Overview of the tectonic history of northern Central America

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1 author:

Paul Mann
University of Houston

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Overview of the tectonic history of northern Central America

Paul Mann*
Institute for Geophysics, Jackson School of Geosciences, University of Texas at Austin, J.J. Pickle Research Campus, Bldg. 196 (ROC), 10100 Burnet Road (R2200), Austin, Texas 78758-4445, USA

TECTONIC PROCESSES IN NORTHERN CENTRAL AMERICA

The geology of northern Central America provides a complex record of how tectonic and volcanic processes operate in tandem (Fig. 1). This volume draws together a multidisciplinary group of papers that look at different aspects of the three main processes that have affected northern Central America since the early Cretaceous: subduction, collision, and strike-slip faulting. Several factors that make this region favorable for integrated studies of the type assembled for this volume are (1) the outcrop record is extensive with a rock record spanning the period from the Precambrian to the Holocene; (2) there is a rich basinal record from which tectonic history can be extracted and compared to the history of the surrounding ocean basins (Figs. 2 and 3); (3) for volcanic arc studies, the outputs of the system are accessible for study in the onland arc; and (4) the oceanic inputs to arc systems are reasonably well-constrained due to the large, digital, and rapidly expanding database of offshore geological and geophysical data (e.g., Ranero et al., 2003) (Figs. 2 and 3).

While this area has many advantages for studies of both modern and ancient plate boundary processes, I believe that the regional Cenozoic tectonic development of northern Central America is more complex than is presently perceived, and that an improved Mesozoic-Cenozoic tectonic framework is an important step for understanding these complexities (Mann et al., 2007). For example, some of the longer term tectonic processes that have shaped the modern Cocos-Caribbean and Nazca-Caribbean subduction plate boundaries 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 modern and Miocene Central American volcanic arc; (2) slab break-off events affecting the subducting Cocos plate of the type described by Rogers et al. (2002) in northern Central America in the Miocene and by Ferrari (2004) for Miocene arcs in southern Mexico; and (3) the influence of the North America–Caribbean strike-slip system on the northern part of the Central American arc (Rosencrantz et al., 1988; Mann, 1999) (Fig. 1).

Such significant changes in plate motions and forcing functions must be taken into account in any effort to understand the ancient and active processes of the Central American subduction system, or "factory," in northern Central America (Plank et al., 2002; Mann et al., 2007). Unfortunately, current plate reconstructions fail to account for all the constraints derived from published literature and ongoing efforts.

TECTONIC RECONSTRUCTIONS OF NORTHERN CENTRAL AMERICA

To elucidate the tectonic setting of Central America, and more specifically to provide the regional setting of the topical papers in this volume, I present a quantitative set of plate reconstructions of the Central America and Caribbean region for the period of 165–0 Ma (Fig. 4A–4H). These reconstructions are modified from Mann (1999), Rogers (2003), and Mann et al. (2007).

I use these reconstructions as a framework to discuss unresolved questions concerning the position and character of plate boundaries influencing the geology of northern Central America since the Late Jurassic. Knowledge of the tectonic setting through time is necessary to support any conclusions concerning the types of sedimentary basins present, the nature of regional deformation events, and the temporal variation of the subducted oceanic input and volcanic and plutonic output of the northern Central American "subduction factory" (Fig. 2).

The reconstructions include constraints compiled from current and recent onshore geologic work (e.g., Balzer, 1999; Johnston and Thorkelson, 1997; Plank et al., 2002) that documents and dates critical tectonic processes and changes in the Central American volcanic arc as well as extensive offshore geophysical observations, which now includes seismic reflection and refraction

*paulm@ig.utexas.edu

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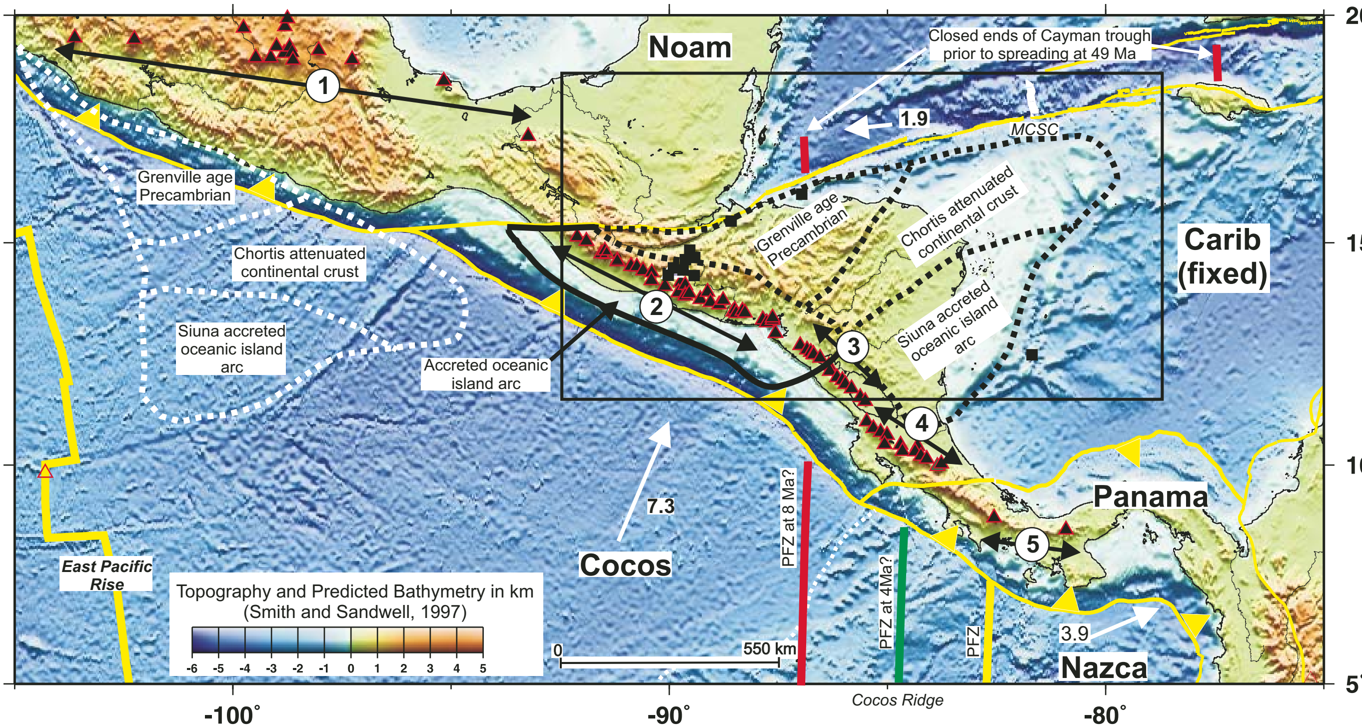


Figure 1. Tectonic and topographic setting of the Central American arc (volcanic arc segments 2–5), Trans-Mexican volcanic belt (segment 1), and the Middle American trench. Box shows study area discussed in this volume. Dark triangles represent Quaternary arc volcanoes; dark squares represent intraplate alkalic volcanoes. Plate motions in centimeters per year; data for Caribbean–North America plates are from DeMets et al. (2000), and data for Cocos-Caribbean and Nazca-Caribbean plates are from DeMets and Dixon (1999). 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 early Tertiary (approximate reconstructed position of Chortis is shown); 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 (Venable, 1994; Walther et al., 2000; Rogers et al., Chapter 6, this volume); 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 (Dickinson and Lawton, 2001); and the Northern Chortis magmatic zone is inferred to record a magmatic overprinting of parts of the Central and Eastern Chortis terranes. Age and position of the ends of the Cayman trough are from Leroy et al. (2000); positions of Cocos-Nazca-Caribbean triple junction are from McIntosh et al. (1993); white dashed outline is reconstructed Late Cretaceous position of the Chortis block from Rogers (2000). Carib—Caribbean; Noam—North America; MCSC—Mid-Cayman spreading center; PFZ—Panama fracture zone.

(McIntosh et al., 1993; Hinz et al., 1996; Christeson et al., 1999; von Huene et al., 2000; Walther et al., 2000; Ranero et al., 2003), gravity, magnetic (Barckhausen et al., 1998), and swath bathymetry data (von Huene et al., 2000) to constrain the tectonic history (Figs. 2 and 3).

