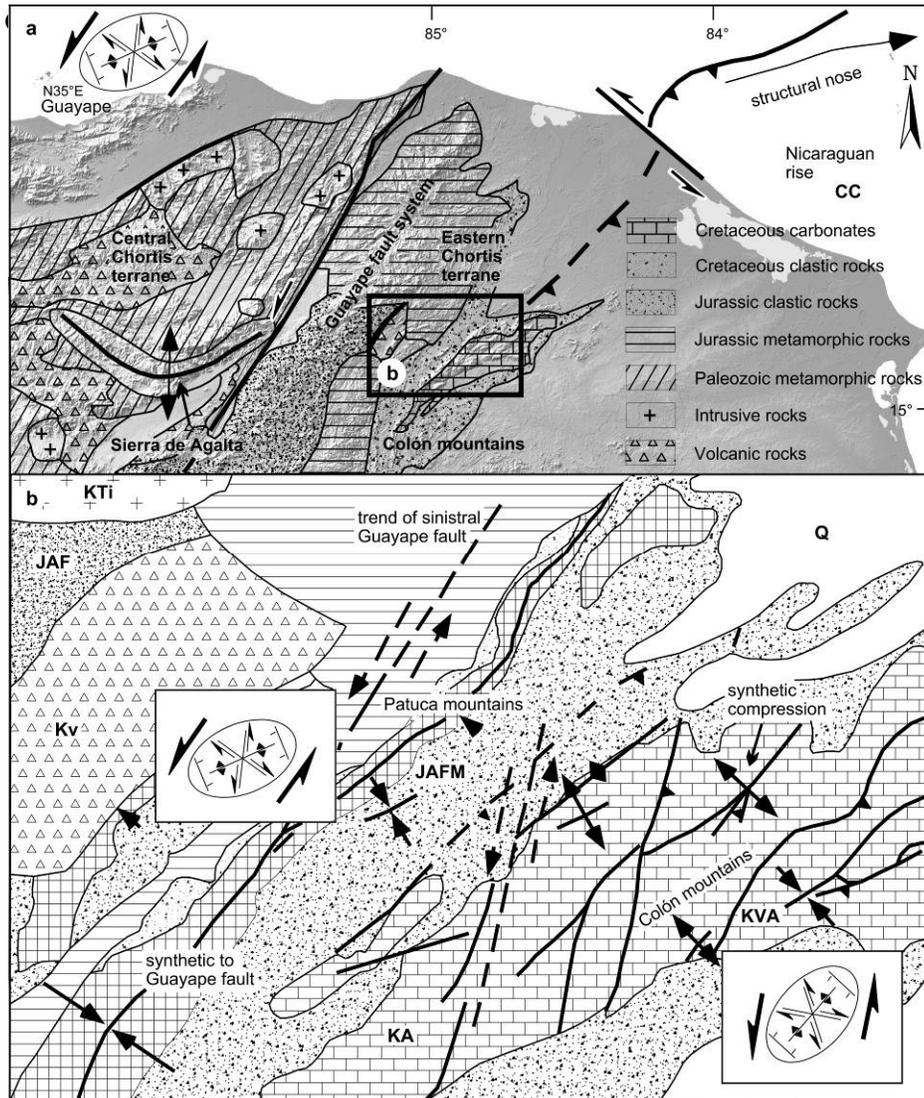


Figure 11.9. (a) Geological map of Honduras, extracted from Rogers *et al.* [45] (b) Geological map of the Colón mountains, Honduras, from Rogers *et al.* [45]. Structures in the mountains could be explained by compression associated with movement synthetic to the sinistral Guayape fault. KTi: Cretaceous–Cenozoic intrusive rocks, Kv: Cretaceous volcanic rocks, KVA: Cretaceous Valle de Ángeles formation., KA: Cretaceous Atima formation, JAF: Jurassic Agua Fría formation, JAFM: Jurassic Agua Fría metamorphosed. Structural interpretation of synthetic faulting and related compression this paper.

the Eocene. South of the basin high, fault-bounded mountains form the north coast of Honduras [64]. The Aguan fault (Fig. 11.1), which bounds these to the south, is transpressional in the west and transtensional in the east where a pull-apart basin accommodates the wide Aguan river valley.

The large Mosquitia basin of eastern Honduras contains 5000 m of Cenozoic and 2500 m of Mesozoic sediments [65]. The NE trending Coco river ridge, a reactivated

Paleozoic structure, divides the basin into two. Mills and Hugh [65] this high extending offshore to the Mosquitia Banks and Jamaica as the Nicaraguan rise.

Cretaceous strata of the Gracias a Dios platform and Mosquitia basin, offshore eastern Honduras, show NW–SE shortening similar to the onshore Colón mountains [66]. Emmet [66] notes that while mafic volcanics are rare within Cretaceous strata in onshore central Honduras they appear to be increasingly common to the east (onshore and offshore). Some plutons intrude the sedimentary section and so are Cretaceous or younger. Closely spaced normal faults downthrowing mainly to the southeast characterize the Mosquitia basin. They cut thick, Eocene and younger strata but most appear to sole-out at the top of the Cretaceous section. According to Emmet [66], a period of regional extension in the Eocene (transension?) appears to have been followed by compression (transpression?) during the Neogene.

11.5.3 Cayman ridge, Nicaraguan rise and Hess escarpment.

The Nicaraguan rise is the physiographic continuation of the Chortis block into the offshore (Figs. 11.1 and 11.4a). The Cayman trough bounds the rise to the north, while the Hess escarpment forms the southern boundary. The Pedro fault zone, which parallels the Hess escarpment, divides the rise into upper and lower parts (Fig. 11.1). Much of the upper rise lies below less than 200 m of water and in places (Providencia and San Andrés islands) it reaches sea level.

Physiography shows that the Nicaraguan rise extends to Jamaica. While no Paleozoic rocks are known from that island, drilling encountered platform carbonates, which suggests continental basement. Meyerhoff and Krieg [67] observed similarity between the Green Bay metamorphic rocks of SE Jamaica and metamorphosed Paleozoic rocks of Honduras and they also suggested that an equivalent of the Jurassic Todos Santos formation is present.

Dengo [6] remarked that the Cayman ridge and Nicaraguan rise seem to be structural continuations of the Sierras of northern Central America (north and south of the Motagua fault zone). In contrast, Leroy *et al.* [68] saw the upper rise as a Palaeocene–Miocene carbonate platform on Late Cretaceous island-arc rocks. However, Holcombe *et al.* [36] noted that the Bay islands (Guanaja, Roatán, Figs. 11.2 and 11.3) contain a wide variety of meta-igneous, metasedimentary and sedimentary rocks of pre-Cenozoic (possibly Paleozoic) rocks. Wells have bottomed in metasedimentary rocks on the Nicaraguan rise as far east as Rosalind bank (Fig. 11.1). Basement consists of andesite, granodiorite and metamorphic rocks. Tuara-1 found late Tithonian–early Neocomian volcanic rocks were seen in the Caribe-1 well (Funkhouser and Gordon, *pers. comm., noted by Morris et al.* [69], east of Honduras.

According to Muñoz *et al.* [70] crust in the northern Nicaraguan rise is up to 25 km thick and is continental. South of the Pedro fault zone a decreasing thermal gradient indicates transition to oceanic crust. The Miskito basin lies between the Pedro fracture and the Hess escarpment. The south-central portion of the basin is considered to be transitional, early Miocene continent-ocean basement where wrench-induced rift volcanism imbricates with ophiolites towards the Hess escarpment. Muñoz *et al.* [70] suggested that breakdown of the major part of the platform occurred in the early Cenozoic, along a second order, NE–SW fault system between the Pedro fault zone and the Santa Elena-Hess system.

