AGU PUBLICATIONS

Geochemistry, Geophysics, Geosystems

RESEARCH ARTICLE

10.1002/2015GC005971

Key Points:

- Cocos Ridge subduction began at ∼2–3 Ma
- Seamount subduction began at 3–4 Ma
- A significant late Miocene plate tectonic reorganization produced the Panama Triple Junction

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Citation:
Morell, K. D. (2015), Late Miocene to recent plate tectonic history of the southern Central America convergent margin, *Geochem. Geophys. Geosyst.*, *16*, 3362–3382, doi:10.1002/2015GC005971.

Received 22 JUN 2015
Accepted 3 SEP 2015
Accepted article online 7 SEP 2015
Published online 5 OCT 2015

Late Miocene to recent plate tectonic history of the southern Central America convergent margin

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Abstract New plate reconstructions constrain the tectonic evolution of the subducting Cocos and Nazca plates across the southern Central American subduction zone from late Miocene to recent. Because of the strong relationships between lower and upper (Caribbean) plate dynamics along this margin, these constraints have wide-ranging implications for the timing and growth of upper plate deformation and volcanism in southern Central America. The reconstructions outline three important events in the Neogene history of this margin: (1) the coeval development of the Panama Triple Junction with the initiation of oblique subduction of the Nazca plate at ∼8.5 Ma; (2) the initiation of seamount and rough crust subduction beginning at ∼3–4 Ma; and (3) Cocos Ridge subduction from ∼2 to 3 Ma. A comparison of these events with independent geologic, geomorphic, volcanic, and stratigraphic data sets reveals that the timing, rates, and origin of subducting crust directly impacted the Neogene growth of upper plate deformation and volcanism in southern Central America. These analyses constrain the timing, geometry, and causes of a number of significant tectonic and volcanic processes, including rapid Plio-Quaternary arc-fore arc contraction due to Cocos Ridge subduction, the detachment of the Panama microplate at ∼1–3 Ma, and the late Miocene cessation of mantle-wedge-derived volcanism across ∼300 km of the subduction zone.

1. Introduction

Decades of research reveals intimate links between the kinematics, geometry, and character of subducting plates and the geologic, geodynamic, and seismic evolution of subduction zone systems [e.g., *Taylor et al.*, 2005; *Regalla et al.*, 2013; *Wang and Bilek*, 2014]. These links are well-documented in southern Central America, where subduction of the Cocos Ridge, a Galápagos hot spot track [*Hey*, 1977; *Hauff et al.*, 2000; *Werner et al.*, 2003] on the eastern edge of the Cocos plate (Figure 1), exerts a strong influence on a host of subduction zone processes (Table 1). These include: (1) increased shortening [*Fisher et al.*, 2004; *Sitchler et al.*, 2007; *La Femina et al.*, 2009; *Bangs et al.*, 2015], vertical tectonism [*Corrigan et al.*, 1990; *Gardner et al.*, 1992; *Kolarsky et al.*, 1995], subduction erosion [*Vannucchi et al.*, 2013], and seismicity inboard of the ridge [*Bilek et al.*, 2003; *Lewis et al.*, 2008; *Kobayashi et al.*, 2014]; (2) exhumation of the Cordillera de Talamanca volcanic arc (CT, Figure 1) [*de Boer et al.*, 1995; *Kolarsky et al.*, 1995; *Gräfe et al.*, 2002; *Gazel et al.*, 2009]; and (3) progressive southeastward shallowing of the Cocos plate slab (Figure 2) [*Protti et al.*, 1995].