METHODOLOGY FOR RECONSTRUCTIONS

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

1. Compilation of all existing Cenozoic magnetic anomaly and fracture zone data from the Cayman trough (Caribbean Sea) and eastern Pacific Ocean; for the latter area, I use data from Udo Barckhausen and Hans Roeser of Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Germany (Fig. 2). They have an extensive anomaly and fracture zone database and have acquired new magnetic and bathymetric data in recent years (cf. Barckhausen et al., 2001). Much of these new offshore geophysical data are summarized in the volume edited by Bundschuh and Alvarado (2007).
2. Integration of main Cenozoic tectonic events in the surrounding ocean basins, which have potentially affected the subduction history of northern Central America, including (a) initiation and subsequent seafloor spreading in the Cayman trough (Fig. 3); (b) early rifting of the Farallon plate at 22.7 Ma; (c) super-fast spreading on the East Pacific Rise between 18 and 10 Ma; and (d) early history of the Cocos Ridge and its offset by the Panama fracture zone ca. 6 Ma (Fig. 2).
3. Integration of main Cenozoic tectonic events onshore in Central America that potentially affect the Central America convergent margin, including (a) eastward migration of the Chortis continental block to northern

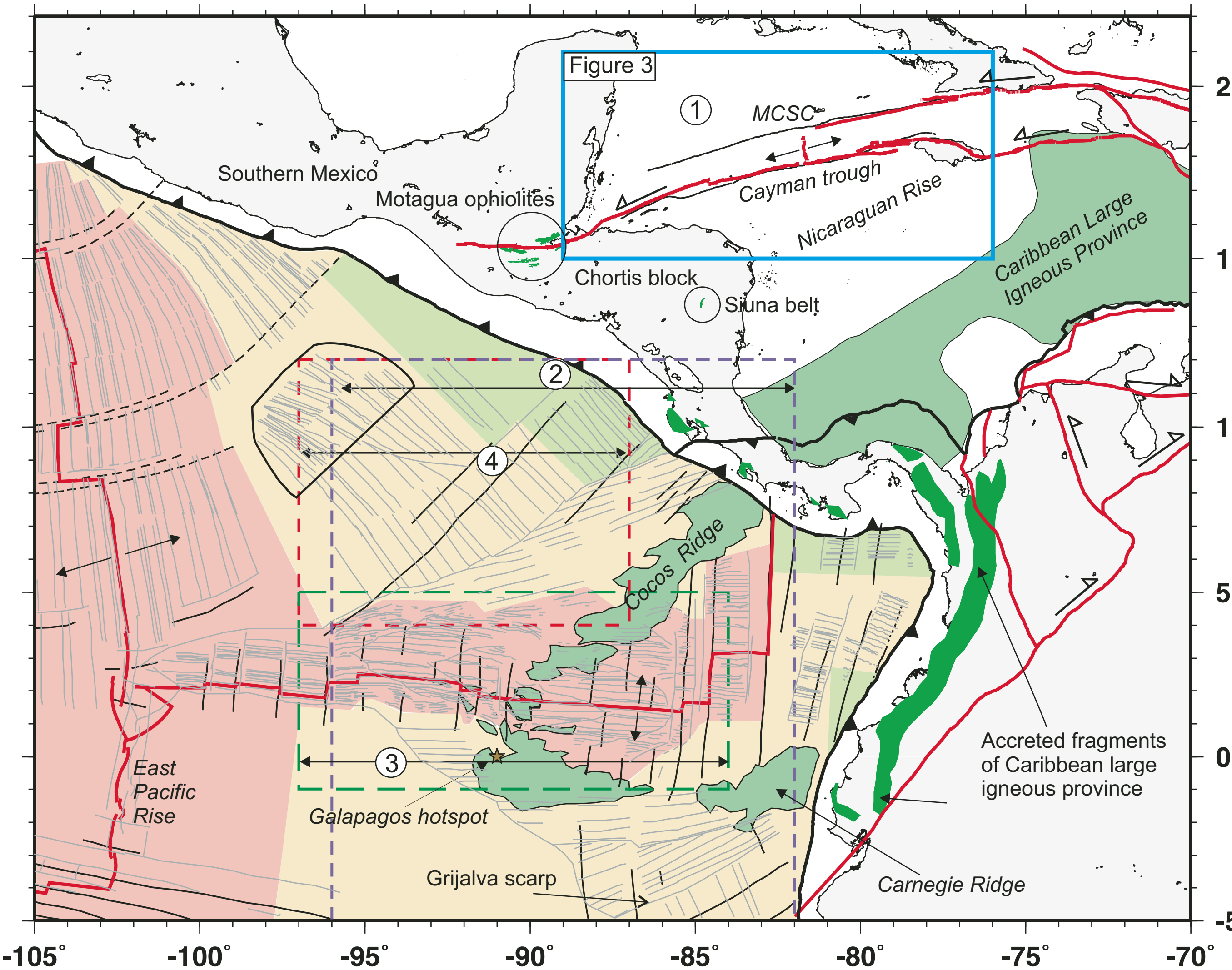


Figure 2. Marine magnetic anomalies and fracture zones that constrain tectonic reconstructions such as those shown in Figure 4 (ages of anomalies are keyed to colors as explained in the legend; all anomalies shown are from University of Texas Institute for Geophysics PLATES [2000] database): (1) Boxed area in solid blue line is area of anomaly and fracture zone picks by Leroy et al. (2000) and Rosencrantz (1994); (2) boxed area in dashed purple line shows anomalies and fracture zones of Barckhausen et al. (2001) for the Cocos plate; (3) boxed area in dashed green line shows anomalies and fracture zones from Wilson and Hey (1995); and (4) boxed area in red shows anomalies and fracture zones from Wilson (1996). 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. MCSC—Mid-Cayman Spreading Center.

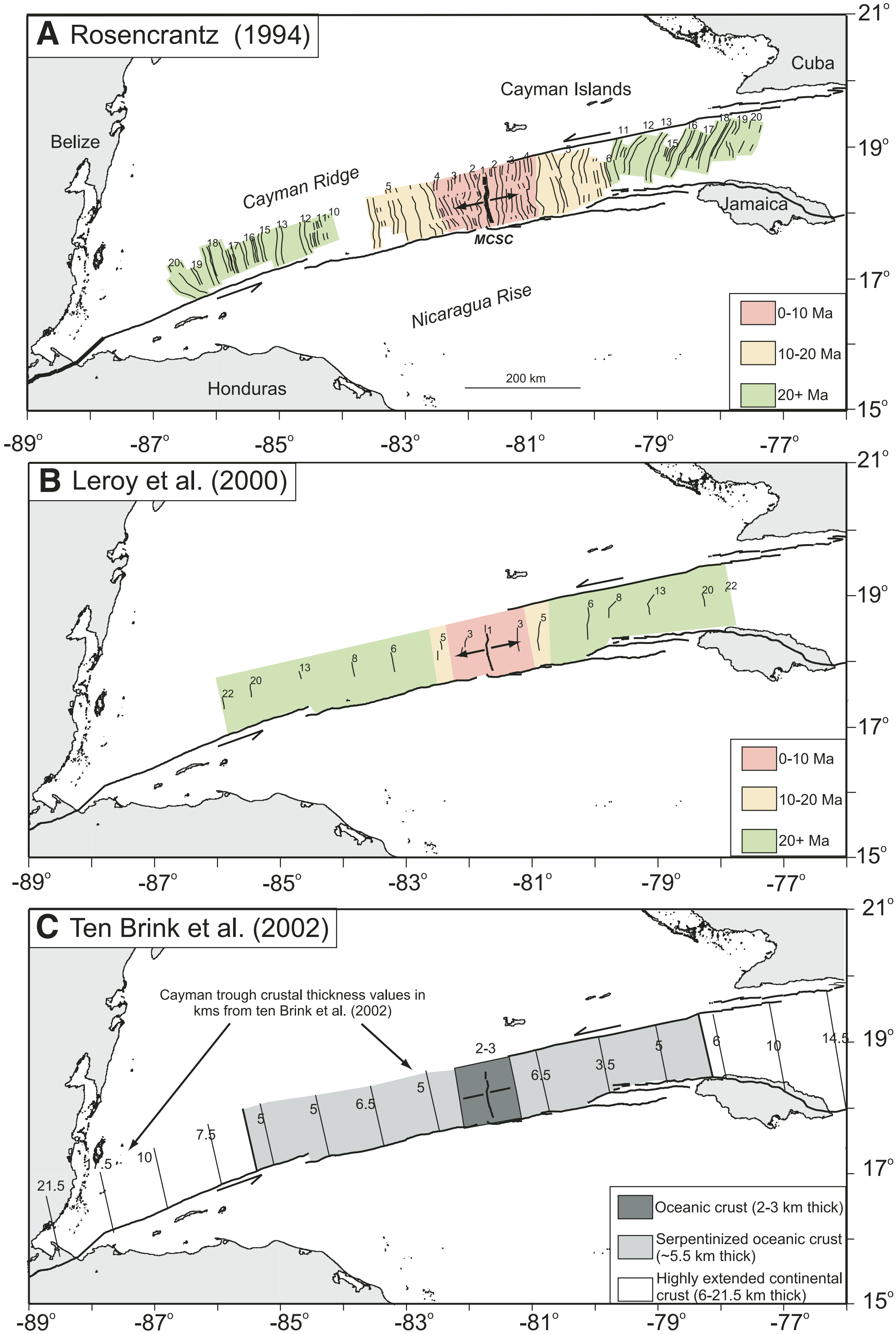


Figure 3. Marine magnetic anomaly interpretations of the Cayman trough. (A) Rosencrantz (1994) interpretation: numbers next to lineations identify magnetic anomalies. MCSC—Mid-Cayman Spreading Center. (B) Leroy et al. (2000) interpretation: numbers next to lineations identify magnetic anomalies. (C) ten Brink et al. (2002) interpretation showing larger area of thinned, continental crust. Numbers next to lineations represent their crustal thickness values.

