Chapter 8

Overview of plate tectonic history and its unresolved tectonic problems

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> "*Although several of the ideas basic to the following discussion have been presented in earlier publications, no attempt has been made to integrate these separate ideas into a broader outline of the geologic history of the Caribbean, nor have many of these ideas been presented in the context of plate tectonics.*" B.T. Malfait and M.G. Dinkelman: Circum-Caribbean Tectonic and Igneous Activity and the Evolution of the Caribbean Plate. *Geol. Soc. Am. Bull.* 83, pp. 251–272, 1972.

8.1 INTRODUCTION AND OBJECTIVES

Central America provides an accessible natural laboratory for the study of how tectonic and volcanic processes operate in tandem (Fig. 8.1). Two factors that make this region favorable for integrated tectonic-volcanic studies are that the outputs of the system are accessible for study in the onland arc, and that the oceanic inputs to arc systems are reasonably well constrained due to the large, rapidly expanding, and digital database of offshore geological and geophysical data (e.g., [1]) (Figs. 8.2 and 8.3).

The various segments of the Central American volcanic arc (CAVA) and its modern volcanic front (CAVF) summarized on Figure 8.1 offer many advantages for researchers to:

Investigate large variations in the slab/sediment component of volcanic products that are observed along the arc, especially the dramatic changes between Nicaragua and Costa Rica. Volcanoes in Nicaragua record the global maximum in recycled sediment signatures, such as ^{10}Be and Ba/La [2–4].

Investigate large-scale forcing functions on the Central American volcanic arc or "Subduction Factory", such as the variation in convergence rate (~65–90 mm/yr; Fig. 8.1) along the margin, and its effect on mass fluxes of sediments, carbonate, and water through the subduction system [4].

Examine the effects of different ages (15–24 Ma) and thicknesses (6–18 km) of subducting oceanic crust on the geochemical properties of the CAVA and CAVF (Fig. 8.2) [1, 5].

Examine a well-exposed, onland temporal record of Miocene–Pliocene arc volcanism that can be tracked through time as a result of the shift in the volcanic axis of the CAVA from the northeast to southwest [4].

Examine the geochemistry of volcanic products which are not significantly contaminated and complicated by the continental arc and oceanic plateau crust of the overriding Caribbean plate [3, 4].

Examine an extremely active arc with closely spaced volcanoes and arc-related faults that often pose major hazards to local populations [6].

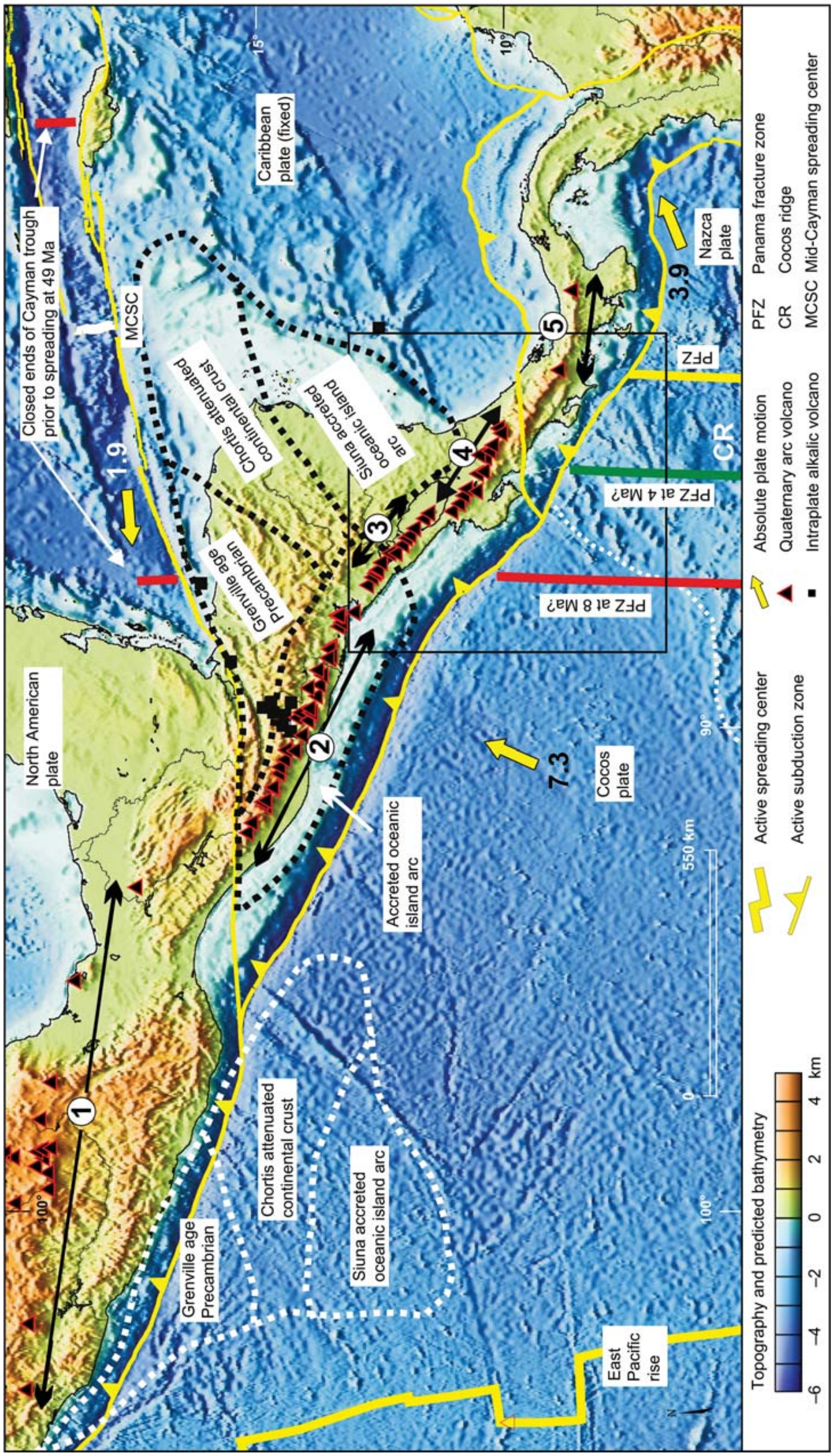
View the plutonic roots of the arc in an area affected by shallow subduction of the Cocos ridge, where the arc can be traced along strike into the modern CAVF to the northwest and southeast [7–9] (Fig. 8.2).

While this area has many advantages for studies of both modern and ancient subduction processes, the regional tectonic development of the CAVA and CAVF is more complex than is presently perceived, and an improved tectonic framework will be an important step in more detailed subduction studies.

For example, there are several potential areas for the study of longer term tectonic processes that have shaped the Cenozoic CAVA and modern CAVF. Some of these longer term tectonic processes include: (1) the detachment, translation and rotation of the continental Chortis block of northern Central America which forms the basement for the northern part of the CAVA and CAVF; (2) slab break-off events affecting the subducting Cocos plate of the type described by Rogers *et al.* [10] in northern Central America in the Miocene and by Ferrari [11] for Miocene arcs in southern Mexico; (3) dramatic increases in the Cocos-Caribbean plate convergence rate, based on the superfast Early to Middle Miocene Cocos-Pacific spreading rates at the East Pacific rise reported by Wilson [12] (Fig. 8.2); and (4) changing positions of the Cocos-Nazca-Caribbean triple junction, now located off the Costa Rica-Panama border (Fig. 8.1); based on current plate motions (Nuvel-1, [13]). Several interpretations show that this triple junction may have swept NW to SE along most of the Costa Rican Pacific margin since ~10 Ma [14, 15] (Fig. 8.1).

Such significant changes in plate motions and forcing functions must be taken into account in any systematic effort to understand the ancient and active processes of the Central American subduction system. Unfortunately, current plate reconstructions fail to explain many geologic constraints in the published literature.

Figure 8.1 (right). Tectonic and topographic setting of the Central American arc (volcanic arc segments 2–5), Trans-Mexican volcanic belt (segment 1) and the Middle America trench. Plate motions in cm/yr for Caribbean-North American plates are from Demets *et al.* [91] and for Cocos-Caribbean and Nazca-Caribbean plates are from DeMets and Dixon [96]. Box shows approximate area of the MARGINS Subduction Factory focused study area of arc segment 3 in Nicaragua and arc segment 4 in Costa Rica. Basement block types of overriding Caribbean plate include the following terranes described in the text: the Central Chortis terrane is underlain by Grenville age Precambrian crust detached from the southern margin of Mexico in the Late Cretaceous to Paleogene (approximate reconstructed Late Cretaceous position of Chortis is shown by dotted outline and is from Rogers [98]); Eastern Chortis terrane is underlain by Jurassic metasedimentary rocks formed along the Mesozoic rifted margin of the Chortis block; the Siuna terrane is underlain by deformed rocks of oceanic island origin that were accreted to the eastern Chortis terrane during Late Cretaceous time [24, 36, 37] the southern Chortis terrane is underlain by a Late Cretaceous island arc accreted to the Central Chortis terrane in Late Cretaceous time; the arc is inferred to represent a fragment of the Guerrero terrane of Mexico [38]; and northern Chortis terrane is inferred to record a magmatic overprinting of parts of the central and eastern Chortis terranes. Age and position of ends of Cayman trough from Leroy *et al.* [40]; positions of Cocos-Nazca-Caribbean triple junction from McIntosh *et al.* [15].


North American plate
Closed ends of Cayman trough prior to spreading at 49 Ma
1.9
MCSC
Caribbean plate (fixed)
15°
10°
Chortis attenuated continental crust
Siuna accreted oceanic island arc
Grenville age Precambrian
1
2
3
4
5
Accreted oceanic island arc
7.3
Cocos plate
3.9
Nazca plate
PFZ
CR
PFZ at 4 Ma?
PFZ at 8 Ma?
0
550 km
90°
100°
East Pacific rise
Grenville age Precambrian
Chortis attenuated continental crust
Siuna accreted oceanic island arc
N
Topography and predicted bathymetry
−6
−4
−2
0
2
4
km
Active spreading center
Active subduction zone
Absolute plate motion
Quaternary arc volcano
Intraplate alkalic volcano
PFZ Panama fracture zone
CR Cocos ridge
MCSC Mid-Cayman spreading center

To elucidate the tectonic setting of Central America, and more specifically, the evolving Central American subduction system, a quantitative set of plate reconstructions of Central America and Caribbean region for the period of 165–0 Ma is presented in this chapter.

The reconstructions are used as background to discuss unresolved questions concerning the changing position of the subduction plate boundary through time, changing rates of subduction, changing angles of subduction, changing ages of the subducted crust, and the current position and past migration of triple junctions. Knowledge of the tectonic setting through time is necessary to support any conclusions concerning the temporal variation of the geochemical output at the CAVA.

The reconstructions presented here take into account a great deal of new magnetic and fracture zone data acquired in the past 12 years [12, 16–18]. These data allow a much more accurate description of oceanic plate motions (Cocos, Nazca, Pacific) compared to reconstructions widely used in the region [19, 20] (Fig. 8.2).

The reconstructions of the Cocos-Nazca-Caribbean plates, linked by magnetic anomalies and fracture zones to the North and South America plates, provide the tectonic framework needed to constrain the large-scale forcing functions of the CAVA. These include properties such as convergence rate, age of subducted lithosphere, and position of plate boundaries through time, which are key elements to a variety of ongoing CAVA studies including geochemistry, GPS geodesy, volcanology, seismology, and geophysics. Recent onshore geologic work (e.g., [4, 21, 22]) document and date critical tectonic processes and changes. The offshore geophysical database, which now includes seismic reflection and refraction [1, 15, 24, 25], gravity, magnetic, and swath bathymetry data [26, 27] constrain the tectonic history.

8.2 METHODOLOGY OF THIS CHAPTER

Reconstructions presented in this paper are based on the following steps:

Compilation of all existing magnetic anomaly (Cenozoic) and fracture zone data from the Cayman Trough (Caribbean Sea) and eastern Pacific Ocean. We use extensive fracture zone and magnetic anomaly data from Udo Barckhausen, Hans Roeser and co-workers of BGR (Germany) [18];

Integration of main Cenozoic tectonic events in the surrounding ocean basins, which have potentially affected the Central American subduction factory, including: (1) initiation and subsequent seafloor spreading in the Cayman trough; (2) early rifting of the Farallón plate at 22.7 Ma; (3) super-fast spreading on the East Pacific rise between 18 and 10 Ma; and (4) early history of the Cocos ridge and its offset by the Panama fracture zone around 6 Ma;

Integration of main Cenozoic tectonic events onshore in Central America that potentially affected the Central America subduction factory, including: (1) eastward migration of the Chortis continental block to northern Central America and progressive 35–28 Ma cessation of plutonic activity in southern Mexico [28]; (2) NE to SW migration of the volcanic arc activity and opening of the Nicaraguan back-arc basin from 10–0 Ma [4]; (3) west to east migration of Carib-Cocos-Nazca triple junction along the Costa Rican margin from 8–0 Ma [15]; and (4) Pliocene to recent collision of the Cocos ridge with the margin [7, 29].