The subduction of smaller-scale bathymetric features on both the Cocos and Nazca plates also significantly affects the subduction zone system in southern Central America (Table 1). On the Cocos plate, "rough" crust subduction of ∼10–25 km wide seamounts and oceanic plateaus (SMD, Figure 1) links to patterns of seismicity [*Bilek et al.*, 2003], fault creep [*Wang and Bilek*, 2014], and subduction erosion [*Ranero and von Huene*, 2000], and also correlates with deformation in both offshore slope sediments [*von Huene et al.*, 1995; *Hinz*, 1996; *von Huene et al.*, 2000; *Sak et al.*, 2009] and the Nicoya Peninsula fore-arc high (NP, Figure 1) [*Marshall and Anderson*, 1995; *Gardner et al.*, 2001]. On the Nazca plate, oblique subduction of the north-south-striking Coiba and Balboa Fracture Zones (CFZ, BFZ, Figure 1) leads to thrust faults among slope sediments on the leading edge of each fracture zone, followed by collapse and subsidence on the fracture zone's trailing edge [*Heil*, 1988; *Moore and Sender*, 1995; *MacKay and Moore*, 1990].

The change in convergence rate and obliquity across the Cocos-Nazca-Caribbean (Panama) Triple Junction (PTJ, Figure 1) [*McIntosh et al.*, 1993] likewise imparts a strong influence on subduction zone dynamics (Table 1). Across the Panama Triple Junction, where the downgoing plate transitions eastward from Cocos to Nazca plate subduction across the Panama Fracture Zone (PFZ, Figure 1), the upper plate experiences a