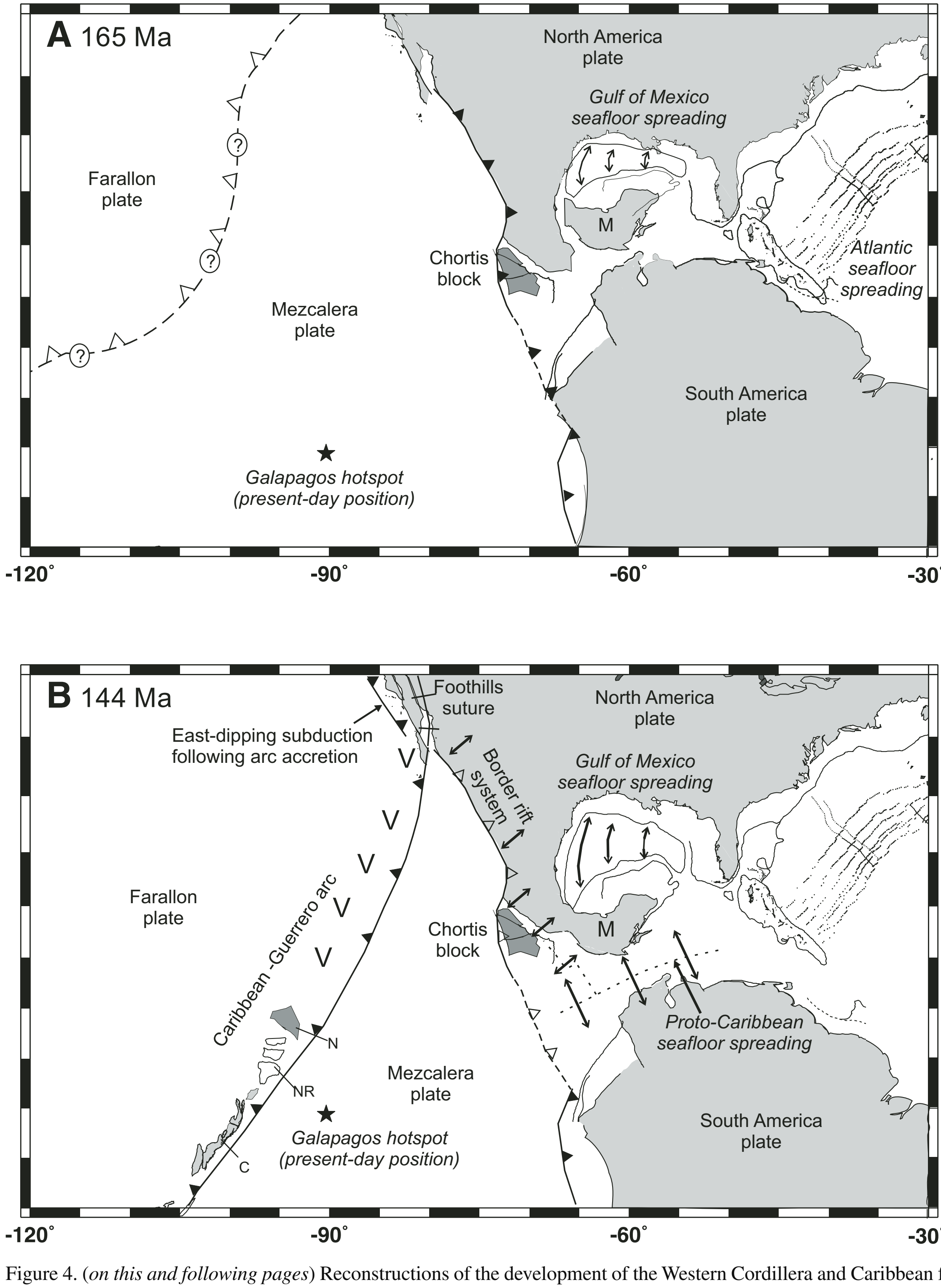


Figure 4. (*on this and following pages*) Reconstructions of the development of the Western Cordillera and Caribbean from Jurassic to present. (A) ca. 165 Ma; (B) ca. 144 Ma; (C) ca. 120 Ma; (D) ca. 90 Ma; (E) ca. 72 Ma; (F) ca. 49 Ma; (G) ca. 22 Ma; (H) present-day. See text for discussion. C—Cuba; CLIP—Caribbean large igneous province; CT—Cayman trough; G—Guerrero terrane; LA—Lesser Antilles; M—Maya block; N—Nicaragua; NR—Nicaraguan Rise; and Y—Yucatan basin. The countries of Costa Rica and Panama correspond to approximate area of the Chorotega block; the countries of Honduras, Nicaragua, and Guatemala correspond to the Chortis block.