Most is known, from hydrocarbon exploration, about the upper Nicaraguan rise,

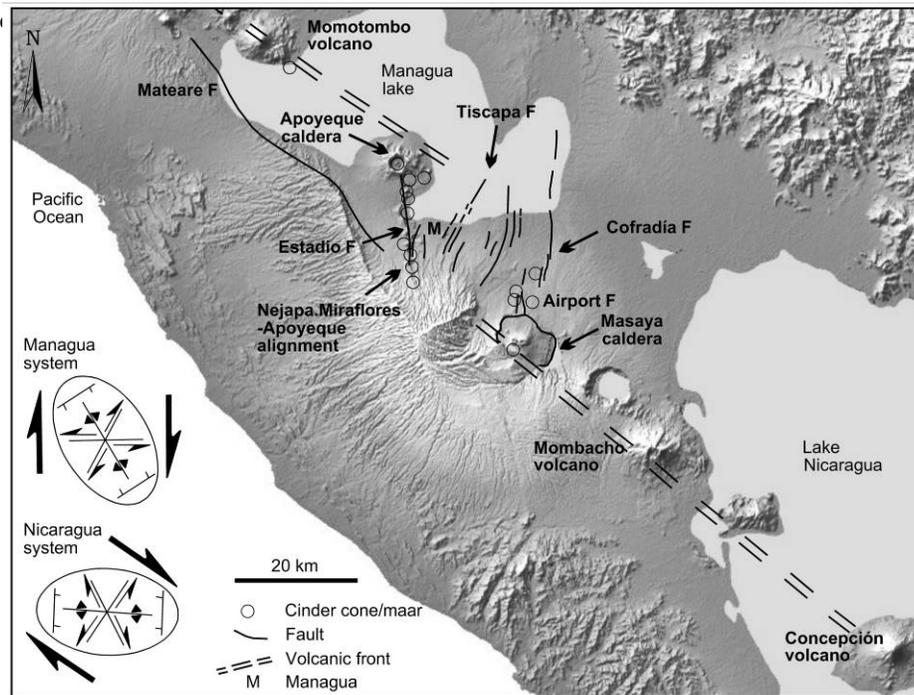


Figure 11.10. Detail of the Managua graben within the Nicaraguan depression. The stress-strain ellipse suggests the graben is a pull-apart, with associated dextral offset, within the dextral depression system. Sinistral faults such as the Tiscapa are antithetic to the system. Compiled from [58, 60]. The 15 km dextral step in the volcanic arc at the N–S trending Managua graben seems to accommodate E–W extension. A NW trending topographic high at the southern limit of the graben would be consistent with N–S dextral slip along the graben itself, while N35°E sinistral slip may be internal and antithetic, albeit parallel to major faults such as the Guayape. North–south trending faults, such as those bounding the Managua graben, would fit extension strain in trench-parallel dextral strike-slip.

150 km long belt of northeasterly trending Jurassic–Upper Cretaceous rocks in the Colón mountains of eastern Honduras that continues for 75 km in the subsurface of the Mosquitia coastal plain. A belt of upper Cretaceous to Eocene rocks continues the trend for a further 75 km on the Nicaraguan rise. The belt consists of NW verging folds and southeast-dipping thrusts thought to have developed in the late Cretaceous to Eocene interval.

Holcombe *et al.* [36] regarded the lower Nicaraguan rise as oceanic, noting that it is characterized by abundant ridges and troughs. They proposed that dextral shear between the Pedro fault zone and the Hess escarpment caused extension. Volcanoes occur throughout the area and some activity is Neogene–recent. The islands of San Andrés (carbonates on volcanic base) and Providencia (basaltic and trachytic lavas with diorite dykes) lie on the western end of the rise adjacent to the San Andrés Rift/Providencia trough and the Nicaraguan continental shelf.

Drilling at Site 1001 on the Hess escarpment penetrated basalt of probable mid-Campanian age (77 Ma) below a conformable basalt-limestone contact [71]. Vesicularity and benthic foraminifera suggest shallow origins followed by rapid subsidence.

A carbonate megabank covered most of the modern northern Nicaraguan rise from the late Oligocene to the Early Miocene [72]. It broke up in the late part of the late Oligocene and foundered in the late Early Miocene [73]. The largest channel, Pedro channel, is a pull-apart related basin related to sinistral strike-slip faults.

The carbonate platform lies at 150–250 m above the adjacent basin and sheds “megabreccias” into the basin [74]. One, exposed at the sea floor, has a fan shape, is 120 m thick and extends 27 km along slope and 16 km into the basin. It contains individual blocks 330 m across by 110 m high. Dredging recovered shallow-water, skeletal grainstones and *Halimeda* packstones mixed with deep-water massive chalks with shallow-water skeletal grains and chalk-block breccias.

Crust of the Haiti basin, between the Beata ridge and the Hess escarpment is rough, block faulted and extensional [75, 76]. The highly asymmetric Beata ridge (Fig. 11.2a) dips east from a steep, extensional western scarp with 3750 m of downthrow in the north [76]. Half graben structures characterize its eastern flank. The ridge broadens and deepens to the south where it is broken by north–south trending grabens. An unconformity overlain by neritic carbonates indicates uplift of the ridge in the Maastrichtian followed by Paleocene–Middle Eocene subsidence [77]. The ridge intersects southern Hispaniola at the southern peninsula of Haiti, where basalts, dolerites, pelagic limestones, turbidites, cherts of the Dumisseau formation could be an ophiolite equivalent to Caribbean crust below horizon B (88–90 Ma) [78].

The Cayman ridge parallels the northern boundary of the Nicaraguan rise on the north flank of the Cayman trough. According to Malin and Dillon ([79], see also [33]) the acoustic basement of the ridge consists of continental rocks. In the west the ridge has near-continental crustal thickness and low magnetic susceptibility, similar to the rift blocks of the margin of Honduras.

Perfit and Heezen [80] developed a stratigraphy for the walls of the Cayman trough. Dredges samples from the north wall of show, deeper, plutonic rocks and metamorphic equivalents, with secondary amounts of volcanic, clastic and volcanoclastic rocks and metavolcanic rocks, along with some Lower Cretaceous–Lower Paleocene shallow-water carbonates. Clastic rocks include volcanic breccias, conglomerates, sandstone and argillites, red bed material, graywacke and arkose. Dredges from the southern wall of the Cayman trough recovered the same stratigraphy, but the deeper section includes more sand clastics and graywackes, breccias, conglomerates and tuffs. Carbonates dominate the upper section. The presence of continental basement below the Cayman ridge and the Nicaraguan rise and of continental sediments along the walls of the Cayman trough rule out a Pacific origin of these elements [81, 82].

11.6 THE MOTAGUA FAULT ZONE

11.6.1 Nomenclature, offsets, current understanding

The Maya and Chortis blocks meet onshore along the Motagua fault zone and most authors agree that the boundary between the Caribbean and North America follows the Cayman trough trend into a Central American “suture” between the Maya and Chortis blocks [83–86]. However, there is much discussion over the amount of offset, when and where it occurred and the origins of oceanic and volcanic rocks found in the zone. This chapter suggests that the Motagua zone is not a suture and that Maya and Chortis are not terranes—they are sinistrally offset elements with similar geological history that never were separated by oceanic crust.

There are several nomenclatures for the faults in the Motagua fault zone. For completeness, Figure 11.1 shows compound names that have been used. The text employs most recently used terminology.

Anderson and Schmidt [87], proposed that displacement of some 1300 km occurred along an Acapulco-Guatemala shear in the Jurassic–Cretaceous. Dengo [7], concluded that the North America-Caribbean boundary is not a single fault (such as the Polochic or Motagua), but is a complex fault system exposed mainly along the Motagua river valley and in the mountains north and south of it. According to Burkart and Self [57] sinistral displacement across the plate boundary is distributed over major, Neogene, arcuate faults (Polochic, Motagua, Jocotán, Guayape). The Jocotán is the major boundary between extended Central America (grabens) south of the fault and a non-extended block between the Polochic and Motagua faults to the north. They explained extension south of the Motagua and Jocotán faults by rotation of the “trailing edge” of the Caribbean plate around the faults [57].

Guzman-Speziale *et al.* [88] recognized at least seven, additional, major, sinistral faults in the Malpaso fault zone (Fig. 11.1) and interpreted the Caribbean-North America plate boundary in Central America as a broad zone distributed over the Malpaso and Motagua fault systems and a zone of extension to the south. Movement occurred along different faults at different times. Some of the sierras of northern Central America (uplifted in the late Cretaceous along with emplacement of the Santa Cruz ophiolite) are structurally and petrologically continuous from southern Mexico to Honduras, across the Motagua fault. They concluded that northern Central America and southern Mexico were a single block (Chiapas-Chortis) during the late Mesozoic orogeny when the sierras formed [88].

Rosencrantz and Sclater [89] stated that the Polochic-Motagua-Chamelecon fault system has been active since the Oligocene. Others suggest that sinistral movement occurred along the Motagua zone and related faults from the Jurassic onwards, migrating southwards (Santa Cruz fault: Jurassic; Malpaso fault: Late Cretaceous [90]; Motagua fault, mid Cenozoic [91]).

Burkart and Scotese [92] saw the faults of Guatemala and adjacent Honduras as defining wedges rotated eastward from Oaxaca, Mexico.

Giunta *et al.* [86] described the Motagua suture zone as a typical flower, with north and south vergence. Narrow valleys occur along the main faults. Plains cover Neogene–recent pull-apart basins and uplifts of older rocks occur at restraining bends.

Shallow earthquake fault plane solutions indicate sinistral movement along the Motagua fault, which does not continue to the west [88].

The Polochic fault crosses the isthmus in an E–W direction and offsets the Middle America trench. Burkart [92] and Burkart *et al.* [93] observed that the Polochic fault offsets Laramide structures, Paleogene rivers and late Miocene conglomerates and therefore is Cenozoic in age. Displacement occurred between 10.3 and 6.6 Ma [94] and today the fault seems inactive. The Motagua and Jocotán faults to the south are curved, trending ENE in the east and WNW in the west where they merge with the Polochic fault. They lose definition in the west below pumice-filled basins. Burkart and Self [57] thought that displacement was zero in the west and developed eastward.