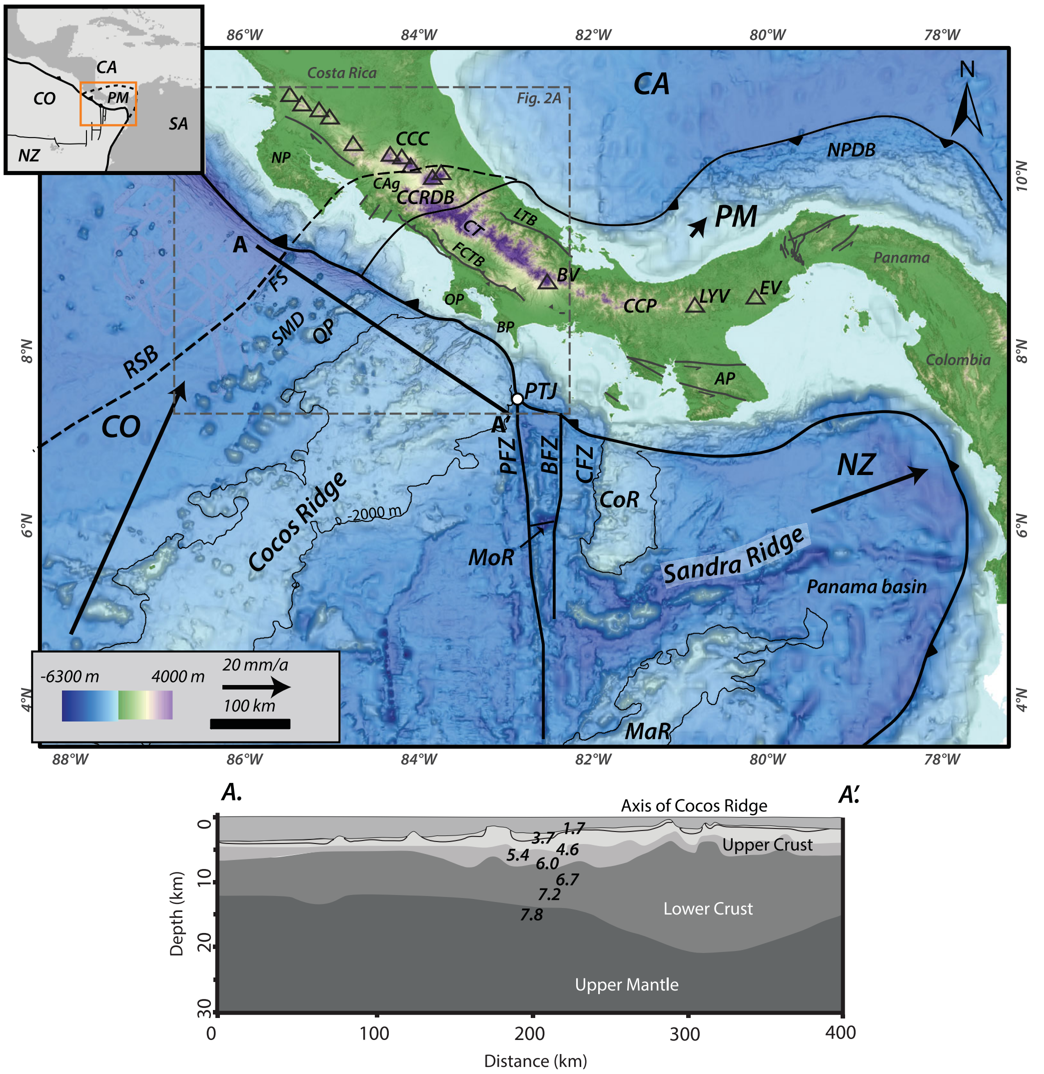


Figure 1. Tectonic setting of the southern Central American subduction zone showing elevation and bathymetry [*Smith and Sandwell*, 1997; *Amante and Eakins*, 2009]. Vectors show plate velocities relative to Caribbean plate based on the MORVEL model [*DeMets et al.*, 2010; *Argus et al.*, 2011; *Kobayashi et al.*, 2014]. AP, Azuero Peninsula; BFZ, Balboa Fracture Zone; BP, Burica Peninsula; BV, Barú Volcano; CA, Caribbean plate; CAg, Cordillera de Aguacate; CCC, Cordillera Central of Costa Rica; CCP, Cordillera Central of Panama; CCRDB, Central Costa Rica Deformed Belt; CFZ, Coiba Fracture Zone; CO, Cocos plate; CoR, Coiba Ridge; CT, Cordillera de Talamanca; EV, El Valle Volcano; FCTB, Fila Costeña Thrust Belt; FS, Fisher Seamount Chain; LTB, Limón Thrust Belt; LYV, La Yeguada Volcano; MoR, Morgan Rift; MaR, Malpelo Ridge; NP, Nicoya Peninsula; NPDB, North Panama Deformed Belt; NZ, Nazca plate; OP, Osa Peninsula; PFZ, Panama Fracture Zone; PM, Panama microplate; PTJ, Panama Triple Junction; QP, Quepos Plateau; RSB, rough-smooth boundary; SA, South America; SMD, seamount domain. Faults in Panama from *Rockwell et al.* [2010a, 2010b]. Crustal cross section of the Cocos Ridge (A-A′) modified after *Walther* [2003] and *Sallarès et al.* [2003]. Seismic velocities shown in km/s.

greater than 3-fold decrease in convergence rate and a significant increase in obliquity [*DeMets et al.*, 2010; *Argus et al.*, 2011; *Morell et al.*, 2013]. These along-strike variations in relative plate velocity and direction, in addition to the effects of Cocos Ridge subduction, correlate with the lateral discontinuation of the Fila Costeña inner fore-arc thrust belt (FCTB, Figure 1) [*Morell et al.*, 2008], an along-strike decrease in width and height of the Cordillera de Talamanca (CT, Figure 1) [*Morell et al.*, 2012], and a dramatic decrease in seismicity from west to east [*Dziewonski et al.*, 1981].

Although it is well-demonstrated that lower plate dynamics greatly influence the geologic, stratigraphic, and geodynamic evolution of this system, there are several details of this influence that remain incompletely understood. For example, one of the most widely discussed debates in Central American tectonics relates to the timing of Cocos Ridge subduction, with estimates of ridge arrival spanning from ~8 Ma [e.g., *Abratis and Wörner*, 2001; *Gazel et al.*, 2009] to ~0.5 Ma [e.g., *Gardner et al.*, 1992]. Second, it remains unclear

Table 1. Documented Upper Plate Response to the Subduction of Lower Plate Features in Southern Central America