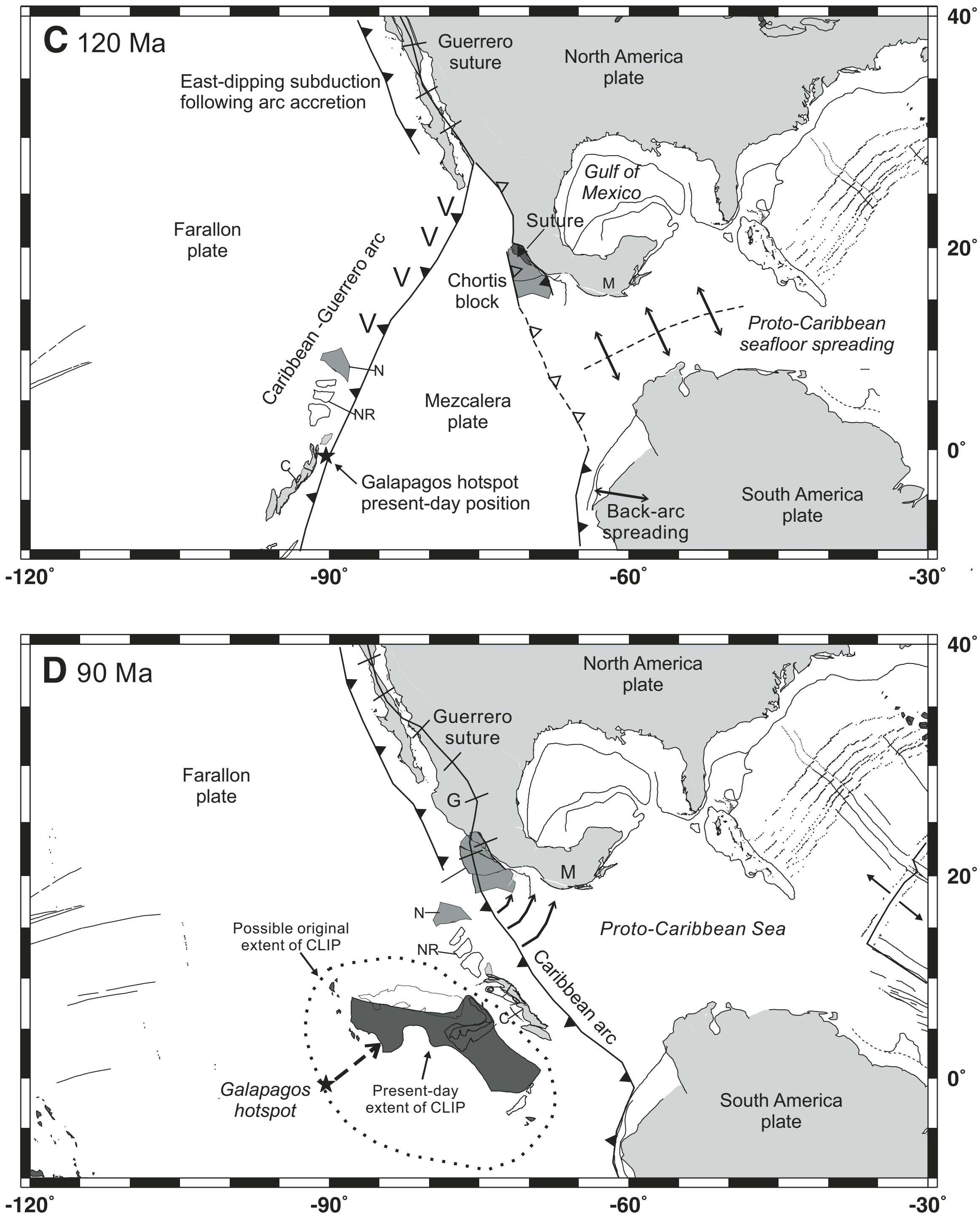
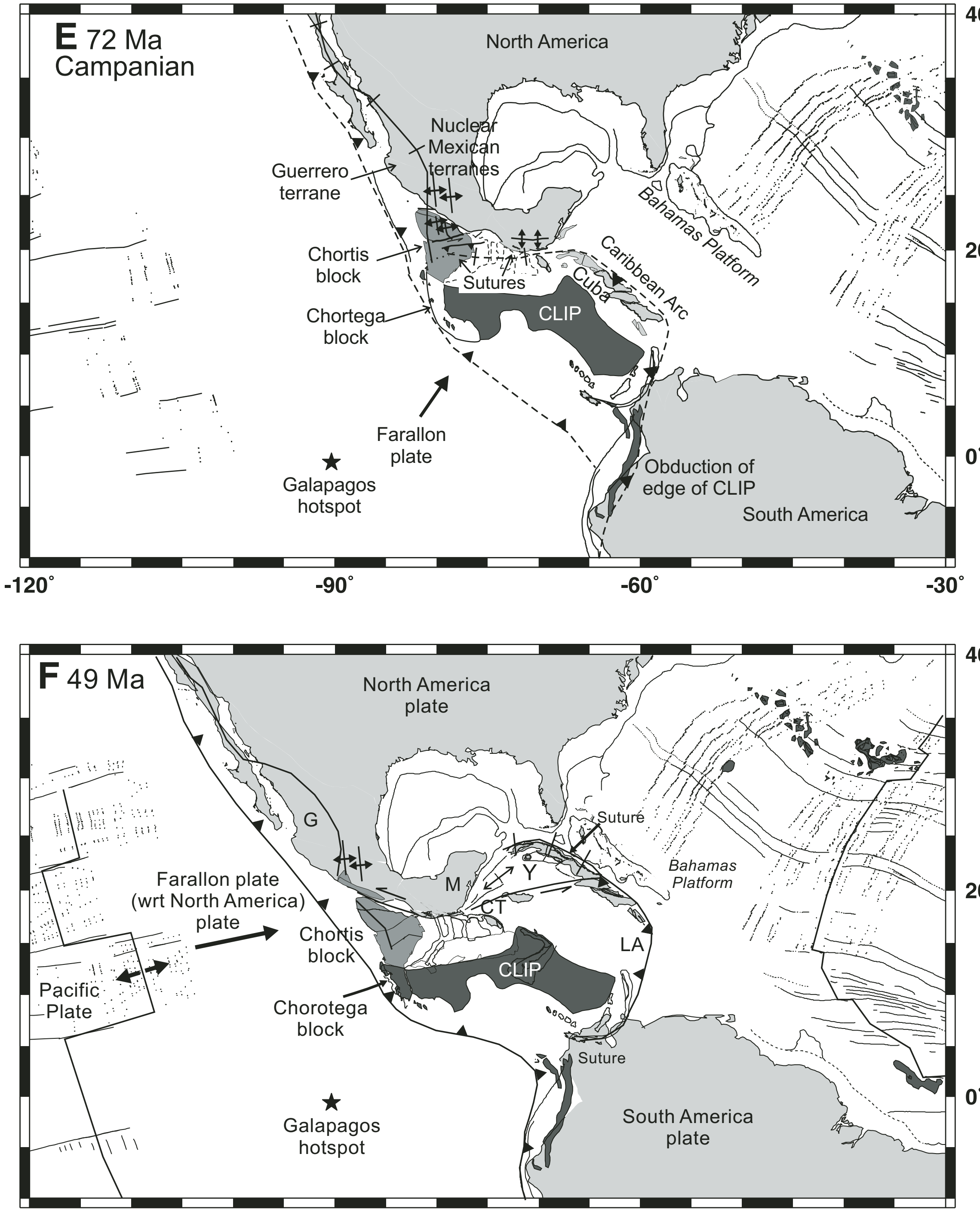


Figure 4. (*continued*)



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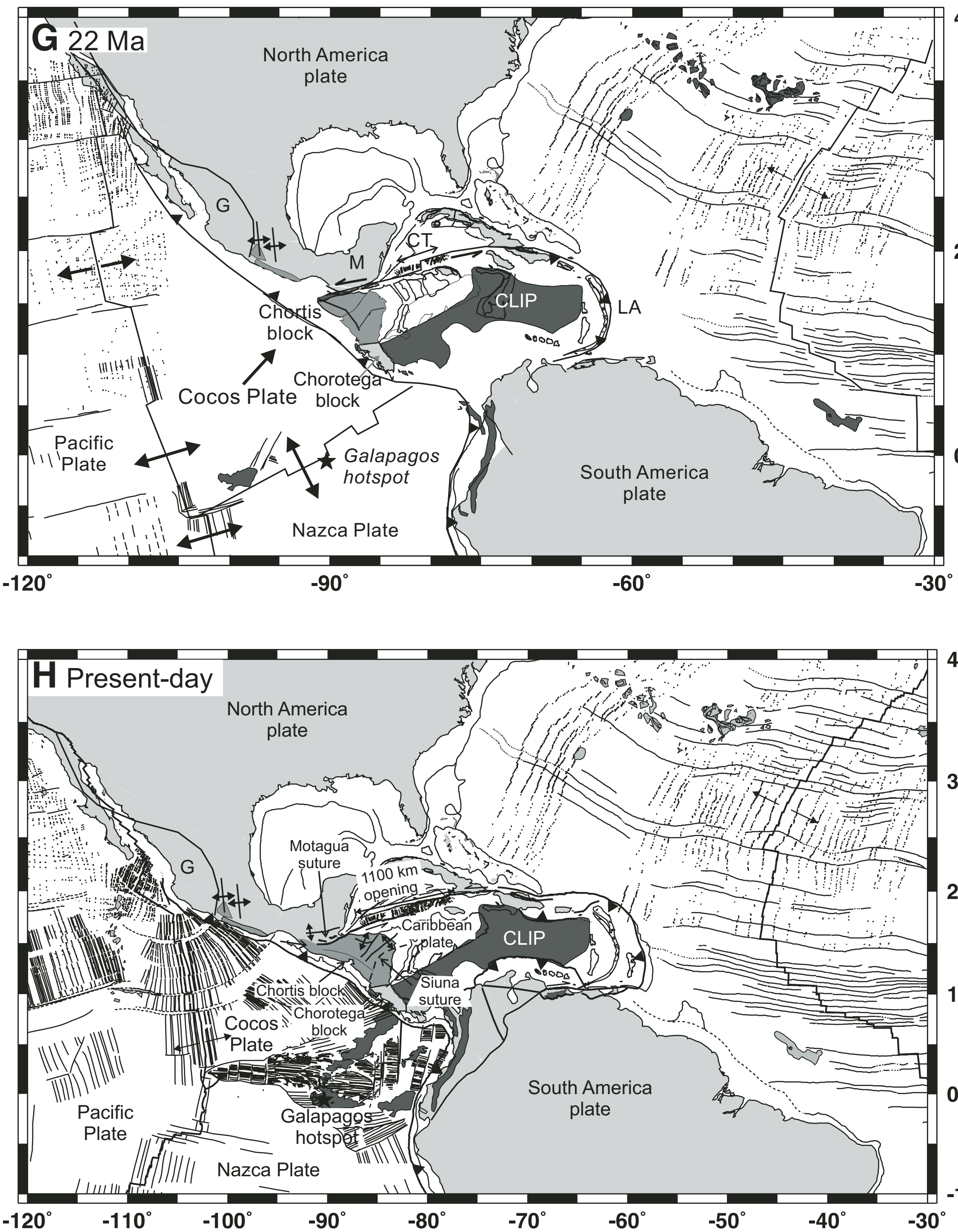

Figure 4. (*continued*)

Central America and progressive 35–28 Ma cessation of plutonic activity in southern Mexico (Rogers et al., Chapter 3, this volume; Schaff et al., 1995); and (b) NE to SW migration of the volcanic arc activity and opening of the Nicaraguan backarc basin from 10 to 0 Ma (Plank et al., 2002).

OVERVIEW OF THE TECTONIC HISTORY OF NORTHERN CENTRAL AMERICA

The geology of northern Central America exhibits 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. 1). Much of the relative movements of these elements has been broadly outlined in previous reconstructions, such as those by Pindell and Barrett (1990), Pindell and Kennan (2001), and Meschede and Barckhausen (2000) (Fig. 2). However, I quantitatively reconstruct these motions by incorporating as many of the recent magnetic (Figs. 2 and 3), fracture zone, and geologic (Fig. 1) constraints as possible. These reconstructions show that many of the tectonic and geochemical complexities of the Cretaceous-Cenozoic geology of northern Central America can be related to plate tectonic parameters, such as subduction direction, arc-continent collision, oblique subduction, and slab break-off.