Gordon [95] summarized the following active fault zones of the Chortis block from earthquake surface breaks, earthquake hypocenters, geologic mapping, air photo interpretation and field reconnaissance, and Landsat, Seasat radar and Shuttle Imaging Radar. Major earthquakes ($M > 7$) occur along the North America/ Caribbean plate boundary faults (Polochic, Motagua, Swan, Fig. 11.1). Active fault traces are mapped

onshore by geologic studies and offshore by sonar imaging. According to Gordon [95] faults within the Chortis block indicate that it is part of broad plate boundary zones between the North America, Caribbean and Cocos plates. Earthquakes along the volcanic arc are typically shallow, strike-slip events. WNW striking faults (parallel to the arc) have dextral slip, and ENE faults have sinistral slip. Earthquakes and surface faulting occur along north-striking grabens (such as the Guatemala city, Comayagua grabens; Figs. 11.1 and 11.5) south of the Motagua fault. Faults in the Chortis block are unconstrained by earthquake data but remote imagery data and aerial photographs show fresh scarps. The La Ceiba, Río Viejo and Aguán (Figs. 11.1 and 11.8) faults are probably active sinistral faults parallel to the Swan Islands fault. The Chamelecón fault is active. Other possibly active faults include WNW-striking normal faults east of the Honduras depression.

Gordon and Ave Lallement [96] used published fault offsets and estimations from fault zone widths to summarize offsets of 130 km on the Polochic fault, up to 500 km along the Motagua fault, 70 km along the Guayape fault [97] and 25 km along the Jocotán-Chamelecón fault. The total (725 km) sinistral displacement does not account for the estimated 1100 km of Cayman offset. Gordon and Ave Lallement [96] recognized sinistral faults from the island of Roatán in the north to the Gulf of Fonseca in the south. They proposed that distributed movement on cryptic strike-slip faults across the entire width of the Chortis block faults accounts for the remaining offset. Faults are more commonly exposed in Cretaceous and older rocks than the Neogene volcanic rocks, suggesting that most slip occurred before 30 Ma.

11.6.2 Cayman trough offset, amount and age

According to Vaughan [98], Taber [99] and Schuchert [4], faulting of the Cayman trough dated from the Pliocene and was dominantly vertical [100]. Hess [101] thought the movement was horizontal and dated from the Late Miocene. Hess and Maxwell [102] applied the concept of strike-slip faulting to the trough, reconstructing the Greater Antilles using metamorphic rock distribution. Ewing and Heezen [103] deduced from gravity data that the crust below the trough was thin. They drew analogy between the (convergent) Puerto Rico trench and the Cayman trough but Ewing *et al.*, [104] later reported that the trough was extensional. Because Paleocene and Eocene pyroclastics of SE Cuba thicken southwards these authors thought that the trough formed in or after the Middle Eocene. Meyerhoff [105] concluded that the Cayman crust was oceanic and formed by the late Turonian. Donnelly *et al.* [106] mapped faults in SE Guatemala that were active in Albian to Maastrichtian time.

Estimates of displacement related to the Cayman trough range from 150 to 1400 km [87, 102, 107–109]. Pindell and Barrett [109] noted that 980 km of the trough are characterized by depths typical of oceanic crust and estimated an additional 70–100 km of extension related to block faulted zones (arc or continental material) at the western and eastern ends of the trough. The faulted eastern margins of Maya and Chortis are offset by around 900 km [110, 111].

Rosencrantz *et al.* [112] proposed that Cayman trough opening provided quantitative measures of relative plate motion along the northern Caribbean plate boundary. Their estimates of the beginning age of trough opening (Eocene) were based upon depth-to-basement and heat flow studies. However, Rosencrantz *et al.* [112] noted that heat flow age estimates were inconclusive and stated: “We suggest that the

question of Cayman trough heat flow be shelved until new and better measurements are obtained". Rosencrantz [113] later suggested that Cayman trough opening recorded local rather than regional plate movements and could not be used to track Caribbean-North American relative plate motion.

James [115, 116] summarized literature reports on the trough, highlighting what is known and comparing this to what is often erroneously stated. The Eocene age of Cayman trough opening has become well established in literature, following the Rosencrantz *et al.* [113] publication. However, James [114, 115] shows that there have been two main episodes of sinistral movement along the Cayman trough. The first is recorded by data from the Atlantic ocean floor east of North and South America. The American continent margin-Mid Atlantic ridge distance north of the Marathon/Fifteen-Twenty fracture zones is markedly wider (ca. 1600 km) than that at the Sierra Leone/Doldrums fracture zones. The additional distance relates largely to Jurassic crust in the central Atlantic that is absent in the south, together with a wider lower Cretaceous zone [114, 115]. Sinistral offset between the continents therefore developed largely in the late Jurassic–Early Cretaceous, along with some 850 km of north-south separation. The offset developed primarily along west–northwest Atlantic Ocean fractures and sinistral faults within North America (Fig. 11.2b). Related strain was distributed over the Caribbean area. The offset of Maya from Chortis and of Chortis from northwest Colombia correspond to the additional 1600 km of North American offset. Thus simple geometry shows that around 600 km of Cayman offset and offset between Maya and Chortis occurred in the late Jurassic–Early Cretaceous.

A second phase of sinistral movement began when the Caribbean plate commenced eastward movement relative to both North and South America. Fill of related pull-apart basins along north and south margins of the plate records Oligocene–recent extension totaling around 300 km. The distance corresponds to the extent of latest spreading in the centre of the Cayman trough.

11.6.3 Nature of the Motagua “suture”

The Cayman trough and the Motagua fault zone clearly are related. However, this chapter shows that the latter is not merely the westward extension of the trough. Timing of movement is critical to understanding the tectonic evolution of the Caribbean. Literature contains a great deal of discussion on these areas, with a wide range of understanding.

Dengo [7] discussed a “collision” between Chortis and Maya, stated by many to have occurred in the late Cretaceous (Paleocene according to Schafhauser *et al.* [116]). It generated rock mixtures (serpentinite, metavolcanic and metasedimentary rocks, phyllites and partially recrystallized limestones) exposed in the Motagua valley and known as the Tambor group [61]. Dengo [7] summarized that the unit is a metamorphosed Mesozoic ophiolite derived from an ocean segment formerly between Maya and Chortis. Mixtures of rocks that contain reworked material are difficult to date [81]. The presence of serpentinites (hydrated peridotites of ocean origin?) is taken to indicate the former presence of oceanic crust between Chortis and Maya.

El Tambor rocks extend 20 km to the south and 50 km to the north of the Motagua fault zone. They include large serpentinite masses (covered by Eocene molasse; [86]). Serpentinite also occurs in the Belize subsurface [25]. Sisson *et al.* [119] and Harlow *et al.* [118] determined Tambor serpentinite $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 125–113 Ma south and 77–

65 Ma north of the Motagua zone, respectively. They interpreted these as records of Chortis suturing first against western Mexico and then against Maya.

Rocks similar to the Tambor occur in southeast Mexico and on the Tehuantepec isthmus ([7] and references therein), in northeastern Honduras (Sierra de Omoa, [119]) and on the Bay islands [36, 61, 80, 120, 121]. The Tambor was earlier thought to be Paleozoic in age [61, 121] but is now seen to be much younger. The unit includes mantle and MORB rocks whose ages range from Late Jurassic [122] to Early Cretaceous overlain by Late Cretaceous metamorphosed limestones and phyllites (e.g., [86]). The contained rocks, however, do not tell when the Tambor was emplaced.

Donnelly *et al.* [25] stated that compressive suturing of the gap between the Maya and Chortis initiated the Sepur group clastic wedge. The unit contains Paleocene and early Eocene fossils. According to Rosenfeld [123] it came from a southern, rising mass with fringing carbonates and locally exposed “ophiolites”. In Guatemala, the Sierra de Santa Cruz ophiolite, emplaced in the post Early Eocene, overlies the Sepur Group north of the Polochic fault. The Sepur equivalent in wells drilled offshore Belize, the Toledo formation, contains Paleocene–Middle Eocene fossils [30]. Such dates led James [111] to conclude that final serpentinite emplacement occurred regionally in the Caribbean in the Eocene (see also [102, 124–128]).

11.6.4 Origin of Motagua zone curvature

Maya and Chortis meet along the Motagua fault zone, a prominent structural feature of Central America. Along with neighboring structures (Libertad arch of southern Guatemala, Sierra de Santa Cruz, Sierra de las Minas, Sierra de los Cuchamantes), the zone forms a major curve, convex to the south. There is an obvious temptation to explain the curvature of the Motagua fault zone as the locus of rotation of Chortis relative to Maya. However, the Río Hondo (Maya) and the Guayape-Patuca (Chortis) faults, all of which were active as normal faults during Jurassic extension, remain today parallel to Triassic–Jurassic grabens in northern South America and southeastern North America. Likewise, northwest trending Jurassic grabens of western Guatemala and along the north flank of the Chiapas massif of Mexico are parallel to coeval grabens [129] in Mexico (Figs 11.1 and 11.4a). Clearly, neither Maya nor Chortis has rotated. Curvature of the Motagua fault zone and the associated oroclinal bending need a different explanation.