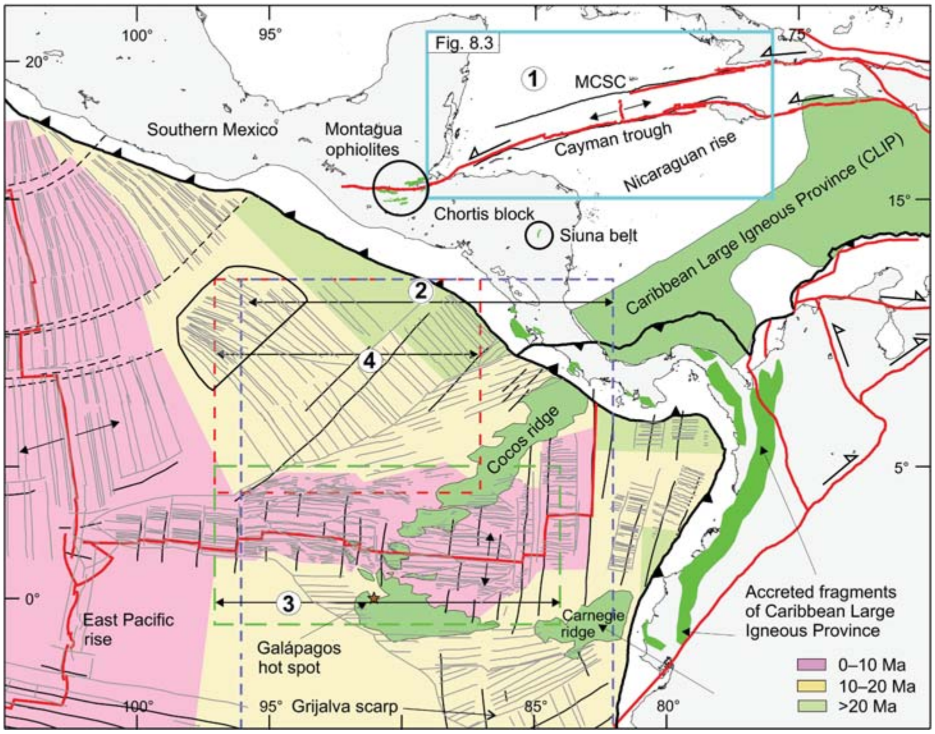


Figure 8.2. Marine magnetic anomalies and fracture zones which constrain tectonic reconstructions such as those shown in Figure 8.5 (ages of anomalies are keyed to colors as explained in the legend; all anomalies shown are from UTIG PLATES data base [97]): (1) Boxed area in solid blue line is area of anomaly and fracture zone picks by Leroy *et al.* [40] and Rosencrantz [56] for the Cayman Trough; (2) boxed area in dashed purple line shows anomalies and fracture zones of Barckhausen *et al.*[18] for the Cocos plate; (3) boxed area in dashed green line shows anomalies and fracture zones from Wilson and Hey [16]; and (4) boxed area in red shows anomalies and fracture zones from Wilson [12]. Onland outcrops in green are either the obducted Cretaceous Caribbean large igneous province, including the Siuna belt, or obducted ophiolites unrelated to the large igneous province (Motagua ophiolites). The magnetic anomalies and fracture zones record the Cenozoic relative motions of all divergent plate pairs influencing the Central American subduction zone (Caribbean, Nazca, Cocos, North America, and South America). When incorporated into a plate model, these anomalies and fracture zones provide important constraints on the age and thickness of subducted crust, incidence angle of subduction, and rate of subduction for the Central American region.

8.3 OVERVIEW OF THE TECTONIC HISTORY OF CENTRAL AMERICA AND THE CAVA

The CAVA and CAVF show complexities related to the mobility of the Caribbean plate and other small plates or microplates in the complexly deformed region between the much larger North and South American plates and along the convergent margin with eastern Pacific oceanic plates (Fig. 8.1). Much of the relative movements of these elements has been broadly outlined in previous reconstructions, such as those by Pindell and Barrett [30], Pindell and Kennan [20] and Meschede and Barckhausen [31]; however, these motions are quantitatively reconstructed by incorporating as many of the recent magnetic (Figs. 8.2 and 8.3), fracture zone, and geologic (Fig. 8.1) constraints as possible. The reconstructions show that some of the tectonic and geochemical complexities of the CAVA and CAVF may be related to structures and crustal variations in the upper plate.

Some important tectonic elements of the CAVA that attest to its mobility, highlighted in reconstructions of the region, include the following features:

Chortis block: This area has been traditionally regarded as the Precambrian–Paleozoic continental nucleus of northern Central America upon which the CAVA formed (Fig. 8.1). Radiometric dating by Schaff *et al.* [28] shows the diachronous nature of magmatism along the southern coast of Mexico that supports the proposed progressive, Cenozoic west to east translation and counter-clockwise rotation of the Chortis block from its Late Cretaceous position proposed by Pindell and Dewey [33] and shown in Figure 8.1. This large-scale left-lateral offset is consistent with a minimum of 1100 km of left-lateral offset recorded on the narrow Cayman Trough to the east (Fig. 8.3). Recent studies by Rogers [34] and Rogers *et al.* [35] show that the block is not homogeneous and can be divided into tectonic terranes shown on Figure 8.1: (1) the Central Chortis terrane, underlain by Grenville age Precambrian crust detached from the southern margin of Mexico in the Late Cretaceous to Paleogene (approximate reconstructed position of Chortis is shown in Figure 8.1); (2) the eastern Chortis terrane, underlain by Jurassic metasedimentary rocks formed along the Mesozoic rifted margin of the Chortis block; (3) the Siuna terrane, underlain by deformed rocks of oceanic island origin accreted to the eastern Chortis terrane during Late Cretaceous time [24, 36, 37]; (4) the southern Chortis terrane is underlain by a Late Cretaceous island arc accreted to the Central Chortis terrane in Late Cretaceous time; the arc is inferred to represent a fragment of the Guerrero terrane of Mexico [38] and (5) the northern Chortis terrane, the area of magmatic overprinting of parts of the Central and eastern Chortis terranes. In Figure 8.1, the boundaries between these varying basement types strike at right angles to the CAVA and may be important controls on the tectonic structures of the arc and types of magmas erupted along this subduction boundary. For example, a large ignimbrite erupted between 19 and 14 Ma and aligned along the northwest-trending boundary of continental terranes of the Chortis block suggests that melting was guided by this crustal break [10]. Movements along block boundaries within Chortis may also account for the changes in strike directions of the active arc segments in Nicaragua and Costa Rica numbered 3 and 4 on Figure 8.1. The interpreted basement boundaries also coincide fairly well with many of the offsets that segment the volcanic arc.

Cayman trough: This 1100-km-long oceanic basin formed as a pull-apart basin at the Mid-Cayman spreading center (MCSC) between 49 Ma and present [39, 40]. The marine magnetic anomalies and fracture zones produced by seafloor spreading provide a partial record of the motion between the North America and Caribbean plates and Chortis block as well as the changing position and counterclockwise rotation of the CAVA through time (Fig. 8.1), provided the complexities of the Gonave microplate, at the southeastern edge of the Cayman trough in Jamaica and Hispaniola, are taken into account [41]. Recent work by Müller *et al.* [42] suggests that the Caribbean plate has remained fixed relative to Atlantic and Indian Ocean hotspots for much of the Cenozoic. By understanding the motion of the Caribbean plate, including the Chortis block, kinematic constraints on the CAVA and CAVF should be able to be improved.

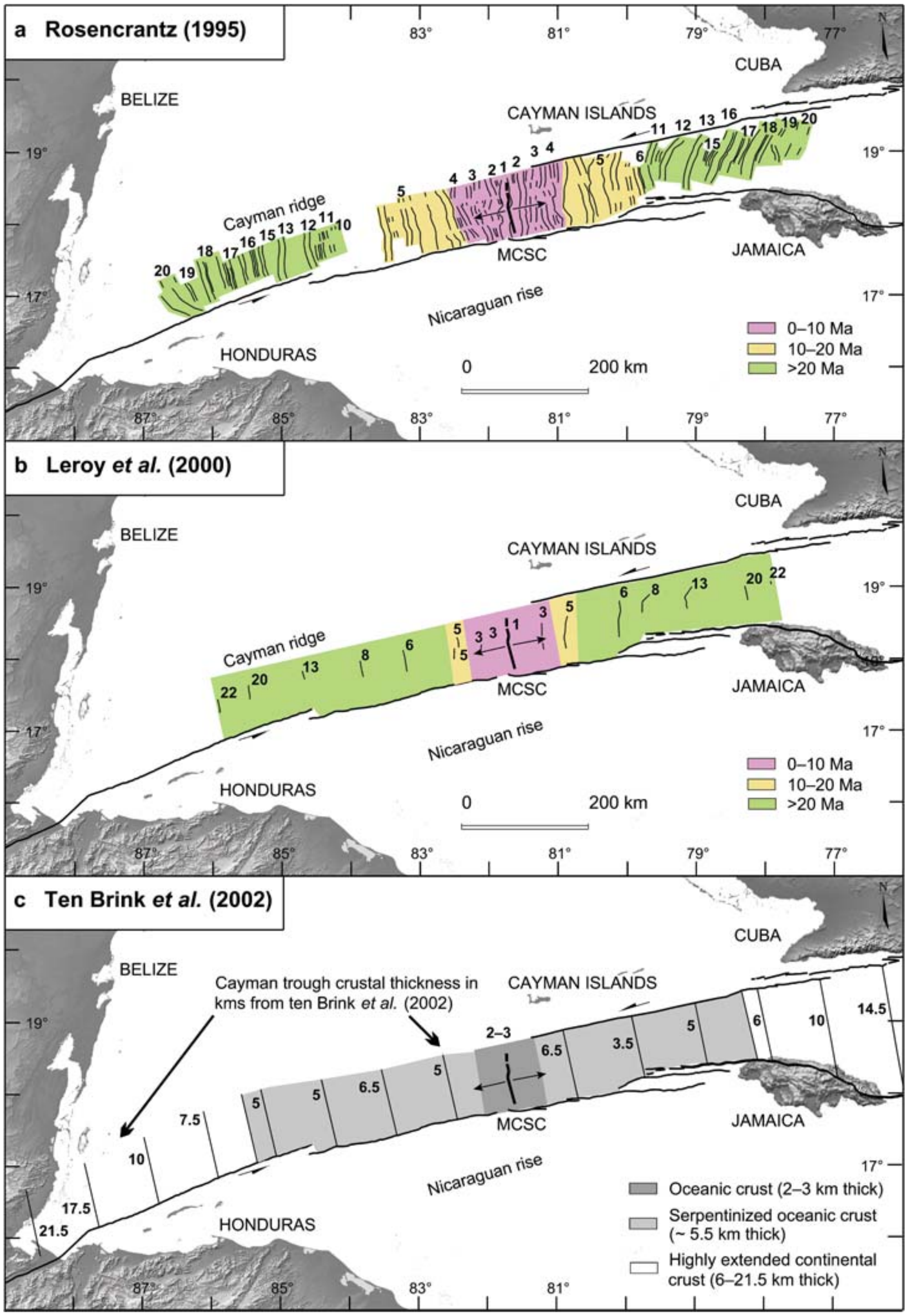


Figure 8.3. Marine magnetic anomaly interpretations of the Cayman trough. MCSC: Mid-Cayman Spreading Center. (a) Rosencrantz [56] interpretation: numbers next to lineations identify magnetic anomalies; (b) Leroy *et al.* [40] interpretation: numbers next to lineations identify magnetic anomaly numbers; (c) Ten Brink *et al.* [99] interpretation showing larger area of thinned, continental crust. Numbers next to lineations represent their crustal thickness values.

8.4 KEY TECTONIC EVENTS AFFECTING CENTRAL AMERICA SHOWN IN THE PLATE RECONSTRUCTIONS

The reconstructions shown in Figures 8.4a–h coincide with major tectonic events. The main Cenozoic tectonic events in the surrounding ocean basins, which have potentially affected the Central American volcanic arc, include the following:

initiation of spreading of the Cayman trough around 49 Ma (diffuse rifting that preceded organized seafloor spreading at the Mid-Cayman spreading center began earlier [43]) (Fig. 8.3);
slowdown or cessation of Cayman trough spreading at 26–20 Ma [56] (Fig. 8.3);
early rifting and breakup of the Farallón plate at 22.7 Ma and the original distribution of now dispersed fragments that include the Cocos, Malpelo, and Carnegie ridges [31] (Fig. 8.2);
super-fast spreading on the East Pacific rise between ~18 and 10 Ma [12];
offset of the Cocos ridge by the Panama fracture zone around 6 Ma [44].

The main Cenozoic tectonic events in the Central America that potentially affected the CAVA and CAVF in a diachronous manner include:

eastward migration relative to the Chortis continental block to northern Central America and progressive 35–28 Ma cessation of plutonic activity in southern Mexico [28];
NE to SW migration of the volcanic arc and opening of the Nicaraguan back-arc basin from 10–0 Ma [4, 21];
NW to SE migration of Carib-Cocos-Nazca triple junction across the Costa Rican margin from ~8–0 Ma [15, 44];
collision of the Cocos ridge with the Costa Rican margin from 5.5 to 3.5 Ma [29, 45] with a slight east to west component of collision;
ridge subduction and slab window (gap in subducting plate) formation beneath Costa Rica and Panama as a result of either triple junction migration [22] or subduction of the Cocos ridge [46].

The reconstructions also integrate the main Cenozoic tectonic events affecting the Caribbean plate as a whole. For example, recent work has suggested that the Caribbean plate has remained stable relative to Atlantic and Indian Ocean hotspots since 38 Ma [42]. North and South America converged rapidly from 38 to 10 Ma and slowly from 10 to 0 Ma [47].

8.5 PLATE RECONSTRUCTIONS OF CENTRAL AMERICA: 165–0 MA

8.5.1 Plate reconstructions of Central America and the eastern Pacific

Several plate tectonic models for the Caribbean and Pacific Ocean appeared during the late 1980s and early 1990s. These works included: Ross and Scotese [19], Rosencrantz *et al.* [39], Mayes *et al.* [48], Atwater and Severinghaus [49], and Pindell and Barrett [30]. Since these early efforts, new marine magnetic anomaly/fracture zone data and new interpretations of existing data have been published in these regions [12, 16, 18, 40, 50, 51]. Some of these data were incorporated in more recent plate models by Meschede *et al.* [52], Meschede and Barckhausen (ODP Leg 170 Scientific Results, [17]), Mann [53], and Müller *et al.* [42]. Mann [53] incorporated the North America-South America-Africa motions determined by Müller *et al.* [42], using the PLATES software [97] and database to expand the area extent of their reconstructions [97]. They did not incorporate of the magnetic anomaly picks of Leroy *et al.* [40] or Barckhausen *et al.* [18] who worked independently.

A series of plate reconstructions is presented from the Middle–Late Jurassic to the present-day that depicts the evolution of Central America in the regional context of the southern Cordillera of western North America, the Caribbean plate, the Cayman trough of the Caribbean, and the oceanic plates of the Pacific Ocean (Fig. 8.4a–h). The reconstructions were made in the mantle reference framework of Müller *et al.* [42] and illustrate the westward migration of the North and South American plates relative to a Caribbean plate fixed in the mantle reference frame. The present position of the Galápagos hotspot provides a stationary point of reference for this framework and is shown in all reconstructions in Figure 8.4. It should be noted that the geologic evidence for its existence can now be extended back to 139 Ma [54, 55].

The principal constraints on the plate motions shown on the reconstructions are published seafloor spreading anomalies and finite rotation poles by previous workers that were compiled by us for the purpose of this study (anomalies used are shown on Figs. 8.2 and 8.3). The plate circuit used for the reconstructions is Caribbean to North America [56]; North America to Africa and South America to Africa [42]; Africa to Antarctica [57]; Antarctica to Nazca [58, 59] and Antarctica to Pacific [58, 60]; and Nazca to Cocos [16, 18]. The nature and location of ancient plate boundaries shown in the reconstructions of Mexico and the Caribbean in Figure 8.4a–h are based on geologic constraints summarized in the synthesis of Mexican geology by Dickinson and Lawton [38] and in the syntheses of Caribbean and northern South American geology by Pindell and Barrett [30], Pindell [61], and Mann [53].