Seamount Subduction	Cocos Ridge Subduction	Panama Fracture Zone Subduction and Panama Triple Junction Migration
Outer Forearc		
Rapid vertical tectonics on Nicoya Peninsula [*Marshall and Anderson*, 1995; *Gardner et al.*, 2001; *Sak et al.*, 2009; *Marshall*, 2008] Vertical tectonism within offshore slope sediments [*von Huene et al.*, 1995, 2000] Subduction erosion [*Ranero and von Huene*, 2000]	Emergence and deformation of the Burica [*Corrigan et al.*, 1990; *Morell et al.*, 2011] and Osa Peninsulas [*Gardner et al.*, 1992; *Sak et al.*, 2004; *Gardner et al.*, 2013] Rapid sedimentation and subduction erosion [*Vannucchi et al.*, 2013] Trench embayment [*Vannucchi et al.*, 2013; *Gardner et al.*, 2013]	Southeastward migration of deformation on Burica Peninsula [*Morell et al.*, 2011]
Inner forearc		
Central Costa Rica Deformed Belt [*Marshall et al.*, 2000; *Sak et al.*, 2009]	Development of the Fila Costeña thrust belt [*Kolarsky et al.*, 1995; *Fisher et al.*, 2004] Escape faulting away from the ridge [*Kobayashi et al.*, 2014]	Southeastward migration of the Fila Costeña Thrust Belt [*Morell et al.*, 2008, 2013]
Arc		
Shift of the active volcanic front [*Marshall et al.*, 2003] Central Costa Rica Deformed Belt [*Marshall et al.*, 2000; *Montero et al.*, 2013]	Exhumation of the Cordillera de Talamanca volcanic arc [*Gräfe et al.*, 2002; *Morell et al.*, 2012] Late Miocene termination of calc-alkaline volcanism [*de Boer et al.*, 1995; *Abratis and Wörner*, 2001]	Volcanism at Barú Volcano [*Hidalgo and Rooney*, 2010, 2014]
Back arc		
No effect	Developnent of the Limón back arc thrust belt [*Goes et al.*, 1993; *Collins et al.*, 1995]	No effect

how Cocos Ridge subduction potentially relates to the slab geometry beneath south-central Costa Rica [*Dzierma et al.*, 2011], and if this geometry could correlate with the termination of calc-alkaline volcanism in the Cordillera de Talamanca [*de Boer et al.*, 1995], or the production of adakitic volcanism [*Abratis and Wörner*, 2001; *Gazel et al.*, 2011]. Finally, despite the demonstrated importance of triple junction migration and seamount subduction (SMD, Figure 1) in the development of fore-arc deformation (Table 1) [*Sak et al.*, 2009], there are few constraints on the timing of seamount subduction or the initiation of the Panama Triple Junction.

Here I present new plate reconstruction models that provide insight into many of these outstanding questions. The reconstructions outline several important tectonic events, including: (1) a late Miocene change from near-orthogonal to highly oblique subduction; (2) the southeastward migration of the Panama Triple Junction from ~8.5 Ma to present; (3) seamount subduction starting at ~3–4 Ma; and (4) the arrival of the Cocos Ridge at ~2–3 Ma. I use these tectonic constraints, together with documented relationships between lower and upper plate features compiled from independent data sets (Table 1), to reconstruct the growth of the Central American convergent margin from late Miocene to recent. The results from this synthesis suggest that many of the unresolved issues in Central American tectonics can be explained by a complex plate tectonic history involving triple junction migration, fracture zone propagation, and the subduction of seafloor created at the Galápagos hot spot. Below, I provide a brief background into the tectonic setting and seafloor properties relevant to the plate reconstructions.

2. Tectonic Setting

2.1. Current Plate Velocities

The southern Central America convergent margin results from the subduction of the Cocos and Nazca plates beneath the Caribbean plate at the Middle American Trench. The Cocos plate (CO, Figures 1 and 3) subducts rapidly (81 mm/a) and orthogonally to the northeast beneath the Caribbean plate [*DeMets et al.*, 2010; *Argus et al.*, 2011; *Kobayashi et al.*, 2014] and is bound to its east by the Panama Fracture Zone (PFZ, Figure 1) [*Lowrie et al.*, 1979; *Bird*, 2003], a transform fault whose intersection with the trench represents the