Analogy suggests that bending of the Motagua fault zone and the neighboring orocline results from sinistral strike-slip along faults of eastern Maya, such as the Río Hondo-eastern margin faults, in the same manner that bending of the Sierra de Agalta occurred along the Guayape fault [45]. Straightening of the orocline requires 350 km removal of sinistral slip, corresponding to the offset estimated by Rosencrantz [130] along the western margin of the Yucatán basin. In both cases (Agalta and southern Maya), NW–SE shortening must have accompanied oroclinal bending. Similar strike-slip/oroclinal bending/thrusting relationships are common in northwestern South America [131], where offset along roughly N–S trending faults transforms into contraction in the northeast and southwest. Oroclinal bending and N–S shortening associated with sinistral strike-slip characterize the western Caribbean.

If the understanding of this chapter is correct, sinistral movement along the SE margin of Maya transforms into compression and oroclinal bending of the Motagua fault zone. The associated serpentinites could have been dragged in from the western

Yucatán basin. They would not imply the former presence of oceanic crust between Maya and Chortis.

11.6.5 Origin of Maya and Chortis

In separating Maya from Chortis, Dengo [5] emphasized differences in metamorphic grade across the Motagua fault zone and set the stage for the perception that the blocks are allochthons (even terranes). On the Maya block amphibolites and garnet amphibolites crop out in Chiapas, central Guatemala and Belize. On the Chortis block mainly phyllites and schists of greenschist facies occur in southern Guatemala, El Salvador, Honduras, northern Nicaragua and the Nicaraguan rise.

Numerous illustrations/models show the Maya and Chortis blocks originating in the Gulf of Mexico [33, 132, 133] or Maya in the Gulf [87, 92, 109] and Chortis alongside SW Mexico [43, 134–137] or west of Colombia [138]. They are shown to have rotated clockwise or anticlockwise by as much as 80° about various poles or migrating poles to their present locations. The variety and complexity of interpretations reflects dominance of models over data. The most popular model relates Chortis and SW Mexico but despite attempts to seek geologic continuity between the two areas (*e.g.*, [43, 137] it does not exist [139].

The conviction that Maya and Chortis are separate terranes impacts the way their stratigraphic sections are interpreted. Thus Gordon [140] wrote “the Jurassic–Early Cretaceous history of Chortis is Caribbean, but the block was not in the Caribbean at that time”. Donnelly *et al.* [23] and Gordon [140] maintained that use of the same name (Todos Santos) for Jurassic red beds on both Maya and Chortis should be discontinued, since these were separate plates. In contrast, Burkart and Clemens [141] observed that the sedimentary and volcanic sequence of southeastern Guatemala is similar to that of bordering western Honduras while Horne *et al.* [119] concluded that differences between basement rocks of the Maya and Chortis blocks are not as evident as previously believed [5]. Permian–Carboniferous argillaceous strata are present in similar relation with older and younger rock from the Altos Cuchumatanes in the west to the Maya Mountains in the north and at least as far as the Sierra de Omoa in the southeast (Fig. 11.2a), if not farther east towards Nicaragua. The strata may be correlated with the Santa Rosa Group of central Guatemala. Underlying rocks are similar throughout the region. Richter (*pers. comm.*, 2003) noted a relationship between Cenomanian rocks of north Chortis and south Maya.

Similarity of basement, Jurassic and Cretaceous sections on Maya and Chortis should be reason to relate the two. Models should not deny stratigraphy. The two blocks have similar tectonic origins and similar structure. They are continental remnants of Pangean breakup, left at the western end of the Caribbean. Maya was sinistrally offset from Chortis when early Cayman offset developed. Neither block is a terrane rotated into place from another location.

The major Jurassic faults on Maya and Chortis (Río Hondo and Guayape) that remain parallel to coeval faults in the North and South America show that no rotation has occurred. Restoration of the blocks along the Cayman trend by re-aligning their eastern faulted margins also results in line-up the Río Hondo-Guayape systems.

11.7 CHOROTEGA AND CHOCÓ (COSTA RICA-PANAMA ISTHMUS: THE ISTHMIAN LINK)

This area includes all of Costa Rica and Panama (Fig. 11.1). It is regarded as an intra-oceanic subduction arc that became welded to South America and nuclear Central America in the Neogene [13, 142]. Its geology of troughs of marine Cenozoic deposits with volcanic and plutonic igneous rocks above Mesozoic oceanic rocks [142] continues along a 200 km wide belt in northwestern Colombia. Escalante [13] described the area as one of the most complex in the Caribbean, sited at the interaction of the Caribbean plate and the Chortis block to the northeast and north, the South America plate to the southeast, and the Cocos and Nazca plates to the southwest.

11.7.1 Chorotega

Chorotega for the most part continues the trend of SW Chortis. The southwestern boundary of this area is easily defined by the Middle America trench. Other boundaries are less obvious.

Escalante [13] described the boundary between Chorotega and Chortis (the Santa Elena suture, Fig. 11.1) as an un-named, E–W trending fault, mostly covered by sediments and Cenozoic volcanic rocks, near the Costa Rica-Nicaragua border. It surfaces on the Santa Elena peninsula, where serpentinized peridotites crop out and where Dengo [143] recognized several transcurrent faults. Escalante [13] related this fault to the southern part of the Hess escarpment. Marshall and Vannuchi [14] described an E–W trending Murciélago fault zone, which crosses the Santa Elena peninsula, as a major upper plate discontinuity separating Cretaceous–Paleogene forearc sediments of the Sandino basin from Late Cretaceous ophiolitic rocks of the Nicoya peninsula to the south.

The E–W trend of the peninsula corresponds to the alignment of magnetic grain [145] in the adjacent, western Colombian basin. Christofferson [146–148] explained these as late Cretaceous spreading anomalies but Diebold *et al.* [149] regarded this as “unpersuasive”. The anomalies continue the E–W magnetic [150] and gravity trends ([151], redrawn by [19], Fig. 11.4) that reflect a broad plate boundary between South America and the Caribbean plate. E–W strike-slip faulting is recorded as far north as 14°40' by the Pecos-Flamingo faults (Fig. 11.2b) [152, 153]. Fig. 11.2b suggests that this trend is common in southern Central America, suggesting a broad plate boundary zone.

Kolarsky and Mann [154] described the geology of the Azuero and Soná peninsulas and the nearby Coiba island (Fig. 11.3). Here sinistral movement along N60°W trending faults such as the Azuero-Soná accommodates oblique slip between the Nazca plate and Panama. These faults are more or less on strike with dextral faults such as the Ballena-Celmira (see also [50]), so opposing directions of motion must be accommodated in the area in between. It is the topographic high northeast of the Cocos ridge (Fig. 11.1).

For Escalante [13] and Escalante and Astorga [155], the Chorotega block was bounded to the NE by the North Panama deformed belt and a SW dipping thrust fault (*Sistema Falla Transcurrente de Costa Rica*). However, the deformed belt is a sedimentary pile driven northwards on the Caribbean plate ahead of the Panamanian

isthmus and the SW dipping thrust shown by Escalante [13] intersects Chorotega approximately halfway along its eastern margin.

The Chorotega/Chocó boundary appears to be located somewhere near the Panama canal zone fault [156] (suggested a N–S boundary much further west). There appears to be a parallel fault (Parriba fault zone, Fig. 11.1) some 100 km further west (shown on three out of six maps in GSA Special Paper 295, e.g. [12]). Lowrie *et al.* [157] noted that topography, bathymetry, seismicity, hot-spring locations, faulting patterns and gravity indicate a major tectonic discontinuity across the Panama isthmus between 79°W and 80°W. This was the Miocene locus of the N–S trending eastern boundary of the Cocos plate. The boundary was further east beforehand. It arrived at the canal area around 27 Ma and migrated westwards, following successive sinistral transform faults. At around 8 Ma spreading ceased east of 83°W and the area to the east moved 400 km sinistrally in response to Nazca plate push [157].

Costa Rica was affected by plate convergence since the Cretaceous and by wrench tectonics through the Cenozoic to present. Thus successive basins formed in an intra-oceanic island-arc setting above E-dipping subduction of Pacific crust (with fore-arc and back-arc basins) and in Middle Eocene transtension and Miocene and Pliocene transpression [158].