Some important tectonic elements of northern Central America that attest to its mobility, highlighted in our reconstructions of the region, include the following features.

1. Chortis Block

This area has been traditionally regarded as the Precambrian-Paleozoic continental nucleus of northern Central America (Fig. 1). Radiometric dating by Schaff et al. (1995) 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 (1982) shown in Figure 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 (Rogers et al., Chapter 4, this volume) (Fig. 3).

Recent studies by Rogers (2003) and Rogers et al. (Chapter 4, this volume) show that the block is not homogeneous and can be divided into four tectonic terranes, shown on Figure 1: (1) the **Central Chortis terrane,** underlain by Grenville and Precambrian age continental crust detached from the southern margin of Mexico in the Late Cretaceous to Early Tertiary (approximate reconstructed position of Chortis is shown in Fig. 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 (Venable, 1994; Walther et al., 2000; Rogers et al., Chapter 6, this volume); and (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 (Dickinson and Lawton, 2001); Northern Honduras is characterized by an elongate belt of magmatic overprinting of parts of the Central and Eastern Chortis terranes (Fig. 1).

In Figure 1, the boundaries between these varying basement types strike at right angles to the northern Central American volcanic arc and may impart important basement controls on the tectonic structures of the arc and types of magmas erupted along this Cocos-Caribbean subduction boundary. For example, the large Central American ignimbrite flare-up that erupted between 19 and 10 Ma and is aligned along the northwest-trending boundary of continental terranes of the Chortis block suggests that magma emplacement is controlled by this crustal structure (Rogers et al., 2002; Jordan et al., this volume). 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 that are numbered 2 and 3 on Figure 1. The interpreted basement boundaries also coincide fairly well with many of the offsets that segment the volcanic arc.

2. Cayman Trough

This 1100-km-long oceanic basin formed as a pull-apart basin at the 100-km-long Mid-Cayman spreading center between 49 Ma and present (Rosencrantz et al., 1988; Rosencrantz, 1994; Leroy et al., 2000) (Fig. 3). 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 the Chortis block (Fig. 1), provided that the complexities of the Gonave microplate, at the southeastern edge of the Cayman trough in Jamaica and Hispaniola, are taken into account (Sykes et al., 1982; DeMets et al., this volume). Recent work by Müller et al. (1999) 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, I should be able to improve the kinematic constraints of northern Central America.

KEY TECTONIC EVENTS AFFECTING CENTRAL AMERICA SHOWN IN THE PLATE RECONSTRUCTIONS

The reconstructions shown in Figures 4A–4H coincide with major tectonic events. Integration of main Cenozoic tectonic events in the surrounding ocean basins, which have potentially affected northern Central America, include the following events:

- Initiation of spreading of the Cayman trough ca. 49 Ma (diffuse rifting that preceded organized seafloor spreading at the Mid-Cayman spreading center began earlier [cf. Mann and Burke, 1990]) (Fig. 3).

- Slowdown or cessation of Cayman trough spreading at 26–20 Ma (Rosencrantz, 1994) (Fig. 3).
- Early rifting and breakup of the Farallon plate at 22.7 Ma and the original distribution of now-dispersed fragments that include the Cocos, Malpelo, and Carnegie ridges (Meschede and Barckhausen, 2000) (Fig. 2).
- Super-fast spreading on the East Pacific Rise between ca. 18 and 10 Ma (Wilson, 1996).

The main Cenozoic tectonic events in Central America include the following:

- Eastward migration relative to the Chortis continental block to northern Central America and progressive 35–28 Ma cessation of plutonic activity in southern Mexico (Schaff et al., 1995).
- NE to SW migration of the volcanic arc and opening of the Nicaraguan backarc basin from 10 to 0 Ma (Balzer, 1999; Plank et al., 2002).

The reconstructions also integrate the main Cenozoic tectonic events affecting the Caribbean plate as a whole, including relative stability of the Caribbean plate with respect to the Atlantic and Indian Ocean hotspots since 38 Ma (Müller et al., 1999) and the rapid north-south convergence of the North and South American plates from 38 to 10 Ma and their slower convergence from 10 to 0 Ma (Dixon and Mao, 1997).

PLATE RECONSTRUCTIONS OF CENTRAL AMERICA: 165–0 Ma

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 include Ross and Scotese (1988), Rosencrantz et al. (1988), Mayes et al. (1990), Atwater and Severinghaus (1990), and Pindell and Barrett (1990). Since these early efforts, new marine magnetic anomaly–fracture zone data and new interpretations of existing data have been published regarding these regions (Cande and Haxby 1991; Wilson and Hey, 1995; Wilson, 1996; DeMets and Traylen, 2000; Leroy et al., 2000; Barckhausen et al., 2001; Rogers, 2003) (Fig. 2). Some of these data were incorporated in more recent plate models by Meschede et al. (1998), Meschede and Barckhausen (ODP Leg 170 Scientific Results, 2000), Mann (1999), and Müller et al. (1999). Mann (1999) incorporated the North America–South America–Africa motions determined by Müller et al. (1999), using the PLATES (2000) software and database to expand the areal extent of his reconstructions. He did not incorporate the magnetic anomaly picks of Leroy et al. (2000) or Meschede and Barckhausen (2000), who worked independently.

Following Mann (1999), I present a series of plate reconstructions from the mid-Late Jurassic to the present-day that depict 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 (Figs. 4A–4H). An earlier but similar version of these reconstructions appears in Rogers (2003) and Mann et al. (2007).

The reconstructions were made in the mantle reference framework of Müller et al. (1999) 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 Galapagos hotspot provides a stationary point of reference of this framework and is shown in all reconstructions in Figure 4. It should be noted that the geologic evidence for the existence of the Galapagos hotspot can only be dated back to ca. 95 Ma (Hoernle et al., 2002).

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 Rogers (2003) and Mann et al. (2007) (marine magnetic anomalies used are shown on Figs. 2 and 3). The plate circuit used for the reconstructions is Caribbean to North America (Rosencrantz, 1994); North America to Africa and South America to Africa (Müller et al., 1999); Africa to Antarctica (Royer et al., 1988); Antarctica to Nazca (Tebbens and Cande, 1997; Rosa and Molnar, 1988) and Antarctica to Pacific (Tebbens and Cande, 1997; Cande et al., 1995); and Nazca to Cocos (Wilson and Hey, 1995; Barckhausen et al., 2001). The nature and location of ancient plate boundaries shown in the reconstructions of Mexico and the Caribbean in Figures 4A–4H are based on geologic constraints summarized in the synthesis of Mexican geology by Dickinson and Lawton (2001) and in the syntheses of Caribbean and northern South American geology by Pindell and Barrett (1990), Pindell (1994), and Mann (1999).

165 Ma (Late Jurassic)

The reconstructions start in the Late Jurassic and resemble the reconstructions of Dickinson and Lawton (2001) for the earlier evolution of Mexican terranes (Fig. 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 (Yucatan) block south to Central America (Marton and Buffler, 1994). The continental terranes of the Chortis block were adjacent to the autochthonous Mexican terranes. The Cretaceous margins of Chortis were likely accreted from elements of the Guerrero-Caribbean arc formed at the leading edge of the Farallon plate that consumed the Mezcalera plate as it advanced from the west (Tardy et al., 1994; Moores, 1998). East-dipping subduction along the western margin of the Americas occurred across the Central America region (Fig. 4A).

144 Ma (Early Cretaceous)

At the start of the Cretaceous, North America and South America continued to separate and form the proto-Caribbean seaway (Pindell and Barrett, 1990). The oceanic crust of the proto-Caribbean was later consumed by the eastward and northeastward advance of the Guerrero-Caribbean arc shown in Figure 4B. Opening of the proto-Caribbean formed the Eastern Chortis terrane of attenuated continental crust (Pindell and Dewey, 1982). The opening event also rifted the Juarez terrane of Mexico (Dickinson and Lawton, 2001).

Rifting along the southeastern margin of North America formed the Arperos basin (Tardy et al., 1994). Widespread rifting along the western margin of North America at this time is attributed to trench rollback as subduction of the oceanic Mezcalera plate slowed during the approach of the Guerrero-Caribbean arc from the west (Dickinson and Lawton, 2001) (Fig. 4B).

I adopt the interpretation by Tardy et al. (1994), Burke (1988), and Moores (1998) 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 eastern North America margin progressed from north (Sierran foothills of California) to south (Guerrero terrane of southern Mexico) (Dickinson and Lawton, 2001) (Fig. 4B). Following this arc-continent collision, eastward-dipping subduction of the Farallon plate stepped outboard (eastward) of the newly accreted Guerrero terrane.