8.5.2 165 Ma (Late Jurassic)

The reconstructions start in the Late Jurassic and resemble the reconstructions of Dickinson and Lawton [38] for the earlier evolution of Mexican terranes (Fig. 8.4a). At this time, North America and South America are shown just prior to their separation to form the now-subducted, proto-Caribbean seaway. Opening of the Gulf of Mexico during this period rotated the Maya (Yucatán) block south to Central America [32]. The continental terranes of the Chortis block were adjacent to the autochthonous Mexican terranes. The Cretaceous margins of Chortis was likely derived from elements of the Guerrero-Caribbean arc formed at the leading edge of the Farallón plate that consumed the Mezcalera plate as it advanced from the west. East-dipping subduction along the western margin of the Americas occurred across the Central America region (Fig. 8.4a).

8.5.3 144 Ma (Early Cretaceous)

At the start of the Cretaceous, North America and South America continued to separate and form the proto-Caribbean seaway [30]. The oceanic crust of the proto-Caribbean was later consumed by the eastward and northeastward advance of the Guerrero-Caribbean arc shown in Figure 8.4b. Opening of the proto-Caribbean formed the eastern Chortis terrane of attenuated continental crust [33]. The opening event also rifted the Juárez terrane of Mexico [38].

Rifting along the southwestern margin of North America formed the Arperos basin [62]. Widespread rifting along the western margin of North America at this time is

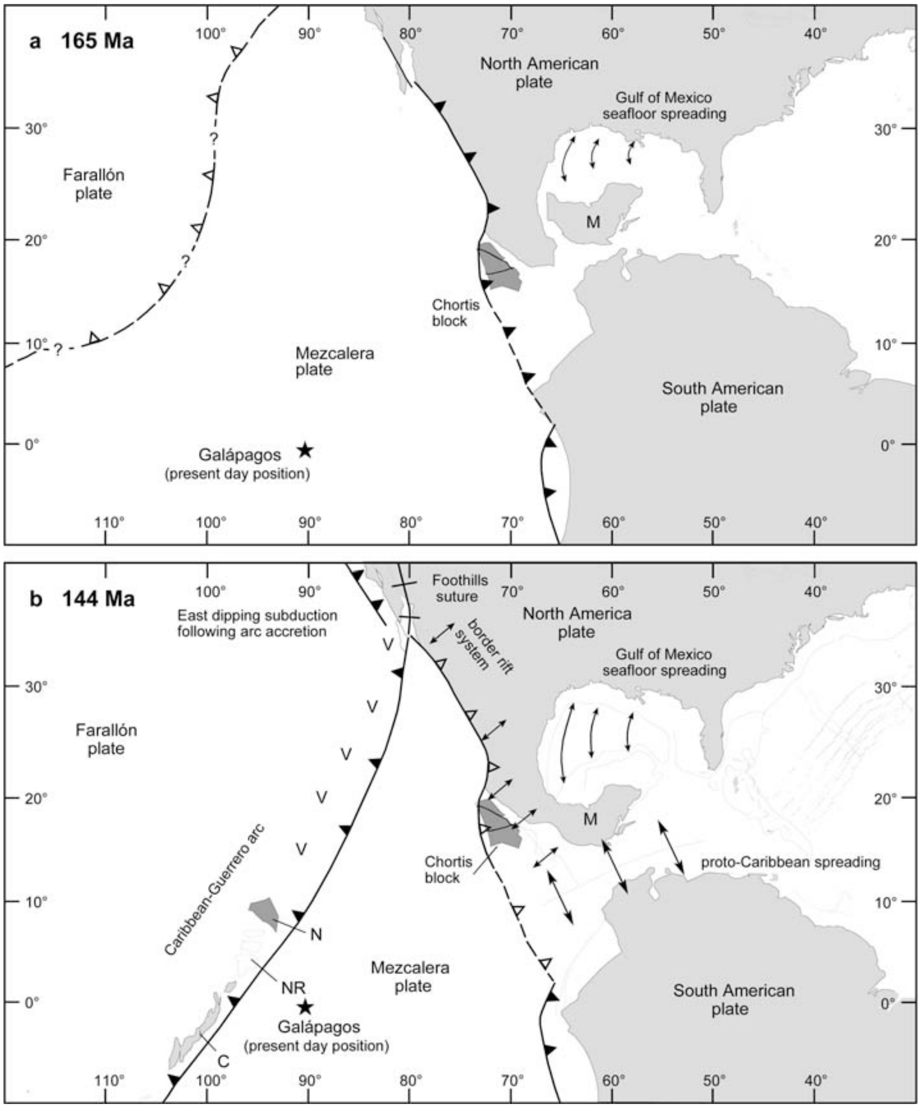


Figure 8.4. Reconstructions of the development of the western Cordillera and Caribbean from Jurassic to present: (a) ~ 165 Ma; (b) ~144 Ma; (c) ~120 Ma; (d) ~90 Ma; (e) ~72 Ma; (f) ~49 Ma; (g) ~22 Ma; (h) Present-day. See text for discussion. Key to abbreviations: N: Nicaragua; NR: Nicaraguan rise; C: Cuba; M: Maya block; G: Guerrero terrane; CLIP: Caribbean large igneous province; Y: Yucatán basin; CT: Cayman trough; and LA: Lesser Antilles. Countries of Costa Rica and Panama correspond to approximate area of Chorotega block; countries of Honduras, Nicaragua, and Guatemala correspond to Chortis block.

attributed to trench rollback as subduction of the oceanic Mezcalera plate slowed during the approach of the Guerrero-Caribbean arc from the west [38] (Fig. 8.4b).

We adopt the interpretation by Tardy *et al.* [62] and Moores [63] that the Caribbean arc and the Guerrero arc are parts of the same segments of the same intra-Pacific ocean arc system that entered the Caribbean region during Cretaceous time. Diachronous collision of this arc with the western North America margin progressed from north

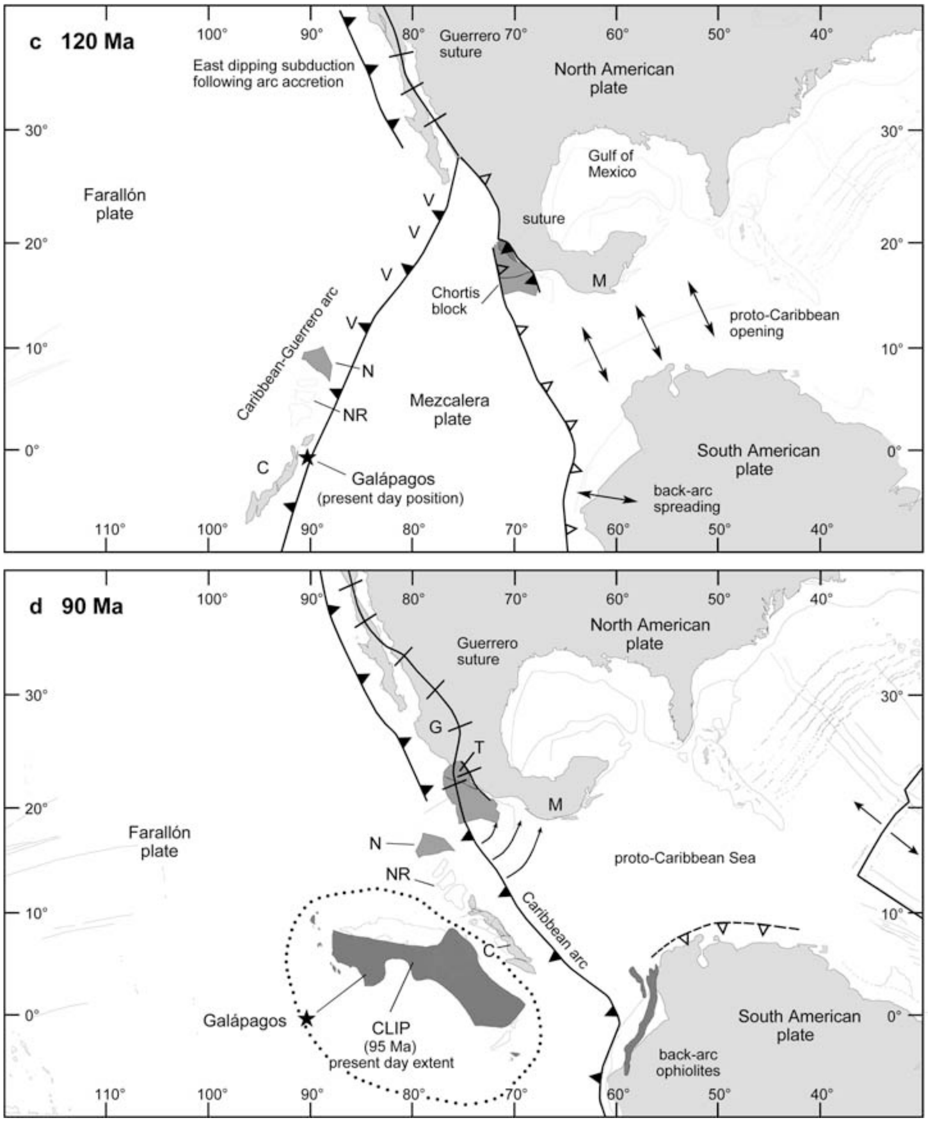


Figure 8.4 (continued).

(Sierran foothills of California) to south (Guerrero terrane with southern Mexico) [38] (Fig. 8.4b). Following this arc-continent collision, eastward-dipping subduction of the Farallón plate stepped outboard (westward) of the newly accreted Guerrero terrane.

An alternative view not supported by the compilation presented here proposes that the present-day area of the Caribbean was created during the period of 130 to 80 Ma but that this newly created area has remained relatively stationary with respect to North and South America and was not consumed by the Caribbean arc system [64] (cf., preface in Mann [65] for a review of salient points of both proposed concepts). The alternative viewpoint of Frisch *et al.* [64] fails to explain the diachronous west to east timing of foreland basin subsidence and thrust deformation related to the diachronous collision between the Caribbean arc and the passive margins of North and South

America (cf., [30, 65]. Rifting of the southwest Mexican margin during the Early Cretaceous detached part of the Oaxaca and Mixteca terranes from nuclear Mexico (Del Sur block of Dickinson and Lawton [38]) to form the Chortis block.

Rifting of Chortis may have occurred along the southward extension of the Arperos basin as proposed by Pindell and Kennan [20] or along a failed rift arm of the proto-Caribbean spreading center (Fig. 8.4a). During this time, the Chortis block underwent intra-block rifting and deposition of pre-Aptian, terrigenous siliciclastic rocks [34, 66].

8.5.4 120 Ma (Early Late Cretaceous)

Extension between North and South America continued and the Guerrero-Caribbean arc advanced eastward to subduct the proto-Caribbean oceanic basin (Fig. 8.4c). By this time, collision of the Guerrero terrane with the margin of western North America and closure of the Arperos basin was complete to the latitude of Baja (W. Dickinson, *pers. comm.*, 2003). It is proposed that prior to the diachronous closure of the Guerrero-Caribbean arc against southwestern Mexico, Chortis-Mexico convergence occurred along a short-lived, westward-dipping subduction zone (Fig. 8.4c). This subduction produced intra-arc rifting and arc volcanism in the overriding Chortis block by 126 Ma [34, 66, 67]. Termination of this subduction cycle between Chortis and southwestern Mexico is recorded by a well-dated, 120 Ma-old subduction complex along the northern edge of the Chortis block presently exposed on the southern margin of the Motagua valley of Guatemala [68, 69]. Structural and stratigraphic continuity between Chortis and southwestern Mexico at this time is suggested by: (1) the geochemical similarity between the volcanics erupted on the Chortis block and the Teloloapan volcanic rocks of Mexico; and (2) the similar Mesozoic stratigraphy and structural trends shared by both areas [34].

8.5.5 90 Ma (Late Cretaceous)

The Guerrero-Caribbean arc continued diachronous suturing along the western and southern thinned, continental edges of the Chortis block (Fig. 8.4d). The short-lived, middle Cretaceous volcanic arc, intra-arc basins, and associated mixed carbonate-clastic deposition on the Chortis block were terminated by a collisional event recorded by the deposition of clastic sedimentary rocks of Late Cretaceous age in Honduras [34, 37]. Collision-related shortening inverted intra-arc basins and created the four alignments of deformed Cretaceous sedimentary rocks seen in the present-day geology of Honduras [66]. Strong shortening effects are also seen in southern Mexico at this time [38].

By this time, the Guerrero-Caribbean arc had overridden the Galápagos hotspot, heralding a vigorous period of submarine oceanic plateau volcanism that began as early as 139 Ma and was widespread by 88 Ma [54, 55, 70]. These elements became amalgamated as the Chorotega block of southern Central America.

8.5.6 72 Ma (Late Cretaceous)

By the latest Cretaceous the Caribbean arc, now adjacent to the thick, young and buoyant Caribbean oceanic plateau, continued to migrate and collide to the northeast.

Convergence between the arc and the southern rifted margin of Honduras (eastern Chortis terrane) led to the obduction of Guerrero-Caribbean arc material (Siuna terrane of northern Nicaragua; Venable [36]) (Fig. 8.4e) and to the formation of the Colón deformed belt [34]. Arc-Chortis convergence was expressed as left-lateral strike-slip motion along the Guayape fault system that developed at this time along the rifted structural grain of the southern Jurassic margin of Chortis (eastern Chortis terrane). Shortening also occurred at this time between the Chortis and Maya blocks as recorded by the well-dated emplacement of ophiolites onto the Maya block [68, 69, 71]. Eastward-dipping subduction developed between the Farallón plate and the western margin of the Caribbean oceanic plateau (Fig. 8.4e). The Caribbean arc detached from the Caribbean oceanic plateau, which was pinned on its northern and southern edges by collision with Chortis and northwestern South America. Continued north and eastward motion of the Caribbean arc by trench rollback detached Cuba from the Caribbean oceanic plateau and formed the Yucatán back-arc basin south of Cuba and the Grenada back-arc basin west of the present-day Lesser Antilles arc [53].