Di Marco *et al.* [13] interpreted paleomagnetic data from Chorotega to indicate an origin close to its present latitude; there has been no significant rotation relative to South America. In contrast, paleomagnetic data from the Nicoya complex indicate a latitude 16° south of the Chorotega block in Late Cretaceous time, indicating a Pacific origin. Paleomagnetic data also indicate a late Cretaceous equatorial paleolatitude for the Golfito terrane (Azuerro peninsula) and counterclockwise rotation relative to Chorotega of 60°. The Burica terrane (Burica peninsula) was at a low northerly paleolatitude in the Paleocene, slightly south of its present position. It experienced almost 90° counterclockwise rotation.

Obducted oceanic rocks extend from Nicoya and Azuerro along the coast of Panama, through Colombia and Ecuador as far as the Gulf of Guayaquil [159] and according to Mickus [160] gravity data suggest continuation of Nicoya rocks northwest as far as Guatemala as discontinuous or thickening and thinning ophiolitic complexes. It is difficult to reconcile the local paleomagnetic latitudinal findings of Di Marco *et al.* with such a regionally distributed unit.

Except for the Osa peninsula and parts of the Nicoya complex the Costa Rican Pacific coast can be regarded as a collage of fragments of ocean basins, oceanic seamounts and/or island arcs [13]. In most cases faults do not represent the original suture of accretion but are Neogene to Recent active faults. Accretion was followed by strike-slip.

Hauff *et al.* [161] summarized that the origin of oceanic igneous basement complexes on the Pacific margin of Costa Rica (Santa Elena, Nicoya, Tortugal, Herradura, Quepos, Osa, Golfito and Burica) is controversial. They have been explained as MORB, Galápagos hot-spot track, Caribbean plateau and as oceanic crust formed at a mid-oceanic ridge followed by intraplate, island arc and back arc volcanism. Moreover, dating inferred from biostratigraphy of associated sediments was suspect since contacts are mostly tectonic or intrusive. New radiometric and biostratigraphic data indicated formation of early Costa Rican basement in three phases: 124–109 Ma (Santa Elena), 95–74 Ma (Nicoya, Herradura, Tortugal, Golfito and Burica) and 65–50 Ma (Quepos and Osa). Thus most igneous basement rock on Costa Rica formed over a short time interval, in contrast to the much longer radiolarian

record (164–84 Ma, Oxfordian–Santonian) of associated rocks. Hauff *et al.* [161] saw Quepos and Osa as part of the Galápagos hotspot track, accreted in the Middle Eocene, possibly causing large-scale regional deformation and uplift of Central America (this was a much wider event). Overlying mid-Eocene olistostromes at Quepos and the presence of middle Eocene through Miocene accretionary wedge on the trenchward side of the Osa peninsula confine the age of accretion to the Middle Eocene. There is a regional early to late Oligocene unconformity in the sedimentary basins of the Costa Rican arc. Based upon trace element and isotopic similarities between the rocks of Tortugal and Santa Elena Hauff *et al.* [161] proposed a N–S fault boundary between Chortis and Chorotega.

11.7.2 Chocó

The southern part of the Chocó block has accreted to northwestern South America. The remaining part of the block is represented in Central America by the Panama isthmus, where Fisher *et al.* [162] recognized a Panamanian microplate—a fragment of volcanic arc separated from the Caribbean plate, defined by active fold and thrust belts. Accretionary prisms to the north and south show bipolar convergence of this area with the Caribbean and Nazca plates. Breen *et al.* [163] described seismic reflection and side-scan sonar indications of mud/melange filled parallel folds at the toe of the North Panama deformed belt. Moore and Sender [164] presented seismic data from southwest Panama indicating that oblique convergence has produced seaward-verging thrusts and folds.

According to Wadge and Burke [165] and Silver *et al.* [166] Middle Miocene–Pleistocene collision of Chocó with South America resulted in oroclinal bending of the isthmus. According to Derksen *et al.* [167] convergence of South America and eastern Panama occurred from the Oligocene onwards, driving NW sinistral faulting along which transpressional folding and as much as 200 km offset have occurred.

Mann and Corrigan [168] concluded that Panama is moving NW away from the zone of convergence between Chocó and South America along a diffuse zone that involves both oroclinal bending and strike-slip faulting. This produced a west-verging thrust system (East Panama deformed belt, EPDB), accommodated by NW trending sinistral faults in the western Gulf of Panama and onshore eastern Panama [169]. However, Trenkamp *et al.* [170] used GPS data to “confirm” the presence of a Panama microplate, with its western margin in central Costa Rica, that is today moving east relative to Colombia and NE relative to the Caribbean plate. They concluded that flexing of Panama [166] or distributed sinistral slip [168] are not occurring today but were important in the past.

For Escalante [13] the eastern margin of the Chocó block is the Romeral fault of western Colombia. However, Aspden *et al.* [171] state that the Romeral is a Cretaceous suture associated with the Central cordillera, while Chocó collided with Colombia in the Miocene–Pliocene [172]. Kellogg and Vega [173] show the boundary as the sinistral Atrato fault, merging southwestwards into the Isthmina fault. The Atrato fault along the eastern limit of the accreted Serranía de Baudó (rocks similar to Nicoya, Azuero) was a former (pre late Miocene) eastern boundary to the Chocó block. The present boundary probably is a dextral fault that cuts the isthmus trending NNE across the mouth of the Gulf of Urubá (see for example [173], Figs. 11.1 and 11.4).

The trench west of the Chocó block is filled with thick Cenozoic deposits [7],

where it overrides the Cocos plate. The northern block boundary is supposed to be the North Panama Fold Belt. Mickus [160, 174] notes that gravity data do not indicate subduction of Nazca beneath the Caribbean. Instead, the southern boundary of Chocó is an E–W, sinistral transform contact with the easterly moving Nazca plate [175]. Westbrook *et al.* [176] estimated 140 km of displacement along this boundary, which is slightly transpressional.

NW trending sinistral faults such as the Panama canal fault zone bound the Chocó block to the west. (perhaps even the sinistral Azuero-Sona fault zone) is part of this system. The conjugate NW sinistral and NE dextral fault pattern repeats that of northward tectonic escape of the Bolívar block [19], bounded by NE trending dextral (Mérida Andes) and NW trending sinistral (Santa Marta-Bucarramanga). The latter drives fold South Caribbean deformed belt. Escape of the Panama arc drives the North Panama deformed belt.

When the offsets described above are removed, Chocó becomes the southeasterly continuation of Chorotega.

11.7.3 Chorotega-Chocó, same origin? —continental crust present?

Dengo [7] remarked that although the Chorotega and Chocó blocks share crustal composition and geological history, a tectonic break along the canal zone is marked by a negative Bouguer gravity anomaly between large positive anomalies to the east and west [14]. Also, Neogene continental volcanic rocks that are abundant in Chorotega are rare in Chocó.

Case (1974 [14]) reported that while Bouguer anomalies of more than +120 mgal indicate an uplifted block of oceanic crust in eastern Panama, much more negative anomalies west of the canal zone possibly indicate the presence of continental crust. Seismic refraction data report a crustal thickness of more than 40 km near San José, Costa Rica [39]. Crustal thicknesses of 40–45 km in Costa Rica and 30–31 km in Nicaragua from broadband seismic data: these are continental thicknesses [177].

Sachs and Alvarado [178] reported granulite xenoliths from the Arenal volcano and discussed findings of micaschists and amphibolites in the Talamanca range and on the Osa and Azuero peninsulas [179–181]. Deering *et al.* [182] and Vogel *et al.* [183] suggested that high silica ignimbrites and granitoids from Costa Rica might indicate early continental crust formation in an oceanic arc environment. The Miocene Coris formation, extensively present in the south and southeast of the Central valley, is a quartz arenite/orthoquartzite [13]. These are indications that continental crust is present.

The Chorotega block shares a common N60°W trend with Jurassic grabens of Mexico, the Middle America trench and fracture zones in the Jurassic–Lower Cretaceous crust east of North America, all related to late Jurassic–Early Cretaceous rifting/drifting. It appears to be defined by continuation of the faults that bound the Nicaraguan depression. This indicates control by rifting of continental crust.

The accreted portion of Chocó in Colombia consists of the coastal Serranía de Baudó and the flanking Atrato basin, sutured along the sinistral Atrato-Isthmina faults. Westward-coarsening quartz sands within late Cretaceous turbidites in the Colombian cordillera Occidental indicate continental basement for the Serranía de Baudó [184]. Restoration of Chocó makes it the southeastern continuation of Chorotega (Fig. 11.11).