An alternative view, which I do not support, proposes that the present-day area of the Caribbean was created during the period of 130–80 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 (Frisch et al., 1992; cf. preface in Mann, 1995, for a review of salient points of both proposed concepts). In my view, the alternative viewpoint of Frisch et al. (1992) 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. Pindell and Barrett, 1990; Mann, 1999).

Rifting of the southeastern Mexican margin during the early Cretaceous detached part of the Oaxaca and Mixteca terranes from nuclear Mexico (Del Sur block of Dickinson and Lawton, 2001) 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 (2001), or along a failed rift arm of the proto-Caribbean spreading center (Fig. 4A). During this time, the Chortis block underwent intrablock rifting and deposition of pre-Aptian, terrigenous siliciclastic rocks (Rogers, 2003; Rogers et al., Chapter 5, this volume).

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. 4C). By this time, collision of the Guerrero terrane with the margin of eastern North America and closure of the Arperos basin were complete to the latitude of Baja (W. Dickinson, 2003, personal commun.). I propose that prior to the diachronous closure of the Guerrero-Caribbean arc against southeastern Mexico, Chortis-Mexico convergence occurred along a short-lived, eastward-dipping subduction zone (Fig. 4C). This subduction produced intra-arc rifting and arc volcanism in the overriding Chortis block by 126 Ma (Drobe and Oliver, 1998; Rogers, 2003; Rogers et al., Chapter 5, this volume). Termination of this subduction cycle between Chortis and southeastern Mexico is recorded by a well-dated, 120 Ma subduction complex along the northern edge of the Chortis block, which is presently exposed on the southern margin of the Motagua Valley of Guatemala (Sisson et al., 2003; Harlow et al., 2004). Structural and stratigraphic continuity between Chortis and southeastern 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 (Rogers et al., Chapters 4 and 5, this volume).

90 Ma (Late Cretaceous)

The Guerrero-Caribbean arc continued diachronous suturing along the eastern and southern thinned, continental edges of the Chortis block (Fig. 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 (Rogers, 2003; Rogers et al., Chapter 5, this volume). 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 (Rogers et al., Chapter 5, this volume). Strong shortening effects are also seen in southern Mexico at this time (Dickinson and Lawton, 2001).

By this time, the Guerrero-Caribbean arc had overridden the Galapagos hotspot, heralding a vigorous period of submarine oceanic plateau volcanism that began by at least 95 Ma and was widespread by 88 Ma (Sinton et al., 1997; Hoernle et al., 2002). These elements became amalgamated as the Chorotega block of southern Central America.

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, 1994) (Fig. 4E) and to the formation of the Colon deformed belt (Rogers et al., Chapter 6, this volume; Fig. 1). 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 (Donnelly et al., 1990; Sisson et al., 2003; Harlow et al., 2004). Eastward-dipping subduction developed between the Farallon plate and the eastern margin of the Caribbean oceanic plateau (Fig. 4E). The Caribbean arc detached from the Caribbean oceanic plateau, which was pinned on its northern and southern edges by collision with Chortis and northeastern South America. Continued north and eastward motion of the Caribbean arc by trench rollback detached Cuba from the Caribbean oceanic plateau and formed the Yucatan backarc basin south of Cuba and the Grenada backarc basin east of the present-day Lesser Antilles arc (Mann, 1999).

49 Ma (Eocene)

The northeastward migration of the Caribbean arc ended when part of the arc collided with the Bahamas carbonate platform (Fig. 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 (Rosencrantz et al., 1988; Mann, 1999).

Along the southeastern Mexican margin, eastward-dipping shallow subduction produced the Xolopa magmatic arc and the Northern Chortis magmatic zone (Schaff et al., 1995). The geometry of the Xolopa arc with respect to the Chortis-Farallon 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. 4F). This geometry would suggest that the Chortis block occupied a forearc setting during oblique convergence of the Farallon plate relative to North America (Schaff et al., 1995). Southeast translation of the Chortis block was facilitated by extending the detachment zone parallel to the zone of Xolopa arc magmatism; this hot, weakened zone of arc was broken under oblique, Farallon–North America convergence, and as a result, the Chortis block was dislodged from Mexico and moved southeastward (Schaff et al., 1995). 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, 2001) (Rogers, 2003; Rogers et al., Chapter 4, this volume).

22 Ma (Miocene)

Deformation arising from Farallon 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 (Wortel and Cloetingh, 1981; Barckhausen et al., 2001) (Fig. 4G). The reorganization led to near-orthogonal subduction of the Cocos plate beneath the Chortis block (Wilson and Hey, 1995), and the abrupt termination of oblique subduction forces that previously drove the eastward motion of the Chortis block. A super-fast spreading period of this segment of the East Pacific Rise preceded the detachment of the Cocos slab beneath northern Central America. Rogers et al. (2002) and Jordan et al. (this volume) proposed that this slab detachment event produced large-scale topographic 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 (Plank et al., 2002) that was perhaps initiated by steepening of the Cocos slab following the break off of its subducted, downdip extension ca. 4–10 Ma (Rogers et al., 2002). Ferrari (2004) has proposed a similar process of slab break off 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-Chamelecon, Polochic, and 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 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 (Rogers, 2003; Rogers and Mann, Chapter 3, this volume).

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. 5G). GPS studies reported in this volume by DeMets et al. for northern Central America will improve constraints on block motions with this area.

DISCUSSION: UNRESOLVED TECTONIC PROBLEMS IN NORTHERN CENTRAL AMERICA

A challenge for future workers is to relate magmatic and deformational events recorded in the Precambrian to Holocene geologic record of northern Central America to changing plate boundary configurations of North America, Caribbean, and Cocos plates as predicted by the plate reconstructions shown in Figures 4A–4H. Part of the problem is that plate motion rates in this region have been very fast (e.g., 5–18 cm/yr range; Wilson, 1996). Future studies should seek consistency between onland and oceanic interpretations by working with data sets from both realms.

Precambrian Connections between North and South America

Fragments of Precambrian-age continental crust occur in central Honduras and in Guatemala (Fig. 1). Renne et al. (1989) proposed that these elements once formed a continuous belt

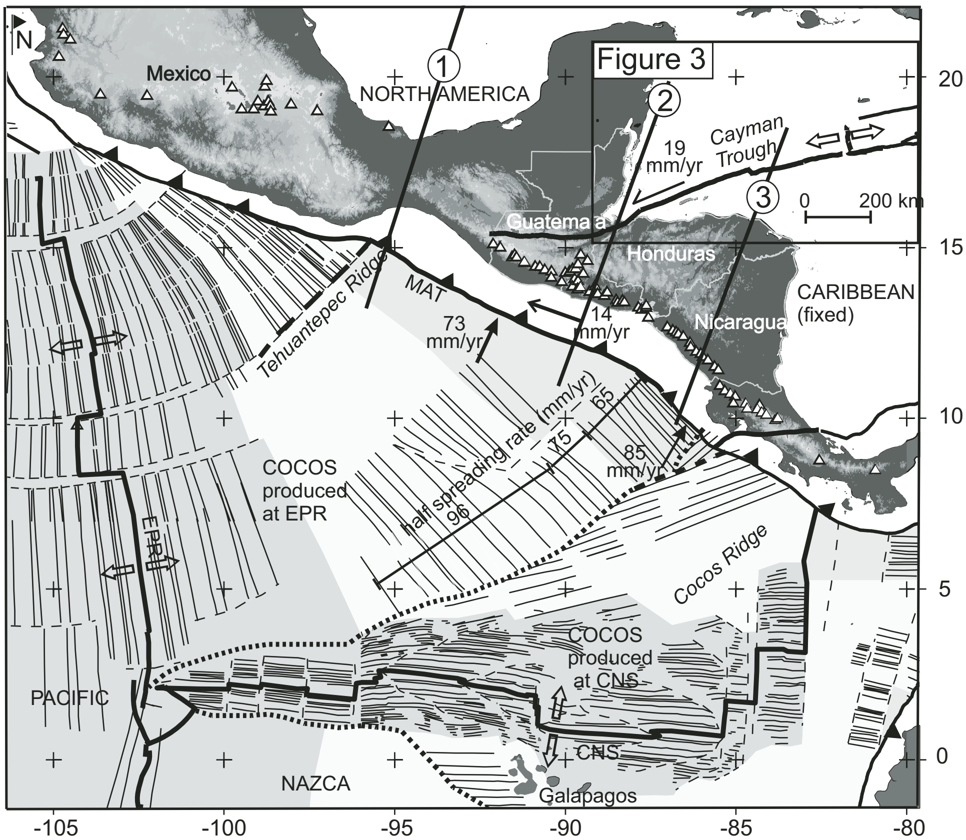

Figure 5. Present setting of Central America showing plates, Cocos crust produced at East Pacific Rise (EPR), and Cocos-Nazca spreading center (CNS), triple-junction trace (heavy dotted line), volcanoes (open triangles), Middle America Trench (MAT), and rates of relative plate motion (DeMets et al., 2000; DeMets, 2001). East Pacific Rise half spreading rates from Wilson (1996) and Barckhausen et al. (2001). Lines 1, 2, and 3 are locations of topographic and tomographic profiles in Figure 6.

linking the more continuous Grenville belts of North and South America. Centeño-García and Keppie (1999) suggest the fragments represent parts of multiple belts that originated as an isolated microcontinent in the eastern Pacific and were reorganized by plate motions since their formation. 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 and reassembling the blocks from the widely separated areas.