8.5.7 49 Ma (Eocene)

The northeastward migration of the Caribbean arc ended when part of the arc collided with the Bahaman carbonate platform (Fig. 8.4f). Collision transferred the Cuban area from the Caribbean plate to the North American plate as the strike-slip boundary moved southward. The Motagua-Cayman trough-Oriente fault zone developed to accommodate this new zone of left-lateral, strike-slip displacement between the North American and Caribbean plates [39].

Along the southwest Mexican margin, eastward-dipping shallow subduction produced the Xolopa magmatic arc and the northern Chortis terrane [28]. The geometry of the Xolopa arc with respect to the Chortis-Farallón margin is highly oblique, similar to the present-day geometry of the Trans-Mexican volcanic belt with respect to the Cocos-North America margin (Fig. 8.4f). This geometry would suggest that the Chortis block occupied a forearc setting during oblique convergence of the Farallón plate relative to North America [28]. Southeast translation of Chortis block was facilitated by weakening of the detachment zone parallel to the zone of Xolopa arc magmatism; this hot, weakened zone of arc was broken under oblique, Farallón-North America convergence and the Chortis block was dislodged from Mexico and moved southeastwards [28]. Magnetic and stratigraphic similarities suggest that a small remnant of the Chortis block was not dislodged in this manner and remained behind in Mexico (Teloloapan subterrane of Dickinson and Lawton [38]) [34, 35].

8.5.8 22 Ma (Miocene)

Stress patterns arising from Farallón plate subduction to the northeast beneath North America and to the southeast beneath South America resulted in its breakup into the Cocos and Nazca plates at 23 Ma (Fig. 8.4g) [18, 72]. The reorganization led to near orthogonal subduction of the Cocos plate beneath the Chortis block [16], and the oblique subduction force previously driving the eastward motion of the Chortis block ended abruptly. A superfast spreading period of this segment of the East Pacific rise preceded the detachment of the Cocos slab beneath northern Central America. Rogers *et al.* [10] proposed that this slab detachment event produced large-scale topographic

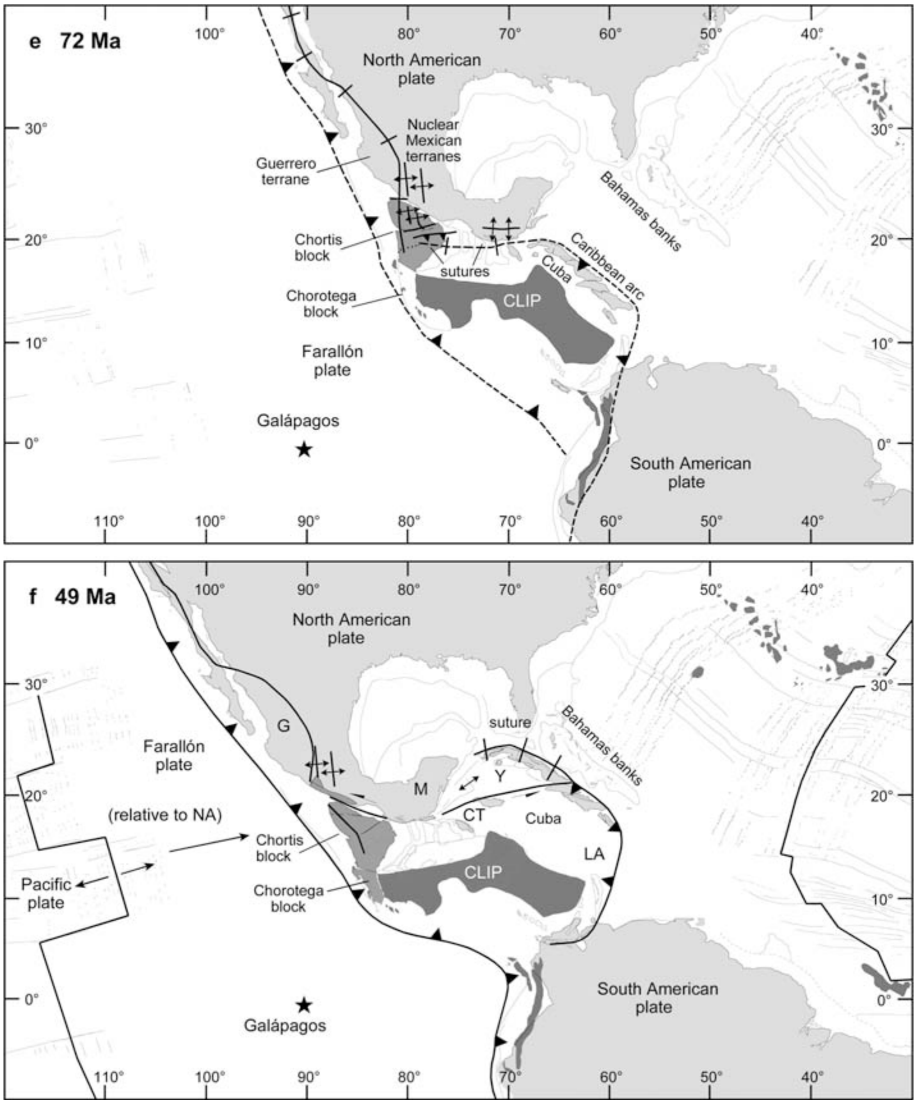


Figure 8.4 (continued).

uplift in northern Central America. The development of the Nicaragua intra-arc depression, a backarc basin, was produced by a late Neogene phase of trenchward migration of the Central America volcanic arc and slab rollback [4] that was perhaps initiated by steepening of the Cocos slab following the break off of its subducted, downdip extension about 4–10 Ma [73]. Ferrari [11] has proposed a similar process of slab breakoff for the arc in southern Mexico.

During this time, Central America became incorporated with the Caribbean plate and moved eastward relative to the North American plate. Several parallel, left-lateral strike-slip faults (Jocotan-Chamelecón, Polochic, Motagua) developed in Guatemala along the Late Cretaceous Motagua valley suture between the Chortis and Maya blocks. To the east, these faults connect to the Swan islands fault zone of the Cayman

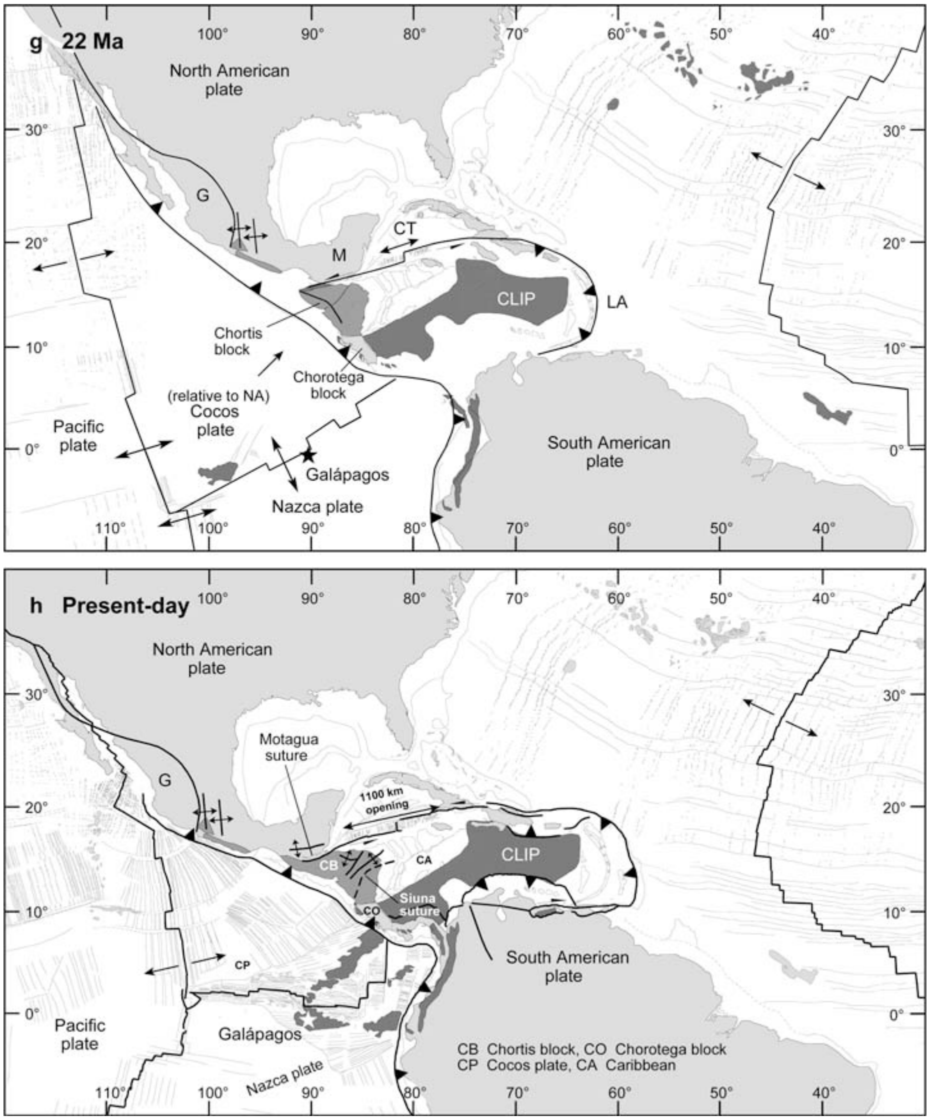


Figure 8.4 (continued).

trough. Internal deformation of the Chortis block and formation of transtensional rifts in the offshore Honduran borderlands resulted from divergence of the Caribbean plate motion vector from the azimuth of these plate boundary faults [34, 74].

8.5.9 0 Ma (Present-day)

Presently, Central America is bounded by the Middle America trench and subduction system to the southwest and the strike-slip faults of the Motagua-Swan islands to the north, and it is attached to the stable Caribbean plate to the east and southeast (Fig. 8.4h). GPS studies now in progress in both northern and southern Central America will improve constraints on block motions with this area.

8.6 DISCUSSION: UNRESOLVED TECTONIC PROBLEMS

8.6.1 Suggested future studies

A challenge for future workers is to relate magmatic and deformational events recorded in the CAVA and CAVF to changing plate boundary configurations of North America, Caribbean, Nazca, and Cocos as predicted by the plate reconstructions shown in Figure 8.4a–h. Part of the problem is that plate motion rates in this region have been fast (e.g., 5–18 cm/yr range; [12]), highly oblique (in the case of Nazca-Caribbean motion along the present-day margin of southern Panama and possibly along the Neogene margin of Costa Rica), and have involved the migration of triple junctions and the subduction of buoyant hotspot-related features like the Cocos ridge as presently observed off Costa Rica. Future studies should seek consistency between onland and oceanic interpretations by working with data sets from both realms.

8.6.2 Precambrian connections between North and South America

Fragments of Precambrian age continental crust occur in central Honduras and in Guatemala (Fig. 8.5a). Renne *et al.* [75] proposed that these elements once formed a continuous belt linking the more continuous Grenville belts of North and South America (Fig. 8.5b). Centeno-Garcia and Keppie [76] suggest the fragments represent parts of multiple belts that have been reorganized by plate motions since their formation (Fig. 8.5c). The Precambrian rocks of Central America represent a key, but largely unconstrained, element to the pre-Mesozoic configuration of the region. Since Precambrian rocks commonly have distinctive age provinces, composition and geochemical signatures, the reconstruction of these blocks could be accomplished by working systematically in the widely separated areas shown on Figure 8.5a.

8.6.3 Defining the edges of the Chortis block in the Middle America trench and Hess escarpment

On the basis of crustal velocities and geophysical profiling, Walther *et al.* [24] proposed that an eastern Pacific oceanic plateau may have accreted to the southern boundary of the eastern Chortis terrane and the Siuna terrane of the Chortis block in latest Cretaceous time to form the Sandino forearc basin (geophysical transect shown in Figs. 8.6a and b). The crustal suture between continental crust of the Chortis block and the oceanic plateau was proposed to lie along the eastern edge of the Nicaraguan depression (Fig. 8.6b). Rollback of the subducted Cocos slab in Late Cenozoic time is thought to have produced extension in the Nicaraguan depression [4].

Similarly, Bowland [77] suggested that the Hess escarpment is a Late Cretaceous to Early Paleogene strike-slip margin separating the Chortis block from the Caribbean oceanic plateau and onland Chorotega block to the south. Bowland [77] noted onlap of Late Cretaceous sediments over faults defining the Hess escarpment showing that motion along this part of the Hess escarpment had largely ceased by Paleogene time. Variations in gravity field suggest the presence of crustal blocks of varying thickness and composition (Fig. 8.6c).

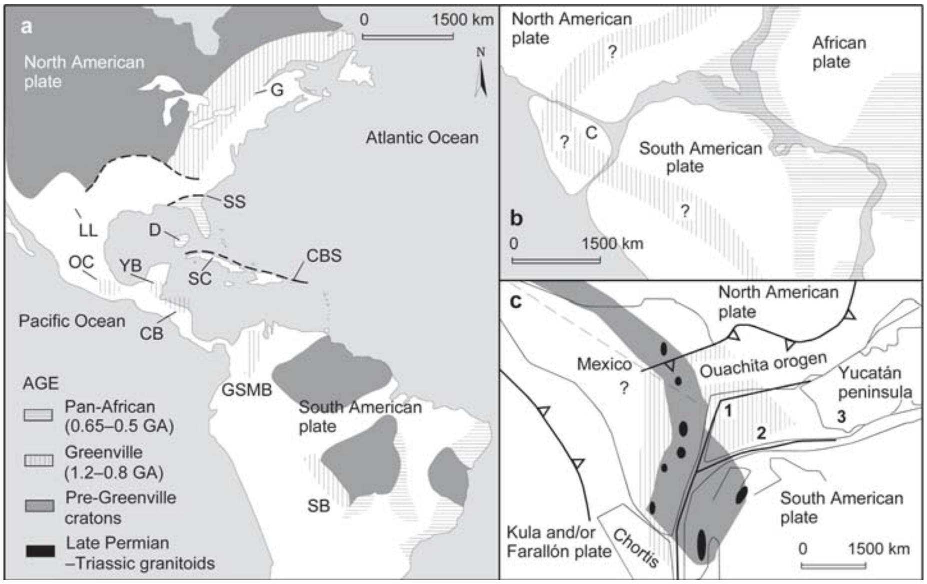


Figure 8.5. Precambrian and Paleozoic connections between North America, the Chortis block, and South America: (a) Present-day map showing the locations of Precambrian and Paleozoic rock belts modified from Renne [75]. CB: Chortis block; CBS: Caribbean-Bahama suture; D: DSDP holes 537 and 538A in southeast Gulf of Mexico; G: Grenville belt; GSMB: Garzon-Santa Maria belt; LL: Llano uplift of Texas; OC: Oaxaca complex; SB: Sunsas belt; SC: Socorro suture; SS: Suwanee suture; YB: Yucatán or Maya block; (b) Reconstruction of Pangea, ~250 Ma, showing possible connection of the Grenville fronts through North America, Chortis, and South America from Renne [75]; C: Chortis block; (c) Distribution of Precambrian elements in reconstruction of Pangea from Centeno-Garcia and Keppie [76]; 1: Mixitequita complex, 2: Chiapas basement, 3: Maya mountains.