Taken together, geometric, gravimetric, seismic, geochemical and sedimentary data

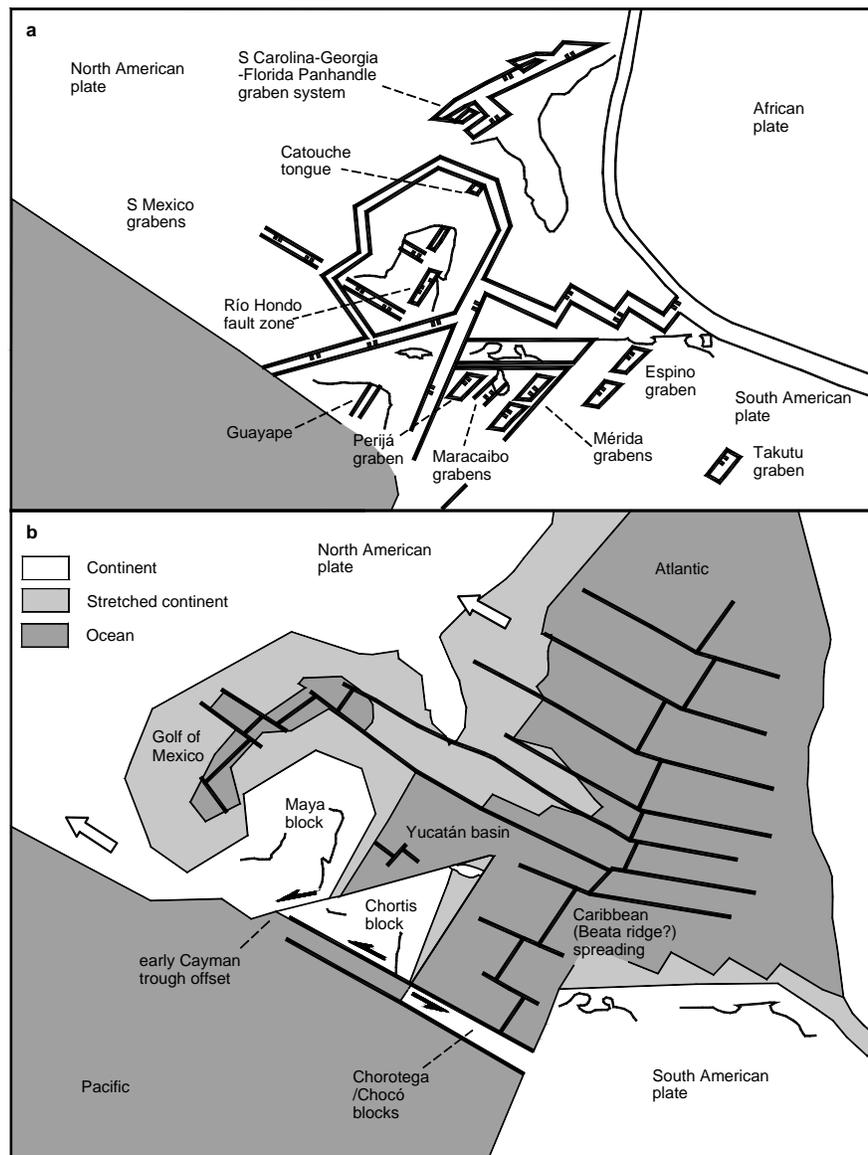


Figure 11.11. (a) Triassic–Jurassic rifting of simple Pangean reconstruction. (b) Callovian–Berriasian drift reconstruction: sea-floor spreading has propagated through the Caribbean area, Maya has moved sinistrally west relative to Chortis (Early Cayman offset) and Chortis has moved sinistrally NW relative to Chorotega-Chocó. The latter separated from Chorotega along the Panama canal FZ in the Miocene–Pliocene. Abbreviations as in Fig. 11.4; large arrows show drift of North America N60°W along fractures in the western Atlantic and SW margin of Central America.

suggest the presence of continental crust below Chorotega-Chocó, and suggests that the blocks were sinistrally offset from the SW margin of Chortis during Late Jurassic–Early Cretaceous rift and drift. Following Miocene collision between southern Chocó and northwestern South America in the Miocene, the Panama arc became extruded northwards, sinistrally offset from Chorotega.

11.8 UNCONFORMITIES

This section considers the main unconformities that seem to have Caribbean-wide distribution and relates these to Central America, where poor access, volcanic and vegetation cover obscure large areas and the record is less complete. The principal unconformities recorded by literature are Late Paleozoic–Middle Jurassic, Early Cretaceous, Late Cretaceous, Paleocene–Middle Eocene, Middle Miocene and latest Miocene/Pliocene, though there are undoubtedly others (see e.g., [185, 186]). Young unconformities specific to southern Central America relate to collision of the Panama arc with South America and of the Cocos ridge with Costa Rica.

11.8.1 Late Paleozoic–Middle Jurassic

The first unconformity covers the interval between the Permian to Middle Jurassic. Following late Permian deformation and intrusion, Triassic–Jurassic uplift and rifting occurred, followed by continental breakup, margin extension and the beginning of drift and ocean crust formation. It is marked in Central America by the appearance of red beds on both the Maya and Chortis blocks. Volcanic activity in Honduras occurred in the latest Jurassic or early Cretaceous as flows beneath the Todos Santos red beds (now called Agua Fría, [140]). Conglomerates in those beds contain angular fragments of primary volcanic origin [188].

Sedimentary Jurassic Agua Fría over metamorphosed Agua Fría on Chortis [42] indicates a further Jurassic unconformity.

11.8.2 Early Cretaceous

In the Caribbean region a pre-Albian unconformity coincides with a change from primitive volcanic activity to calc-alkaline volcanism that marks the onset of subduction [188]. Aptian–Albian rifting occurred on Chortis [42] and an Aptian–Albian calc-alkalic volcanic complex (Manto formation) occurs on Chortis [45]. Subduction in Central America has been underway since at least the Albian [189]. The unconformity is overlain by shallow-water limestones throughout the Caribbean region [190], recording regional uplift to the photic zone. Donnelly [191] discussed Albian–Campanian platform limestones on the Maya block (Cobán/Ixcoy, Campur formations), while Scott and Finch [192] noted that a carbonate platform developed on the Chortis block beginning in the Berriasian–Aptian and ending in the Albian. On Chortis low grade metasedimentary basement phyllites and quartzite of presumed Jurassic age (Agua Fría) are followed by 1500 m of massive shallow marine, late Albian–early Cenomanian Atima limestones [42], also seen offshore north east of Honduras [43].

11.8.3 Late Cretaceous

In the Late Cretaceous an angular unconformity developed on Chortis between the marine shales of the Late Albian to Early Cenomanian Krausirpe formation and the overlying clastics of the Late Cretaceous Valle de Angeles formation and there is a palaeo-karst on top of the Albian–Cenomanian Atima limestone [43]. The Nicoya complex of Costa Rica includes plutonic and volcanic arc detritus recording Late Campanian uplift and the beginning of the Laramide orogeny [193]. Late Senonian

carbonate reefs and platforms overlie the unconformity here [194]. The onset of the orogeny coincides with the beginning of rapid convergence ($> 100 \text{ km/m.y.} = 10 \text{ cm/yr}$) of the Farallón plate with North America.

11.8.4 Paleocene–Middle Eocene

A Middle Eocene unconformity is commonly seen as marking the end of Maastrichtian–Palaeogene (Laramide) orogeny and is often related to collision of a volcanic arc at the leading edge of a migrating Caribbean plate (e.g., [109]). However, this unconformity occurs throughout the Caribbean and is one of many arguments for the plate's evolution in place [114, 115]. The unconformity records a particularly violent event, when extremely large olistostromes, olistoliths and nappes formed around the Caribbean area. It is overlain by regional middle Eocene limestones [81, 190], that again record uplift to the photic zone. In Central America such limestones occur in Costa Rica and Panama [13, 195]). Kolarsky *et al.* [50] described angular basalt breccia (Tonosí formation) stratigraphically overlying basaltic basement on Coiba island, Panama. It is overlain by reefal limestone dated as Middle Eocene by *Lepidocyclina*. The Middle Eocene Punta Gorda limestone occurs above deformed upper Cretaceous on the Nicaraguan rise [45, 196] and offshore Belize an argillaceous limestone—dolomite occurs above an angular unconformity on top of the Paleocene–Middle Eocene Toledo formation [197].

Quepos and Osa are part of the Galápagos hotspot track, accreted in the Middle Eocene, possibly causing large-scale regional deformation and uplift of Central America. Middle-Eocene olistostromes overlie the unit at Quepos (see Chapter 13).

11.8.5 Early Oligocene

There is a regional Oligocene unconformity in the sedimentary basins of the Costa Rican arc [161]. In the Caribbean area a regional pulse of block faulting followed the Middle Eocene event, marking the beginning of eastward movement of the plate relative to North and South America [110]. It resulted in highs, capped by unconformities, separated by pull-apart basins whose fill date the episode.

11.8.6 Middle Miocene

The Middle–late Miocene/Pliocene is seen as the time when the Panama arc collided with South America (e.g., [172, 198]) but middle Miocene unconformities occur also in the Tobago trough [100], east of Trinidad and the eastern Venezuela basin [199, 200]).