Slowing of Spreading in the Cayman Trough and Relationship 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 (Rosencrantz, 1994) (Fig. 3). The Cayman trough is a valuable, long-term recorder of motion between northern Central America on the Caribbean plate (Chortis block) and the North American plate (Fig. 3). Through closure conditions, these motions can be used to better-constrain motions of the Farallon plate and, after 22 Ma, the Cocos and Nazca plates beneath Central America. Cayman trough aeromagnetic data suggest that the motion was not steady but began quickly from ca. 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 (Rosencrantz, 1994) (Fig. 3).

Slab Break-off of the Cocos Plate beneath Northern Central America

P-wave tomographic images of the mantle beneath northern Central America reveal a detached slab of the subducted Cocos plate (Figs. 6A–6C) (Rogers et al., 2002). Landscape features of the region of Honduras and Nicaragua above the detached slab are consistent with epeirogenic uplift produced by mantle upwelling following slab break-off between 10 and 4 Ma.

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. Wortel and Spakman, 2000). Thermomechanical modeling of the slab-detachment process demonstrates large (>500 °C) transitory heating of the base of the upper plate for several million years (cf. van de Zedde and Wortel, 2001). 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 (Walker et al., 2000). Slab detachment and uplift of the Central American plateau occurred between the end of the subduction-related ignimbrite flare-up at 10 Ma (Jordan

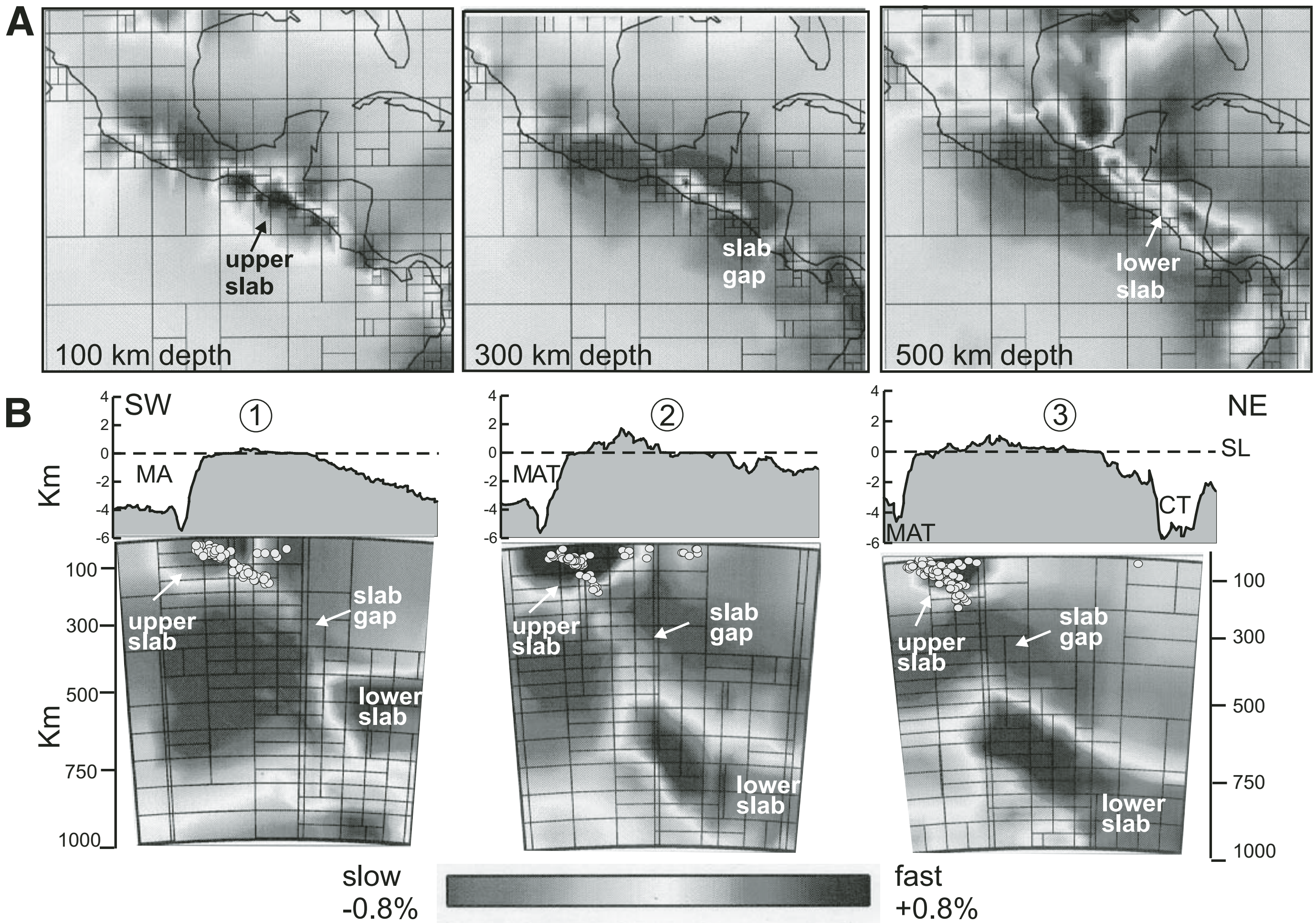

Figure 6. (A) Tomographic slices of the P-wave velocity of the mantle at depths of 100, 300, and 500 km beneath Central America. (B) Upper panels show cross sections of topography and bathymetry. Lower panels: tomographic profiles showing Cocos slab detached below northern Central America, upper Cocos slab continuous with subducted plate at Middle America Trench (MAT), and slab gap between 200 and 500 km. Shading indicates anomalies in seismic wave speed as a ±0.8% deviation from average mantle velocities. Darker shading indicates 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., 2002).

et al., this volume) 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) (Fig. 6).

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 (Wortel and Spakman, 2000). Rogers et al. (2002) 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 (Wilson, 1996) along the southernmost Cocos-Pacific segment of the East Pacific Rise. 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 (Morris et al., 2002), tomographic observations showing slab break-off require highly variable rates of subduction and rates of slab melting during the Neogene.

Models for the Internal Deformation of the Chortis Block and the Eastern 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 (Fig. 7A) (Burkart and Self, 1985; Gordon and Muehlberger, 1994) (Fig. 7A); and (2) as fault termination features along the North America–Caribbean margin (Guzmán-Speziale, 2001) (Fig. 7B). Offshore extensional deformation is generally attributed to a diffuse strike-slip plate margin south of the Swan Islands fault zone (Case et al., 1984). DeMets et al.