8.6.4 Slowing of spreading in Cayman trough and relation to events in Central America

Cayman trough history includes the initiation of oceanic spreading at 49 Ma and a slowdown in spreading rate from 26 to 20 Ma [57] (Fig. 8.3). The Cayman trough is a valuable, long-term recorder of motion between the northern end of the CAVA on the Caribbean plate (Chortis block) and the North American plate (Fig. 8.3). Through closure conditions, these motions can be used to better constrain motions of the Farallón plate and, after 22 Ma, the Cocos and Nazca plates beneath the CAVA. The Cayman trough aeromagnetic data suggest that the motion was not steady but began quickly from about 49 Ma to 26 Ma, slowed down considerably between 26 and 20 Ma, and then maintained a slow but steady spreading rate between 20 and 0 Ma [56].

8.6.5 Farallón plate breakup and relation to events in Central America

This critical event subdivided the Farallón plate into the Cocos and Nazca during the Early Miocene around 22 Ma (Fig. 8.2). Key questions include: What was the position of the breakup relative to the Galápagos hotspot? Was the hotspot active at this time, and, if so, did it influence the breakup? What was the strike of the new spreading center? Was it an immediate opening over the entire distance from the EPR to the

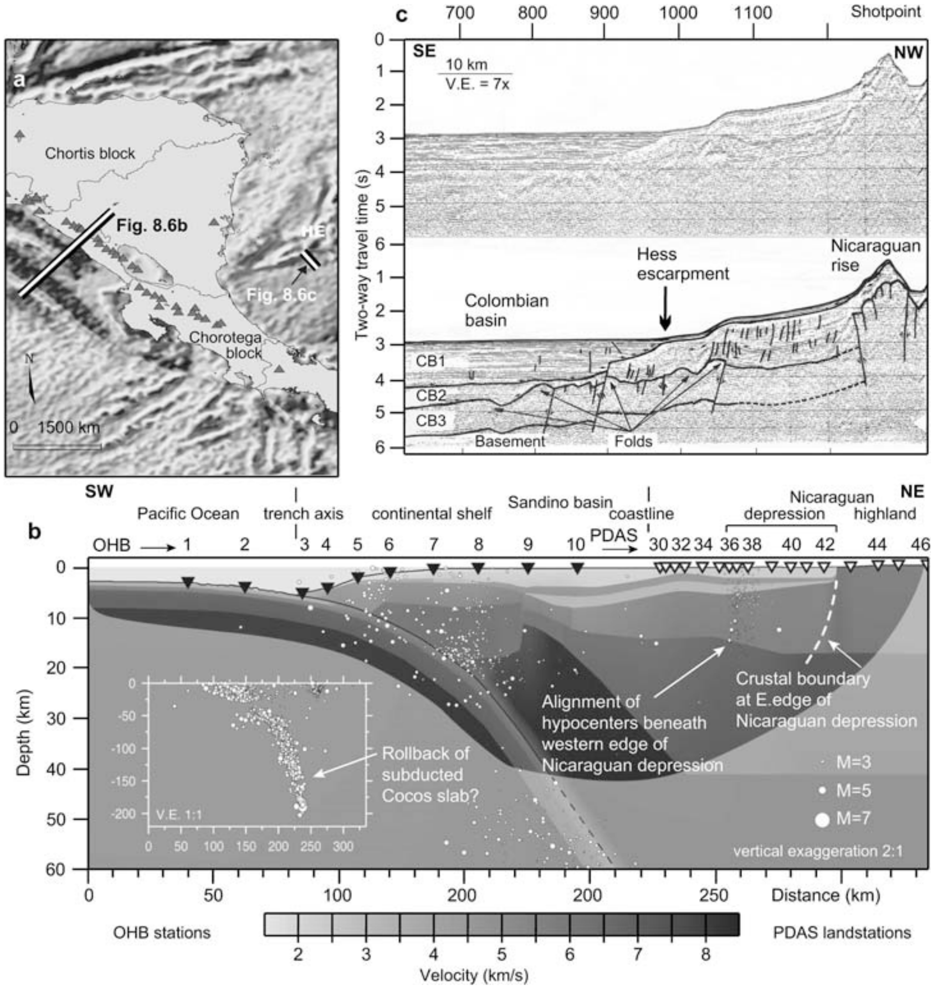


Figure 8.6. (a) Free-air gravity map (from Sandwell and Smith [101]) of the oceanic crust adjacent to Central America. the locations of the seismic profile in Figure 8.6b and the velocity transect model in Figure 8.7 are shown as thick lines; (b) Velocity transect across the forearc of Nicaragua from Walther *et al*. [24]. Mantle velocities at shallow levels of the upper plate interpreted as accreted plateau material along edge of Central America. This collision presumably occurred along the southern boundary of the Chortis block and formed the substrate for the forearc basin of the Middle America trench. Location shown in Figure 8.6a. Inset shows steeply dipping Cocos slab as defined by earthquake epicenters; (c) Seismic reflection profile and interpretation of the Hess escarpment [77]. CB3: Late Cretaceous pre-deformation sequence; CB2: Paleogene syndeformation sequence containing folding and internal onlap horizons; CB1: Neogene post-deformational sequence. Onlap relationships indicate that the Hess escarpment was active during the Late Cretaceous and became inactive in the Cenozoic.

subduction zone, or was it a propagating rift? Can it be seen somewhere in the geology of the CAVA or the CAVF the effects of the subduction of an active spreading center, beginning 22.7 Ma? Barckhausen *et al.* [18] and Barckhausen (*pers. comm.*, 2000) traced magnetic anomalies along the Grijalva scarp off the coast of northwestern South America (Figs. 8.2 and 8.7) and did not find evidence of ridge propagation in this area, which is presumably the conjugate margin to the 22 Ma rifted area. The widely used rotation poles of Mayes *et al.* [48] are based on only a small part of the data shown on Figure 8.2 and can be improved by using the more recent magnetic anomaly data that are now available.

8.6.6 Evolution of the Panama fracture zone

Recent work by Barckhausen *et al.* ([18] and *pers. comm.*, 2000) on north–south magnetic profiles between the Malpelo and Carnegie ridges (profiles from 1999 German cruise SO-144) shows that both ridges (Fig. 8.7) were once contiguous as originally interpreted by Lonsdale and Klitgord [44] (Fig. 8.8a). Separation of these aseismic ridges began at 14.7 Ma and ended around 10 Ma. The cessation of spreading on the ridge segment between these hotspot tracks marks a critical reorganization in the plates, which was detected by Wilson [12] and coincides with a jump in the Cocos-Nazca transform boundary 100's of km to the west to the Coiba fracture zone (and later, the nearby Panama fracture zone). This jump in the Panama fracture zone occurred when part of the Cocos plate was transferred to the Nazca plate [44] (Fig. 8.8a). An alternative interpretation of McIntosh *et al.* [15] reconstructs the position of the Cocos-Caribbean-Nazca triple junction and finds that the boundary was originally located much farther to the west (Fig. 8.8b). In their interpretation, the direction of triple junction migration was to the southeast, and did not jump northwest as proposed by Lonsdale and Klitgord [44].

The direction of triple junction migration is a key factor for understanding the southern CAVA, which most workers have not considered as a major impact on forcing functions for this segment of the CAVA. Figures 8.1 and 8.8b show calculated positions of the triple junction from 8 Ma to the present according to the reconstructions of McIntosh *et al.* [15], who used the NUVEL-1 [13] instantaneous poles. If the triple junction did occupy these positions along the Costa Rica margin, then the direction of Nazca-Carib plate convergence east of the triple junction would have been at a much lower angle than the area west of the triple junction and would have resulted in a much different forearc structure, slab convergence angle, slab convergence rate, and volcanic arc history.

8.6.7 Early ridge jumps between Cocos and Nazca plates and the original shape of the now subducted Cocos ridge

Two major ridge jumps that occurred at 19.5 Ma and 14.7 Ma are discussed in detail by Barckhausen *et al.* [18]. These jumps are reflected in the changing directions of the magnetic anomalies off central Costa Rica from N50°E to N70°E, and finally to the nearly E–W orientation of spreading fabric that is observed today in the subducting seafloor along the Middle America trench [1] (Fig. 8.2). Meschede and Frisch [17] have tried to define the position of the spreading axis relative to the Galápagos hotspot from observations on Cocos and Carnegie ridges (Fig. 8.2). Their paper is a solid start but the interpretation could benefit from the input of additional magnetic data now available.

The original shape of the Cocos ridge, which may be inferred through reconstruction, is key for assessing its effect on the Central American margin because part of the ridge is now subducted beneath Costa Rica [44, 78] (Fig. 8.9). A longer

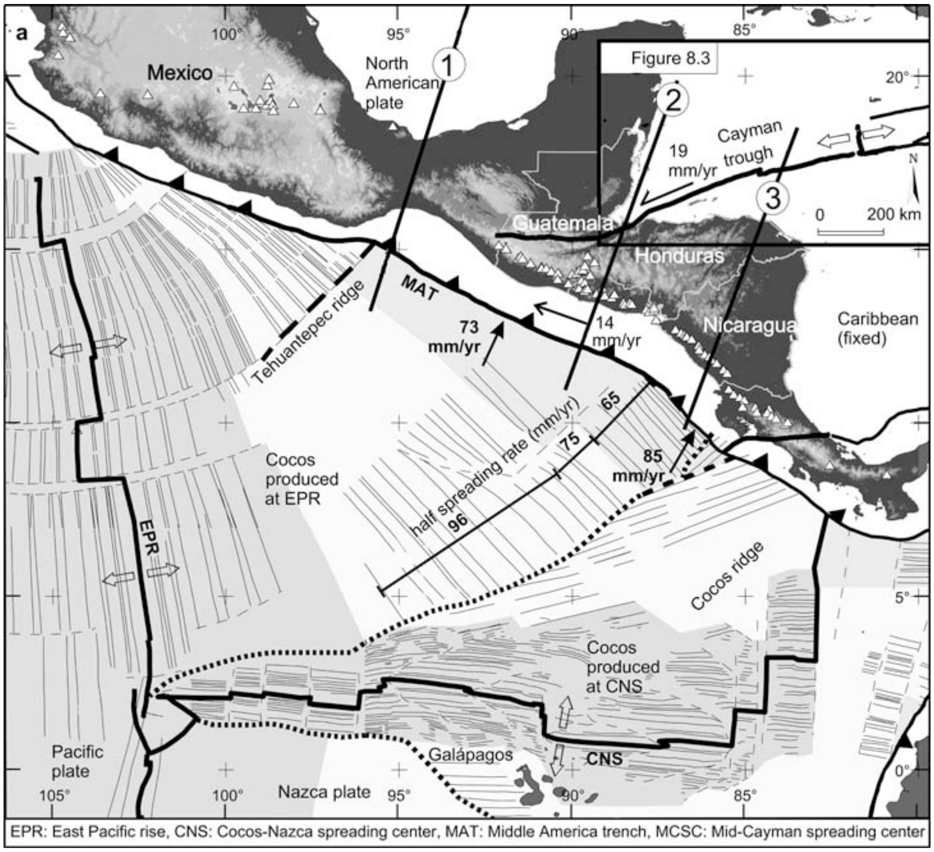


Figure 8.7. (a) Present setting of Central America showing plates, Cocos crust produced at East Pacific rise (EPR) and Cocos-Nazca spreading center (CNS), triple-junction trace (heavy dots), volcanoes (open triangles), Middle America trench (MAT), western edge of detached slab (dashed line), and rates of relative plate motion [91, 95]. East Pacific rise half spreading rates from Wilson [12] and Barckhausen *et al.* [18]. Ocean-crust age: 10 Ma, 20 Ma, older than 20 Ma. Lines 1, 2, and 3 are locations of topographic and tomographic profiles in (c); (b)Tomographic slices of the P-wave velocity of the mantle at depths of 100, 300 and 500 km beneath Central America; (c) Upper-Topography and bathymetry. Lower-Tomographic profiles showing Cocos slab detached below northern Central America, upper Cocos slab continuous with subducted plate at Middle America trench, and slab gap between 200 and 500 km. Grey tones and ± symbols indicate anomalies in seismic wave speed as a ±0.8% deviation from average mantle velocities. The minus symbol indicate colder, subducted slab material of Cocos plate; Circles are earthquake hypocenters. Grid sizes on profiles correspond to quantity of ray-path data within that cell of model; smaller boxes indicate regions of increased data density; CT: Cayman trough; SL: sea level (modified from Rogers *et al.* [10]).

reconstructed ridge would imply an older, more protracted collision history in Costa Rica while a shorter ridge would imply a more recent collisional event.