11.9 PLATE TECTONICS

11.9.1 Cocos–Central America interaction, control of current structures

Control over current structural activity in Central America is logically related to interaction with the Cocos and Nazca Plates in the west and by movements along the north and south Caribbean plate boundaries. GPS data indicate the latter to be largely strike-slip at around 20–21 mm/yr, sinistral in the north and dextral in the south [201,

202]. Guzman-Speziale *et al.* [203] used GPS measurements from SE Mexico to show about 10 mm/yr NNE (27°) directed Cocos-North America convergence. In the Pacific things are less clear. Kellogg and Vega [173], for example, summarized numerous models for Caribbean-Nazca-South America triple junctions (the Eastern cordillera of Colombia; the Panama fracture zone; the Gulf of Guayaquil, Ecuador).

For Hey [204] the Farallón plate broke apart at about 25 Ma. Lonsdale [205] published new data showing that throughout the Paleogene the Farallón oceanic plate was episodically diminished by detachment of large and small northern regions, which became independently moving plates and microplates. The nature and history of Farallón plate fragmentation has been inferred mainly from structural patterns on the western, Pacific-plate flank of the East Pacific rise, because the fragmented eastern flank has been subducted. The final episode of plate fragmentation occurred at the beginning of the Miocene, when the Cocos plate was split off, leaving the reduced Farallón plate as the Nazca plate and initiating Cocos-Nazca spreading. Spreading began at 23 Ma; reports of older Cocos-Nazca crust in the eastern Panama basin had been based on misidentified magnetic anomalies.

A variety of proposed relative plate velocities for the Central American region indicates that precise knowledge is still lacking. GPS data exist only for very short time intervals and are subject to some uncertainty (Mao *et al.*, 1999, quoted by [206]). Ninety-five percent confidence ellipses shown by Kellogg and Vega [173] indicate up to 30° variation. The following extracts illustrate evolution of thought and differences in understanding.

Molnar and Sykes [59] used focal mechanisms of 70 earthquakes to show underthrusting of the Cocos plate below Mexico and Guatemala in a northeasterly direction and below the rest of Central America in a more NNE direction. Deng and Sykes [207] noted that different proposed Euler poles for North America-Caribbean relative motion result from factors such as a small number of focal mechanism solutions, short length of plate boundaries, multibranch faults and bias in selection of slip vectors along the Middle America trench to close plate motion circuits. Slip vectors show a Cocos-Central America pole located at 22 degrees N, 120 degrees W, explaining subduction along the trench as well as dextral strike-slip and extension along the Central American volcanic zone. Deng and Sykes [59] argued that slip vectors are the strongest constraints on plate motion.

Kellogg and Vega [173] discussed GPS data that record NE convergence between Cocos island, on the Cocos plate, and Costa Rica at 72 mm/a, and NNE convergence between Costa Rica and San Andrés island, on the Caribbean plate, at 11 mm/yr. Kellogg and Vega [173] suggest that the latter movement explains some of the difference between the observed Cocos/Costa Rica convergence and the computed 91 mm/yr rate reported by DeMets *et al.* [208].

DeMets [206] noted that lack of data describing present-day Caribbean plate motion precluded rigorous determination of Cocos-Central America motion (trench oblique? partitioned? explains trench-parallel dextral faulting?). With respect to Caribbean motion, DeMets *et al.* [209] presented a new model for Caribbean-North America, based on GPS data from four sites in the Caribbean plate interior and two azimuths of the Swan Islands transform fault (data poorly explained by previously published models). They indicate motion 65% faster than earlier predicted (NUVEL-1A, [208]). This is a large change based on what seems a relatively small data set [210] earlier described motion that was twice the NUVEL-1A prediction).

The NUVEL-1A Cocos-Central America model of DeMets *et al.* [211] used 56

earthquake slip directions and predicted angular velocity differing from trench-normal by only 2–4°. DeMets [206] determined a new estimate of Cocos-Central America relative motion by closure of a Caribbean-North America-Pacific-Cocos plate circuit. It involved GPS data from four sites on the Caribbean plate and 139 on the North American plate, 2 azimuths from the Swan Islands transform fault, transform faults offsetting the Pacific-Cocos rise axis and Pacific-Cocos spreading rates (quite a variety of data). Convergence predicted by this model along the Middle America trench occurs around 10° counter-clockwise to trench-normal. Since most horizontal slip directions for shallow-thrust earthquakes are orthogonal to the trench, DeMets [206] concluded “the evidence that the oblique convergence is fully partitioned is compelling”. In contrast, Norbuena *et al.* [212] discussed new seismic and geodetic data from Costa Rica and concluded that in the Osa region convergence is orthogonal to the trench.

The ocean fractures shown in Figure 11.1 seem to be trench-orthogonal and they parallel ancient structures within the continental roots of Central America. It seems that convergence between the Cocos plate (N35°E) and Central America (N60°W) is close to orthogonal, so it is difficult to explain dextral movement in terms of horizontal strain partitioning. Instead, this chapter notes the perfect fit of trench-parallel dextral movement as antithetic strain to sinistral movement along N35°E trending faults (such as the Guayape fault).

11.9.2 Tectonic evolution

The geology of foregoing sections suggests the following plate tectonic implications for the evolution both of Central America and of the Caribbean plate.

Central America comprises a series of continental blocks (Maya, Chortis, Chorotega and Chocó), separated during Triassic–Jurassic rifting and distributed along the western boundary of the Caribbean area during Jurassic–Early Cretaceous northwesterly drift of North America away from Pangea (Fig. 11.11a, b). Maya moved west relative to Chortis along a broad zone of distributed (geographical and temporal) sinistral shear (the northern Caribbean plate boundary) in the Late Jurassic–Early Cretaceous and again from the Oligocene onwards. Chortis and Chorotega became sinistrally offset along the NW trending, western Caribbean plate boundary, parallel to the Middle America trench (along Jurassic rift faults). Convergence between first the Farallón and later the Cocos plate and Chortis-Chorotega resulted in subduction and related volcanicity in Central America since at least the Albian (probably Jurassic) and caused obduction of ophiolites on the SW margin of the area. Spreading of the Nazca plate has driven the Chocó block northwards, causing it to collide with and accrete to northwestern South America in the Miocene and driving the deforming Panama arc northwards. Volcanicity consequently subsided in this area

Since the Oligocene the northern and southern boundaries of the Caribbean plate have been broad zones of sinistral and dextral strike-slip along which the plate moves eastward relative to North and South America [111, 114, 115]. The zones continue into Central America, where no single fault defines the boundaries between the commonly recognized blocks. Chorotega and Chocó probably lie completely within the southern boundary zone.

Convergence between the Pacific plates and Central America reactivated N15°E and N35°E normal faults as sinistral faults. Areas east of these are moving northeastwards. Drag and compression on the western side of the faults results in

oroclinal bending (Motagua, Agalta) and inversion/shortening of formerly NW trending Triassic? Jurassic and Cretaceous depocentres. Figure 11.12 suggests that complementary compression and oroclinal bending occur to the east at the northern terminations of the faults. This tectonic configuration accommodates convergence between Pacific areas and Central America. It allows net NE–SW shortening while preserving linearity of the SW margin of Central American and the northern Caribbean plate boundary.

Convergence of Cocos plate oceanic crust with Central America is largely orthogonal to the Middle America trench. The Tehuantepec ridge trends towards the Salina Cruz fault (Fig. 11.1). Magnetic anomaly data over the Cocos plate indicate a ridge (here named the Guayape ridge) that trends towards the Guayape fault. The Cocos ridge trends N35°E and converges with Central America in that direction. Spreading at the north–south trending East Pacific rise is approximately east–west. Between the Central America trench and the rise fracture zones curve to accommodate the change of directions (spreading–convergence). This implies that spreading rate increases southwards along the East Pacific rise. It suggests that spreading at the ridge and major fractures in the Cocos plate are influenced by long-lived fractures in the continental crust.

In summary, Maya becomes sinistrally offset from Maya along the Motagua fault zone in the Late Jurassic–Early Cretaceous. Neither of these largely continental blocks has rotated. Continental fragments also underpin Chorotega and Chocó. They formerly lay SW of Chortis and became left behind as Chortis drifted NW in the Late Jurassic–Early Cretaceous. Chocó became sinistrally offset from Chorotega in the Miocene–recent. Chortis, Chorotega and Chocó lie on the western end of the Caribbean plate, which clearly did not migrate from the Pacific.

11.10 SUMMARY

Literature contains a wide variety of models explaining aspects of Central American structural geology. Few of these integrate all data and fewer consider the area in its regional setting. There is considerable variation in interpreted scale, control and timing of fault activity and related structures (oroclines, thrust belts), origin and type of basement and of major blocks.

The tectonic history of the area proceeded as follows:

1) Major, ancient lineaments within Pangea determined the alignment of Triassic–Jurassic rifts N35°E and N60°W transfer faults in the area of future southern North America, Caribbean and northern South America.