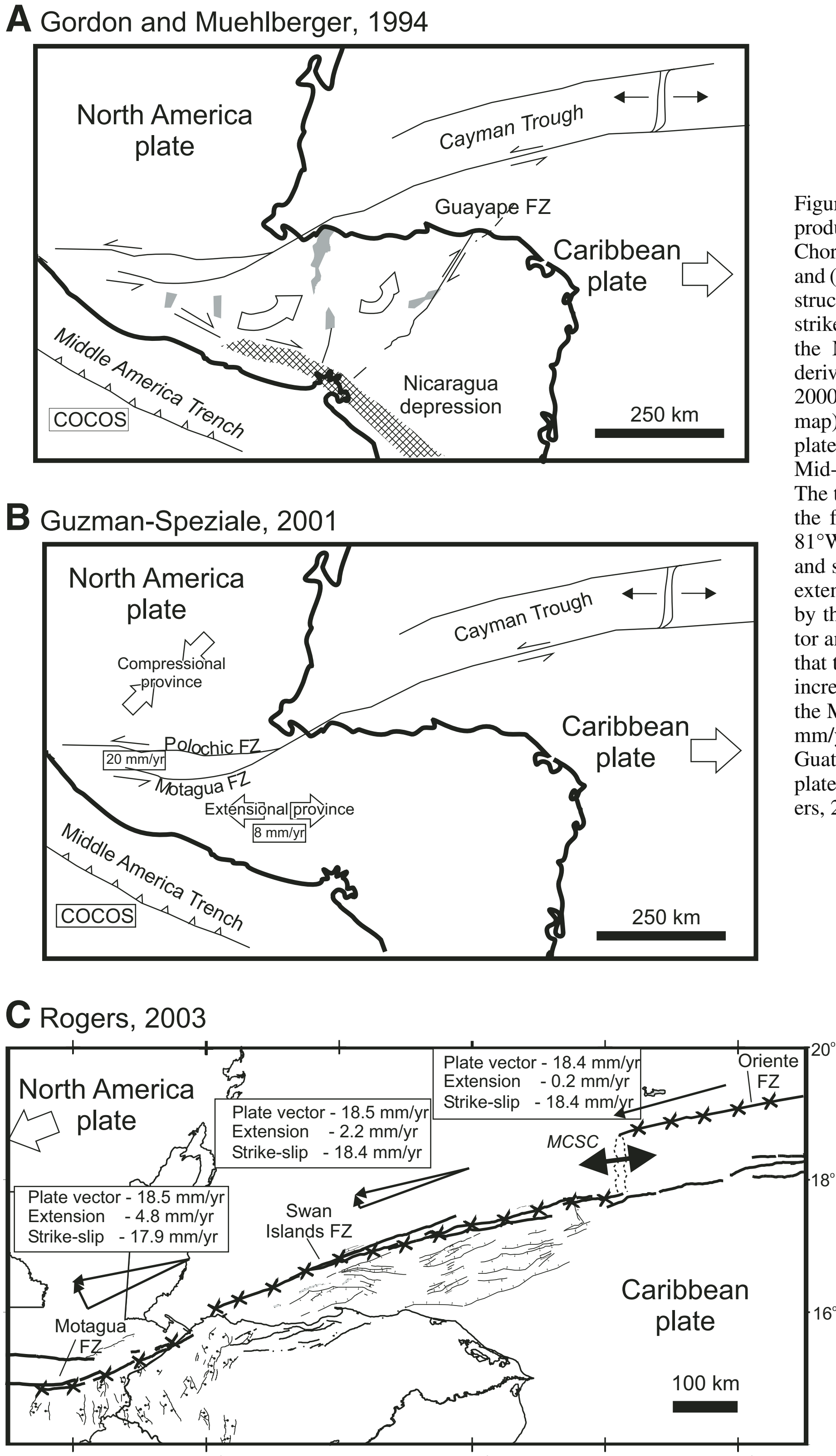

Figure 7. Internal deformation of the Chortis block, produced by: (A) counterclockwise rotation of Chortis block (Gordon and Muehlberger, 1994); and (B) fault termination (Guzmán-Speziale, 2001) structures north and south of the Motagua-Polochic strike-slip fault zone (FZ). (C) Transtension along the Motagua–Polochic–Swan Islands FZ. GPS-derived Caribbean plate velocity (DeMets et al., 2000) was calculated at 30 min increments (Xs 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 89°W, 85°W, and 81°W 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 81°W near the Mid-Cayman spreading center (MCSC) to 4.8 mm/yr at longitude 89°W in the Motagua Valley of Guatemala and is consistent with the widening of plate margin deformation from east to west (Rogers, 2003; Rogers and Mann, this volume).

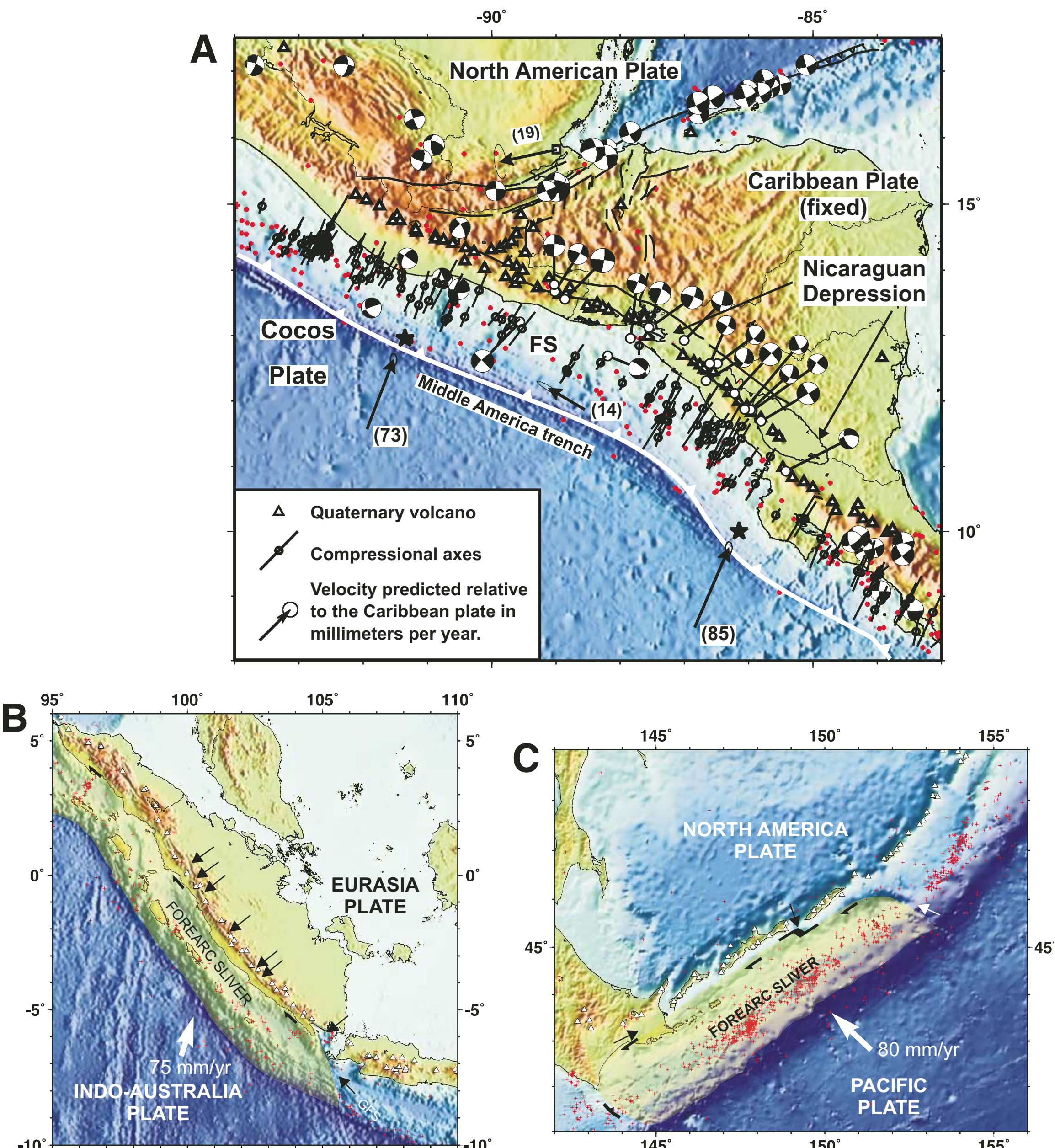

Figure 8. (A) The Central American forearc sliver (FS) is produced by the slight (~10°) oblique convergence of the Cocos plate at the Middle America trench, resulting in the northward migration of the forearc sliver (DeMets, 2001). Earthquake focal mechanisms show right-lateral strike-slip motion along the Central America arc. Motion vectors are shown in millimeters per year. 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). In B black arrows highlight pull-apart basins at right-steps along the right-lateral Sumatra strike-slip fault zone that bounds the forearc sliver. In C small black and white arrows show trace of right-lateral strike-slip fault zone with one pull-apart segment, which bounds the Kurile forearc sliver.

(2000) 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 (2003) and Rogers and Mann (this volume) refine the observations of Demets et al. (2000) for the eastern Caribbean plate and relate the pattern of active borderlands and oblique-slip faulting to the angular divergence of Caribbean motion and the local azimuth of the plate margin faults (Fig. 7C). This view of the western Caribbean deformation is also compatible with the fault termination model of Guzmán-Speziale (2001) (Fig. 7B).

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 ~600 km from the northern Gulf of Fonseca in El Salvador and northern Nicaragua to the Caribbean Sea in Costa Rica (Fig. 8A). 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 backarc position. Two hypotheses have been proposed to explain the tectonic origin of this regional structure within the framework of the Central American volcanic arc. 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 (Plank et al., 2002). 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 ~50° at ca. 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% pure shear over the past 12 Ma.

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. 8A). 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 (DeMets, 2001). 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 Central American volcanic arc, which mostly exhibit right-lateral focal mechanisms (Figs. 8B and 8C). One controversy is whether the fault accommodating the strike-slip displacement of the forearc sliver is a single strike-slip fault zone parallel to the arc or is composed of "bookshelf faults" that accommodate strike-slip by motion on a series of oblique faults (La Femina et al., 2002).

FUTURE WORK

It is my 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 northern Central American "subduction factory."

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