8.6.8 Slab breakoff of the Cocos plate beneath Central America

P-wave tomographic images of the mantle beneath northern Central America reveal a detached slab of the subducted Cocos plate (Figs. 8.7b and c) [10]. Landscape features

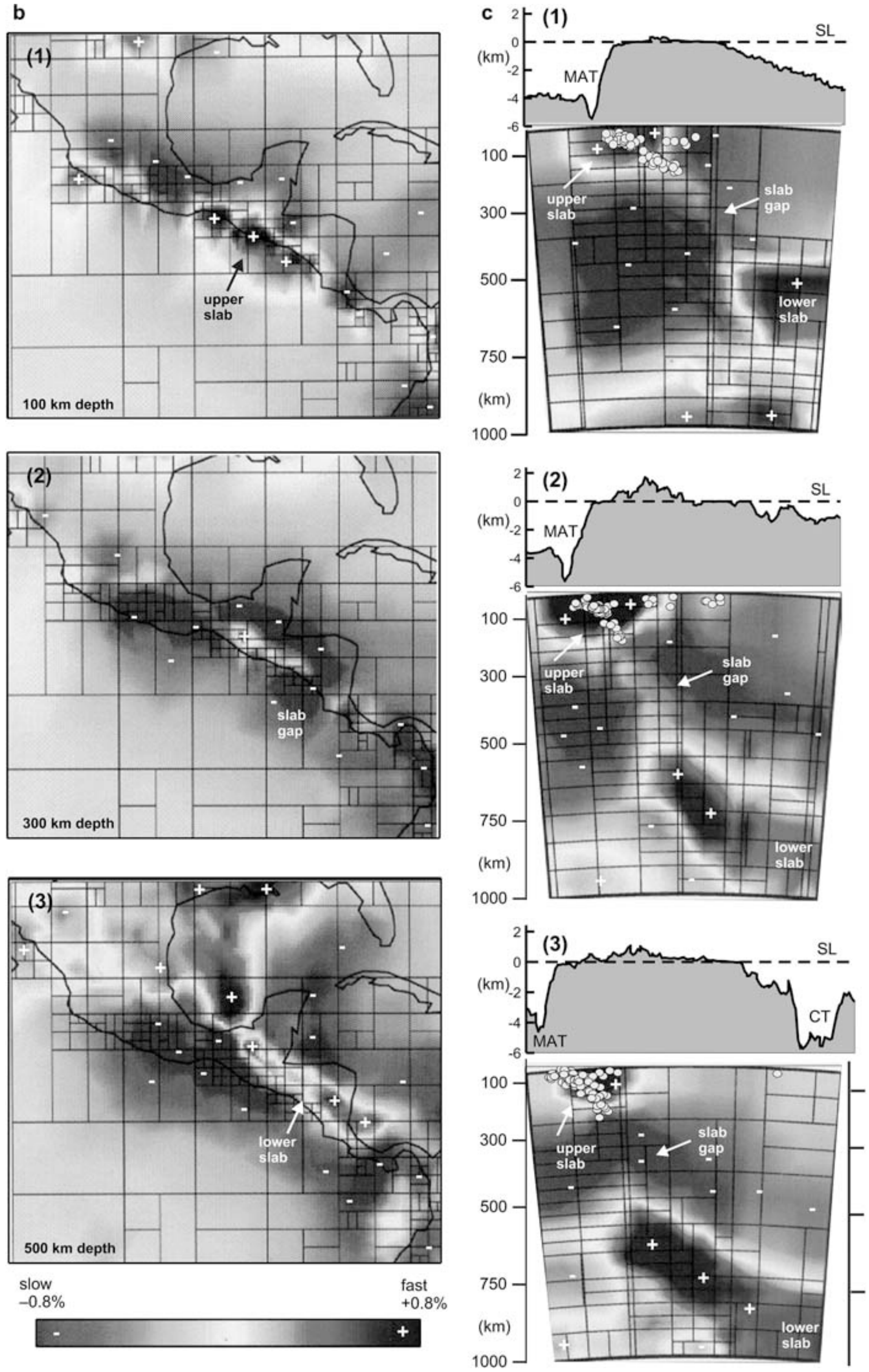


Figure 8.7 (continued).

of the region of Honduras and Nicaragua above the detached slab are consistent with epeirogenic uplift produced by mantle upwelling following slab breakoff between 10 and 4 Ma.

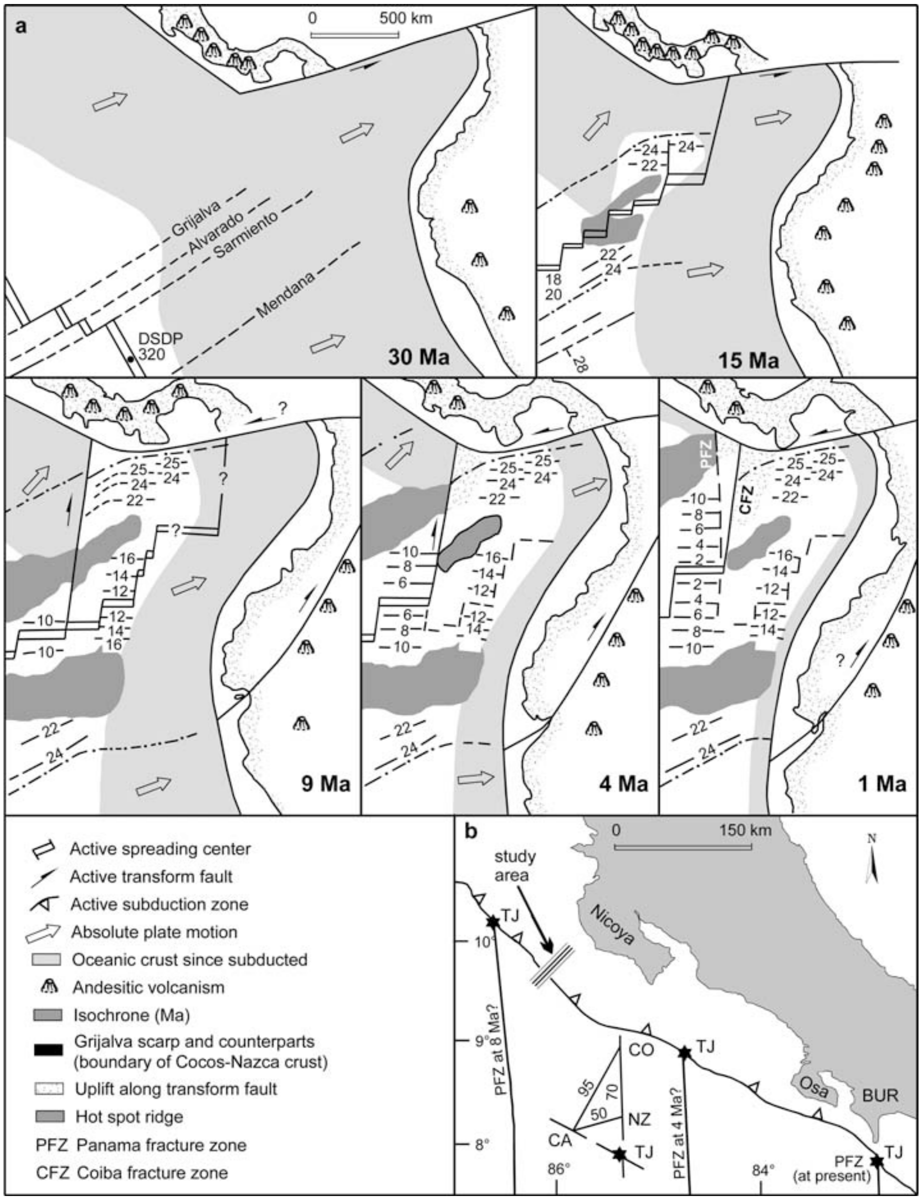


Figure 8.8. (a) Reconstructions of Costa Rica and Panama by Lonsdale and Klitgord [44] based on their interpretation of magnetic anomalies and fracture zones available at that time. The main events shown include the breakup of the Farallón plate into the Nazca (east) and Cocos (west) plates; the abandonment of an early ridge system south of Panama; and the breakup of the Cocos, Malpelo and Carnegie ridges which formed as continguous spreading ridge about 15 Ma; (b) Reconstruction of McIntosh *et al.* [15] showing the eastward migration of the Cocos-Nazca-Caribbean triple junction along the Nicaraguan and Costa Rican margin (inset shows plate motions at triple junction); see text for discussion.

Following slab detachment, hot asthenospheric mantle flows inward to fill space vacated by the cold, more dense slab as it sinks into the mantle (cf., [79]). Thermomechanical modeling of the slab-detachment process demonstrates large

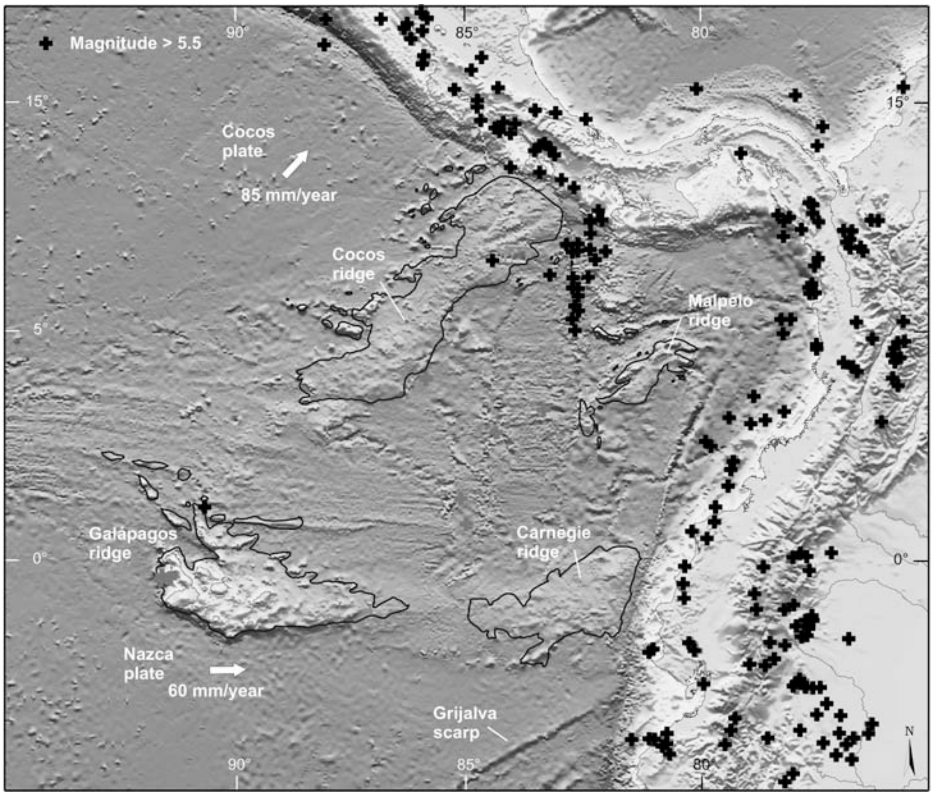


Figure 8.9. Convergence and subduction of Cocos ridge on southern Central America. Motion vectors of Cocos and Nazca plates are from Nuvel-1A model of Demets [100]. Location of earthquake epicenters (ISC catalog; magnitude greater than or equal to 5.5) overlaying the topography and predicted bathymetry data from Smith and Sandwell [102]. White arrows are the present-day plate motion vectors relative to a fixed Caribbean plate.

(>500 °C) transitory heating of the base of the upper plate for several million years [81]. Asthenospheric upwelling can produce decompression-induced volcanism, and the geochemistry of the basaltic lavas from behind the volcanic front in Honduras and Guatemala is consistent with mantle upwelling [81]. Slab detachment and uplift of the Central American plateau occurred between the end of the subduction-related ignimbrite flare-up at 10 Ma and prior to 3.8 Ma, the time at which the tip of the Cocos slab was subducted (i.e., beginning of the “modern subduction” period in Central America) (Figs. 8.7b and c).

In collisional settings, slab detachment occurs as the force of slab-pull near the trench is resisted by buoyant lithosphere producing a tear in the downgoing slab [79]. Rogers *et al.* [10] suggest that this mechanism occurred along the non-collisional Middle America trench margin as a result of the decreasing age and increasing buoyancy of the incoming Cocos oceanic plate during the 19–10 Ma interval of super fast spreading [12] along the southernmost Cocos-Pacific segment of the East Pacific rise (Fig. 8.7a). Although steady-state subduction at the Middle America trench since 2.5 Ma has been inferred from the presence of cosmogenic isotopes in the modern arc lavas of Central America [2], tomographic observations showing slab breakoff require highly variable rates of subduction and rates of slab melting during the Neogene.

8.6.9 Timing of impact of the Cocos ridge on the southern Central American arc

The Cocos ridge (500 km long by 100 to 200 km wide; Fig. 8.9) is a hotspot trace of the Galápagos hotspot that stands 2 to 2.5 km higher than the surrounding seafloor and is presently being subducted beneath the southern CAVA in Costa Rica. Estimates of the timing of the arrival of the Cocos ridge at the trench vary from a minimum of 0.5 Ma [83] to intermediate ages of 3.6 [29] to 5.5 Ma [45] to maximum estimates of Middle Miocene [84].

Most workers assume that the point of contact has remained stationary from the time of its arrival to the present-day when in fact the angularity between the plate convergence direction (~N27°E) and trend of the ridge (~N44°E) suggests that the collision should propagate northwestward along the trench.

A localized fold-thrust belt in the Fila Costeña and Talamanca cordillera of Costa Rica summarized on Figure 8.10 correlates well with the area of the bathymetrically highest and thickest part of the Cocos ridge [7]. Outcrop patterns suggest that a pre-existing Eocene–Late Miocene forearc basin was inverted locally by the Cocos ridge subduction. This event is also recorded by rapid uplift and exhumation of arc rocks along with thrusting in the backarc (Caribbean area) of Costa Rica [29].

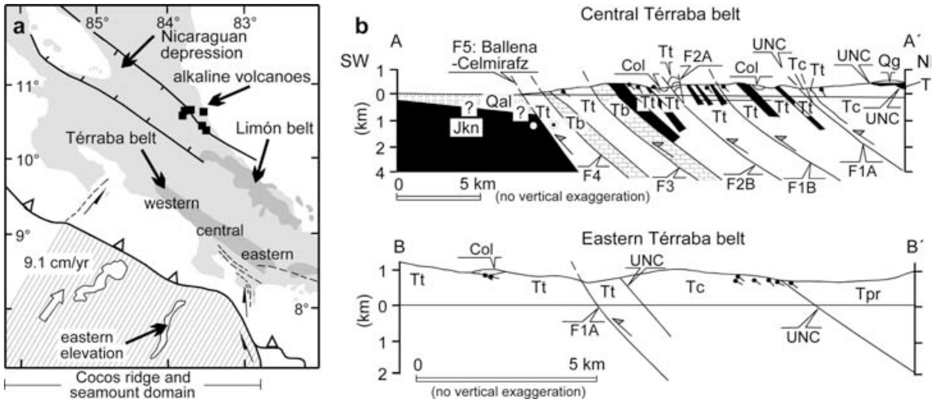


Figure 8.10. (a) Basin inversion of the Térraba forearc basin (shaded) spatially associated with highest and thickest part of the subducting Cocos ridge (crosshatched). Térraba belt is now a fold-thrust belt and the Limón belt is the inverted backarc basin. The backarc basin is not inverted in northern Costa Rica and merges with the actively subsiding intra-arc Nicaraguan depression to the northwest. Cross sections across the central Térraba belt (b) and the eastern Térraba belt (c). Numbers identify regionally inverted faults [7]. Jkn: Nicoya complex; Tb: Brito Fm.; Tt: Térraba Fm.; Tc: Curré Fm.; Tpr: Paso Real Fm.; Qg: El General Fm., F: faults.