2) Movement of North America away from South America in the Jurassic–Cretaceous occurred along transform faults/oceanic fractures that extrapolated N60°W transfer faults generated during 1). These have bracketed the area between the diverging North and South American plates to the present day. A N35°E spreading ridges (Beata ridge, [81, 110, 115]) propagated between North and South America. Subsidence, thinning and magmatism along the margins of continental fragments (Maya, Chortis) followed N35°E Triassic–Jurassic rifts. In the west, margin-parallel (N60°W) Jurassic rifts formed (now seen in Mexico–western Guatemala; possibly further expressed by the Nicaraguan depression). The triangular forms of Maya and Chortis developed at this time by the combination of these two trends.

A first episode (late Jurassic–Early Cretaceous, [110, 115]) of Cayman trough

sinistral offset occurred as Maya moved several hundred kilometers west relative to Chortis, formerly attached to southwestern Mexico and south Maya. Normal faulting, related to this early offset was oriented N15°E. It controlled the southern segments of the Caribbean margins of Maya and Chortis. Chorotega-Chocó became sinistrally offset from Chortis along a N60°W trend.

3) Subduction occurred at the western and eastern ends of the Caribbean area at least as early as the Albian, producing volcanic arcs and isolating the plate [110, 115].

4) Major sinistral movement occurred along NE trending faults such as the Guayape, Río Hondo, and eastern boundary faults of Maya in the Paleogene, causing oroclinal bending of NW trending Jurassic and Cretaceous depocentres. Sinistral movement along the faults is taken up by NE-directed contraction (NW trending folds/thrusts) to the west. Antithetic dextral movements and related pull-apart occurred along the southwestern boundary of Central America, manifest as the Nicaraguan depression. Pull-apart related to both sinistral and dextral faulting generated a system of grabens crossing Honduras. Where these trends intersect at the Nicaraguan depression a series of depressions accommodates the Gulf of Fonseca, Managua lake, and Lake Nicaragua.

5) Paleogene clastic deposition culminated violently in the Middle Eocene with emplacement of nappes and large olistoliths/olistostromes.

6) Oligocene–recent eastward movement of the Caribbean plate relative to North and South America resulted in an initial pulse of pull-apart extension and then eastward-migrating folding and thrusting along the northern and southern plate margins. This segmented and extended the Nicaraguan rise, separated elements along the Greater Netherlands-Venezuelan Antilles and generated an easterly migrating thrust/foreland basin couple along the northern margin of South America.

N35°E convergence between the Cocos and Caribbean Plates is the current dominant driver of western Caribbean tectonics (Fig. 11.12). NE sinistral movement occurs along N35°E trending faults such as the Río Hondo and Guayape. The displacement transforms into north-concave and south-concave oroclinal bending and compression west of the faults in Central America and east of the faults in Cuba and Jamaica. Antithetic dextral movement occurs along trench-parallel faults such as those defining the Nicaraguan depression.

NE convergence between the Nazca plate and northwestern South America drives northward extrusion of the Bolívar block [131] and of the Panama arc along NE dextral and NW sinistral faults (east and west, respectively). The South Caribbean deformed belt and the North Panama deformed belt accretionary prisms formed ahead of these areas. The southern half of Chocó has accreted to northwestern South America and is separated from the northern half (the Panama arc) by a NE trending dextral fault.

11.11 CONCLUSIONS

The structural geology of Central America is best explained in its regional setting at the western end of the Caribbean. It is controlled by strain generated during Triassic–Jurassic rifting (reactivating older lineaments) and Jurassic–Cretaceous drifting of North America from South America. The structures have been reactivated through subsequent history, often in a reverse sense (inversion, change of strike-slip direction). They retain a regional integrity that harmonizes movement and deformation.

If continental crust exists beneath Chorotega and Chocó, as argued in this chapter,

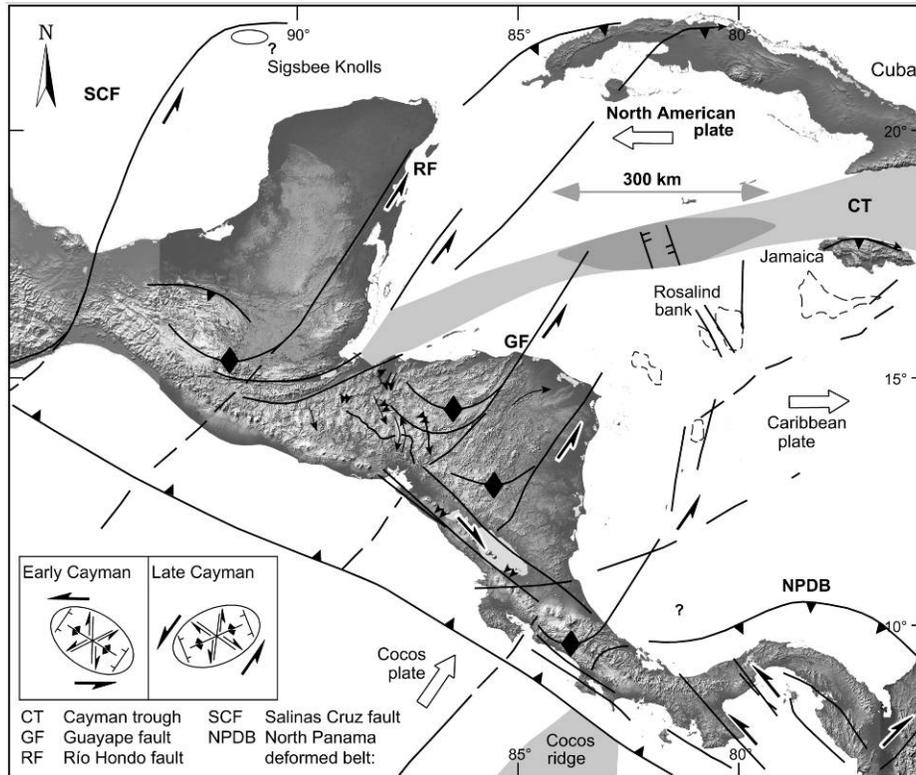


Figure 11.12. Synthesis of the current tectonic setting of Central America suggests that the western Caribbean is dominated by convergence of the Cocos plate. Late Eocene/Oligocene-recent pull-apart-strong pattern - in the centre of the Cayman trough (CT) accommodates 300 km of eastward movement of the Caribbean plate relative to North America (earlier, Jurassic-Cretaceous Cayman offset —greyed pattern/stress-strain ellipse— occurred during drift of North America from South America). The convergence drives sinistral movement along a series of parallel faults, such as the Río Hondo (RF) and Guayape faults (GF), which earlier experienced extension (greyed stress/strain ellipse). Oroclinal bending, folding and thrusting accommodates the sinistral offset west of the faults (thus there is no sinistral offset of the trench-parallel coast/Nicaraguan depression). The system allows net NE-SW shortening while preserving linearity of the SW margin of Central America and of the northern Caribbean plate boundary. Dextral offset along the Nicaraguan depression is antithetic to the sinistral offsets. The Panama regions and the Bolivar block of NW South America (not shown [131]) are moving north along NW sinistral and NE dextral faults, driving the North Panama (NPDB) and South Caribbean deformed belts ahead of them.

distinction between Nuclear Central America (Maya and Chortis) and the “Isthmian Link” is inappropriate.

The boundaries between Maya and Chortis and Chortis and Chorotega are broad zones of E-W strike-slip faulting. The boundary between the Panama arc and South America is probably a NE trending fault crossing the isthmus and running north of the Gulf of Urubá. The Chorotega-Chocó boundary is marked by the Panama fault zone.

The Panama area (northern Chocó) is being shunted northwards over the southwestern-most part of the Caribbean plate, driving before it the North Panamanian fold belt sedimentary prism. The latter does not mark the northern boundary of Chocó or of Chorotega. Chorotega is fixed on the western margin of the Caribbean plate. The

southern extension of Chocó is accreted to South America.

Separation of stratigraphy premised upon perceived (modeled) “terrane” rather than its use to correlate between adjacent blocks should be reconsidered. Maya and Chortis share common geology. They are joined, not by a suture where pre-existing oceanic crust was consumed, but along a zone of sinistral shear.

The only terranes in Central America may be small, accreted oceanic areas of western Costa Rica (Nicoya, Azuero), though reported paleomagnetic rotations/migrations could reflect local effects of strike-slip faulting.

Chortis, Chorotega and Chocó have always been at the western end of the Caribbean area. Migration of the Caribbean plate from the Pacific was not possible.

Future investigations could seek structures that conform (or not) to the suggested regional pattern. This indicates a systematic grid of “Guayape” trend faults throughout Central America, accompanied by oroclinal bending, folds and thrusts. Systematic sinistral/dextral fault interactions and related extension might control the spacing of volcanoes along Central America. Knowledge of the regional structural pattern could help understand earthquake and volcanic activity. The suggestion that Chorotega and Chocó are underpinned by continental crust should be investigated.

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