The history of the interaction of the Cocos ridge with the Central American trench can now be reconstructed using marine magnetic anomalies and fracture zones from the surrounding ocean basins. For the recent past (~9 Ma to present), a plate circuit can be closed using the seafloor spreading in the Gulf of California [51]. One key question future work could address is when the Cocos ridge impacted the margin. A second question is to determine what part of the margin it has affected: has the impact area remained stationary or has the zone of impact swept along the margin?

Several papers have shown the Cocos ridge collision event is the dominant event affecting the CAVA in Costa Rica starting about 1 to 6 Ma [7, 9, 29, 45, 85]. This event has produced a rapid along-strike variation in crustal exposures, which was one of the original attractions of this area as a Subduction Factory focus area. Estimates of initial ridge subduction, which are key to many geochemical studies of the SUBFAC, vary from 0.5–1.0 Ma [83, 44] to 3.6 Ma [29] to 3.5–5.5 Ma [45]. Variation is related to the different methods used, which include plate reconstructions, paleobathymetry, age of volcanism, and fission-track dating. A goal of future work is to work interactively to better constrain the initial arrival of the ridge and its modification of the subduction zone, which has evolved to the present-day situation of a volcanic arc gap shown in Figure 8.1.

8.6.10 Impact of migration of the Caribbean-Cocos-Nazca triple junction on land geology

This process may prove to be as or more important than the Cocos ridge collision for shaping the forearc and volcanic arc. The velocity vector triangle describing the relative motion of these plates predicts a migration of the fault/trench/trench triple junction from northwest to southeast along the trench through time [15] (Fig. 8.8b). Motion of the Nazca plate east of the triple junction would be highly oblique (cf., Fig. 8.8a) as it is observed today along the southwestern Panama margin [7, 9]. Motion northwest of the junction is currently nearly orthogonal to the margin. The assumption of most workers is that the present-day orthogonal motion is representative of past Neogene motions when in fact a highly oblique Nazca-Caribbean scenario is predicted for the recent past by tectonic reconstructions [14, 15, 44] (Fig. 8.8a).

A tectonic implication is that the forcing functions are quite different for the Nazca-Caribbean case where motion is slower, much more oblique, and involves younger more buoyant crust. Future work could aim to better quantify the triple junction position through time using recent magnetic constraints provided by Barckhausen and the BGR group and using the results of Wilson [12] and Wilson and Hey [16]. Once the migration of the triple junction is better quantified, its tectonic and volcanic manifestations will become better understood.

8.6.11 Slab windows beneath the southern Central American arc

Johnston and Thorkelson [22] proposed that a ridge subducted beneath the Costa Rica-Panama segment of the CAVA has produced a slab window, and that this process can explain the many geochemical anomalies of the arc volcanoes in this area (Fig. 8.11a). This interpretation differs from previous interpretations including that of Lonsdale and Klitgord [44] (Fig. 8.8a) and Hardy [86], which show no evidence in the magnetic anomaly record for the limb of a subducted ridge south of Panama as proposed by Johnston and Thorkelson [22]. However, the western Panama region of the Nazca plate is complex and characterized by short spreading segments separated by long fracture zones, which could potentially have led to the formation of a slab window. For this problem, future work could resolve the spreading history in this area of the Nazca plate in order to evaluate the slab window proposal and its effects on the CAVA. Abratis and Wörner [46] proposed an alternative model for a slab window opening beneath Costa Rica that is related to slab breakoff during the Cocos ridge subduction (Fig. 8.11b).

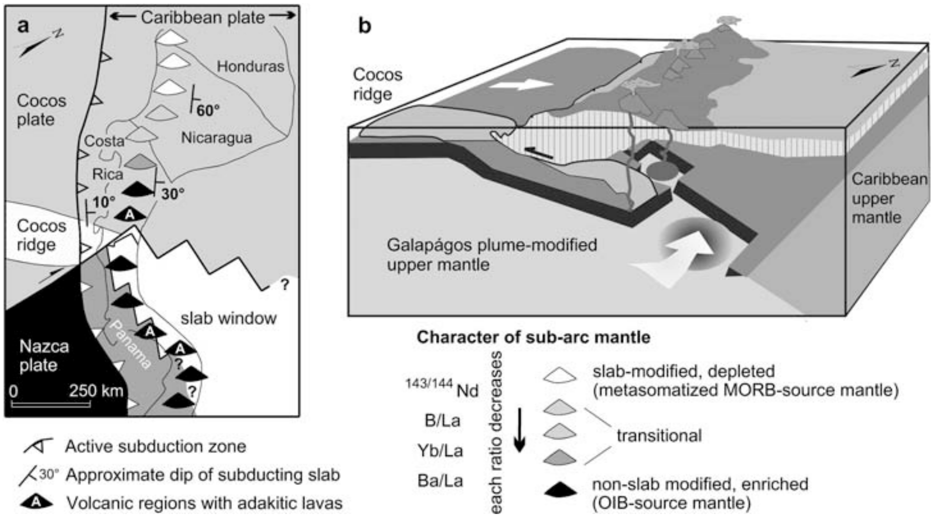


Figure 8.11. (a) Interpretation of a slab window and its effects on volcanic products in the subduction factory area of southern Central America based on the reconstructions of Johnston and Thorkelson [22]; (b) Alternative interpretation of slab window development from Abratis and Wörner [46] where slab breakoff and window are related to the subducting Cocos ridge.

8.6.12 Models for the internal deformation of the Chortis block and western Caribbean plate

Onshore extensional deformation of the western Caribbean plate has been explained as resulting from: (1) Counter-clockwise rotation of the Chortis block around the arcuate Motagua-Polochic plate boundary faults [87, 88] (Fig. 8.12a) and (2) as fault termination features along the North America-Caribbean margin (Fig. 8.12b) [89]. Offshore extensional deformation is generally attributed to a diffuse plate margin south of the Swan islands fault zone [90]. Demets *et al.* [91] relate the deformation along the northern margin of the Caribbean plate to the angle between the GPS-derived motion vector of the Caribbean plate and the azimuth of the plate boundary zone. Rogers [34] refines the observations of Demets *et al.* [91] for the western Caribbean plate and relate the pattern of active borderlands, oblique-slip faulting (Fig. 8.12c) to the angular divergence of Caribbean motion and the local azimuth of the plate margin faults. This

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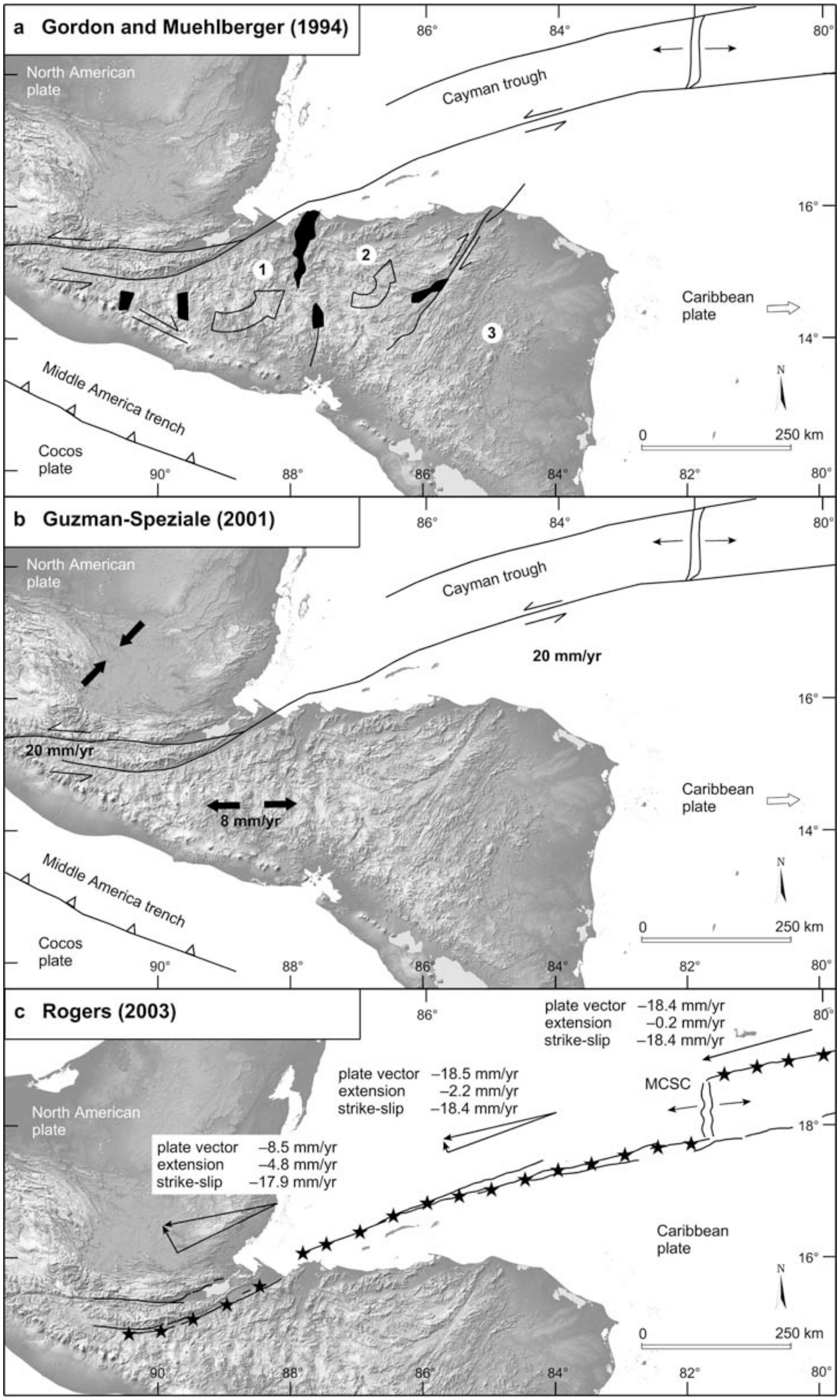
Figure 8.12 (right). Internal deformation of the Chortis block, produced by: (a) Counterclockwise rotation of Chortis block [88]; and (b) Fault termination [89]; (c) Compilation of active faults along the north coast of Honduras by Rogers [35]; GPS-derived Caribbean plate velocity [91] was calculated at 30 minute increments (X's on map) along the main North America-Caribbean plate boundary faults (Motagua-Swan islands-Mid-Cayman spreading center-Oriente system). The three plate vectors shown are for points along the fault system at longitudes 89ºW, 85ºW, and 81ºW and are decomposed to show the extensional and strike-slip component of the plate vector. The extensional component of motion is controlled by the angular divergence between the plate vector and the trend of the plate boundary fault. Note that the extensional component of the plate vector increases from 0.2 mm/yr at longitude 81ºW near the Mid-Cayman spreading center to 4.8 mm/yr at longitude 89ºW in the Motagua valley of Guatemala and is consistent with the widening of plate margin deformation from east to west. Vertical arrows show location of Caribbean-North America velocity predictions of Demets *et al.* [91]. The area marked "inactive rifts" is an area of north-trending rifts that are less prominent than the ones to the west and appear to be inactive in Late Pleistoene time.


a Gordon and Muehlberger (1994)
North American plate
Cayman trough
1
2
3
Caribbean plate
Middle America trench
Cocos plate
0
250 km
N
86°
84°
80°
16°
14°
90°
88°
82°
b Guzman-Speziale (2001)
North American plate
Cayman trough
20 mm/yr
20 mm/yr
8 mm/yr
Caribbean plate
Middle America trench
Cocos plate
0
250 km
N
c Rogers (2003)
plate vector –18.4 mm/yr
extension –0.2 mm/yr
strike-slip –18.4 mm/yr
MCSC
plate vector –18.5 mm/yr
extension –2.2 mm/yr
strike-slip –18.4 mm/yr
North American plate
plate vector –8.5 mm/yr
extension –4.8 mm/yr
strike-slip –17.9 mm/yr
Caribbean plate
18°
16°
0
250 km
N

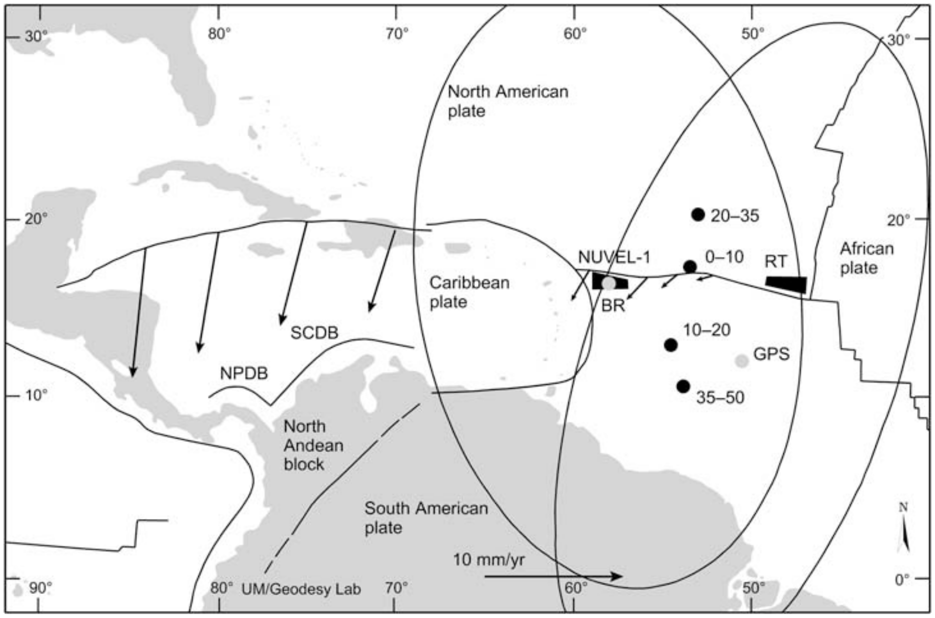
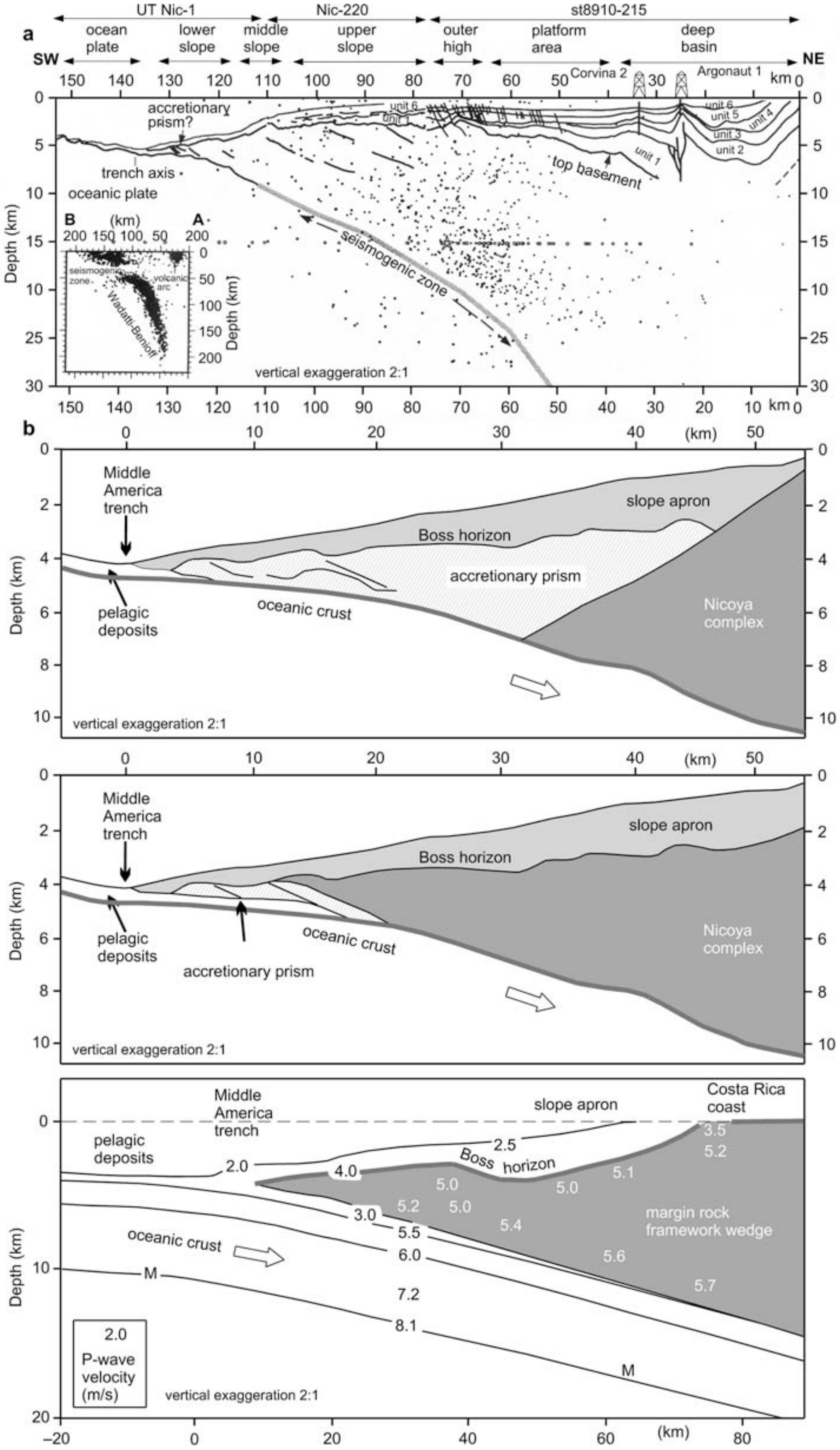


Figure 8.13. GPS-derived vector of North America (NA) relative to South America (SA) across the Caribbean (CA) plate. Note the convergence increase to the west, reaching a maximum in Central America. NAB: North Andean block; NPDB: Northern Panama deformed belt; SCDB: Southern Caribbean deformed belt. (From Dixon and Mao [47]).

view of the western Caribbean deformation is also compatible with the fault termination model of Guzman-Speziale [89] (Fig. 8.12b).

On a larger scale, North America and South America are converging in a north–south direction across the Caribbean plate (based on both plate tectonic reconstructions [42] and GPS results [47]; Fig. 8.13). This convergence is greatest in the western Caribbean and in Central America and decreases in an eastward direction. Western Caribbean features that may be attributed to this gradient of north–south shortening includes Neogene bending of the Panama arc, Miocene age of right-lateral slip on the Hess escarpment [77] and late Neogene right-lateral slip on the Guayape fault of Honduras [88]. GPS data will assist in distinguishing this broad regional shortening from more localized effects of fault rotation and termination.

Figure 8.14 (right). (a) Schematic diagram across the Sandino forearc basin on the Pacific margin of Nicaragua derived from multiple seismic surveys (from Ranero and von Huene [92]). Units 1–6 represents Cretaceous to Holocene depositional sequences deposited on a basement of at least Cretaceous age. Dots represent earthquake hypocenters. Inset shows true scale section of subducting Cocos slab; (b) Comparison of accretionary (top), non-accretionary (middle) and velocity models for the submerged margin of Costa Rica from Vannucchi *et al.* [103]. The accretionary model for the margin ascribes margin evolution to massive underplating of oceanic sediment since the Paleogene. The contrasting, non-accretionary model contends that the margin is mostly underlain by Cretaceous crystalline rocks that extend seaward from coastal outcrops to near the trench axis. The velocity structure of the margin supports the non-accretionary origin.


a
UT Nic-1
Nic-220
st8910-215
ocean plate
lower slope
middle slope
upper slope
outer high
platform area
deep basin
SW
NE
Corvina 2
Argonaut 1
km
accretionary prism?
unit 6
unit 5
unit 4
unit 3
unit 2
unit 1
trench axis
oceanic plate
top basement
seismogenic zone
B
(km)
A
seismogenic zone
volcanic arc
Wadatti-Benioff
Depth (km)
vertical exaggeration 2:1
b
Middle America trench
slope apron
Boss horizon
accretionary prism
pelagic deposits
oceanic crust
Nicoya complex
(km)
Depth (km)
vertical exaggeration 2:1
Middle America trench
slope apron
Boss horizon
pelagic deposits
accretionary prism
oceanic crust
Nicoya complex
vertical exaggeration 2:1
Middle America trench
slope apron
Costa Rica coast
pelagic deposits
2.0
2.5
4.0
Boss horizon
3.5
5.2
5.1
5.0
5.0
5.2
5.0
5.4
3.0
5.5
6.0
margin rock framework wedge
5.6
5.7
oceanic crust
7.2
8.1
M
M
2.0
P-wave velocity (m/s)
vertical exaggeration 2:1
Depth (km)
(km)

8.6.13 Tectonic erosion vs. tectonic accretion models for the Middle America trench

Several recent interpretations of subduction processes along the southern Middle America trench suggest that subduction erosion may be an important regional tectonic process [1]. Regional cross sections such as those shown in Figures 8.14a and 8.14b have been interpreted as both evidence for tectonic erosion and for slow accretion. Proponents of tectonic erosion cite evidence for widespread bathymetric subsidence as evidence for removal of the oceanic plateau forearc basement by incoming bathymetric highs (e.g., [52]). Proponents of slow subduction accretion cite seismic data show small imbricate structures at the base of slope [15]. Concepts of subduction erosion propose a relatively static plate configuration through the Neogene (e.g., [17, 92]. However, if the Panama fracture zone or Coiba fracture zone were present off the Nicoya peninsula of Costa Rica as the active Cocos-Nazca plate boundary, then most of Costa Rica should have experienced highly oblique plate convergence during subduction of the Nazca plate.

This tectonic environment can cause disruption of the forearc by strike-slip slivers driven by oblique subduction. It is suspected that some structural anomalies of this margin, including proposed subduction erosion effects by Meschede *et al.* [17], may have formed in this oblique subduction environment. The oblique-subduction process is currently active where the Panama fracture zone and Coiba ridge, moving with the Nazca plate, intersect the margin in western Panama and SE Costa Rica. These ridges apparently erode the upper plate as they sweep southeasterly along the margin [93, 94]. The long-term influence of subduction erosion along the Middle America trench is difficult to reconcile with the presence of the Cretaceous to recent Sandino forearc basin off the Pacific margin of Nicaragua (Fig. 8.14a). The basin is locally up to 10 km in thickness [92]. Why, if long-term subduction erosion occurred at today's rates, could such an extremely thick and long-lived forearc basin develop? Aggressive and long-lived tectonic erosion would have undermined the forearc and not allowed such longterm subsidence.

8.6.14 Defining the Central American forearc sliver and the origin of the Nicaraguan depression

The Nicaraguan depression is a prominent Quaternary morphologic and structural depression aligned roughly with the belt of active Central American volcanoes and extending approximately 600 km from the northern Gulf of Fonseca in El Salvador and northern Nicaragua to the Caribbean Sea in Costa Rica (Fig. 8.15a). The Nicaraguan depression is an atypical backarc basin in that the depression commonly encompasses the entire active volcanic chain rather than occurring only in a back-arc position. Two hypotheses have been proposed to explain the tectonic origin of this regional structure within the framework of the Central American volcanic arc (CAVA). The first mechanism, supported by geochemical analyses and radiometric dating of volcanic rocks adjacent to the depression, supports the traditional two-dimensional view of arc-normal extension accompanying trenchward or southwestward migration of the arc from 24 Ma (Middle Miocene) to the present [4]. Trenchward shifts in the position of the volcanic arc through time are related to a steepening or "rollback" in the dip of the subducted slab of the Cocos plate from about 50° at about 12 Ma to a current dip >65°. Increased slab dip was directly expressed by an increase in crustal extension of the volcanic arc with up to 20 percent pure shear over the last 12 Ma.

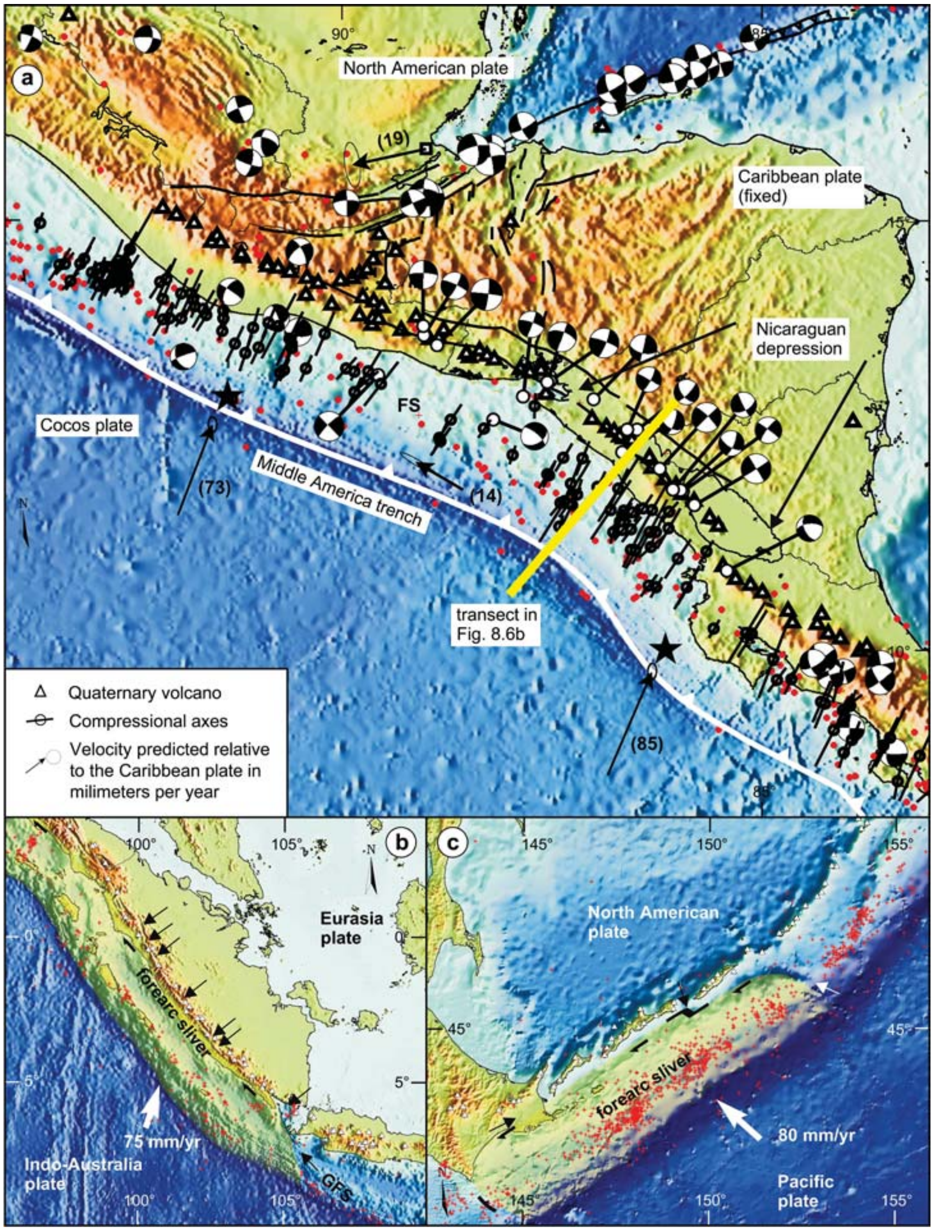


Figure 8.15. (a) The Central American forearc sliver (FS) is produced by the slight (~10 degrees) oblique convergence of the Cocos plate at the Middle America trench resulting in the northeastward migration of the forearc sliver [95]. Earthquake focal mechanisms, beachballs, show right-lateral strike-slip motion along the Central America arc. Motion vectors, shown in mm/yr. For tectonic comparison, forearc sliver produced by oblique convergence of Indo-Australia plate and the Eurasia plate in Sumatra (b) and by convergence of Pacific plate and the North America plate in the Kurile islands and northern Japan (c).

The second hypothesis states that the Nicaraguan depression has formed as a consequence of pull-apart extension at right-stepping stepovers along a major right-lateral fault system aligned with the active volcanic chain and parallel to the trend of the topographic and structural depression (Fig. 8.15a). The driving force for this deformation is slightly oblique subduction of the Cocos plate, which drives a forearc sliver along the right-lateral fault, formed along the thin, hot crust along the active volcanic axis [95]. This forearc sliver interpretation, which explains plate motions and strain partitioning in the obliquely subducting Sumatran and Kuril arcs, is consistent with the belt of damaging earthquakes along the volcanic arc of the CAVA, which mostly exhibit right-lateral focal mechanisms (Figs. 8.15b and c). One controversy is whether the fault accommodating the strike-slip displacement of the forearc sliver is a single zone or is composed of "bookshelf faults" that accommodate strike-slip by motion on a series of oblique faults [6].

8.7 FUTURE WORK

It is our hope that this review helps to stimulate increased work in Central America, particularly with regard to how the plate setting has evolved through time and how this plate evolution has changed the forcing functions along the CAVA and CAVF.

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