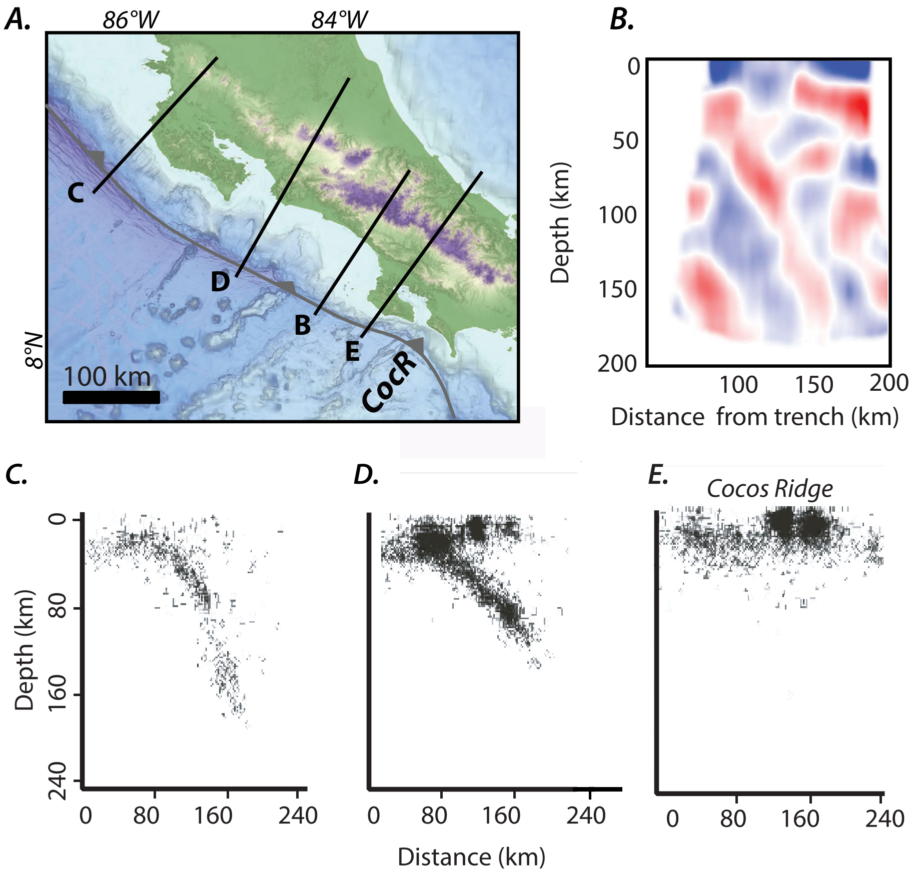


Figure 2. (a) Map showing location of geophysical transects mentioned in the text, with location of map shown in Figure 1. CocR denotes Cocos Ridge. (b) Receiver function profile from *Dzierma et al.* [2011]. Red amplitudes denote positive conversions and blue amplitudes denote negative conversions. Wadati-Benioff zone seismicity lines c, d, and e are from *Protti et al.* [1994, 1995].

Panama Triple Junction (Figure 1). To the east of the Panama Fracture Zone, Nazca plate subduction (NZ, Figure 1) occurs both more slowly (37 mm/a) and with greater obliquity than the Cocos plate to the west [*DeMets et al*., 2010; *Argus et al*., 2011]. The Caribbean (upper) plate of this system (CAg, Figure 1) contains the Panama microplate (PM, Figure 1) [*Fisher et al*., 1994; *Marshall et al*., 2000], which extends for ~1000 km along the trench [*Kellogg and Vega*, 1995; *Bird*, 2003; *Kobayashi et al*., 2014] and moves north-northeast with respect to the Caribbean plate (7.5 mm/a to N39°E) [*Kobayashi et al*., 2014]. Given this tectonic configuration, a triple junction velocity diagram (Figure 4) suggests that Cocos-Panama convergence (~70 mm/a) is more than three times faster than Nazca-Panama convergence (~20 mm/a).

2.2. The Cocos Plate

2.2.1. Bathymetry

The northwestern part of the Cocos plate was created by the East Pacific Rise and exhibits relatively few seamounts or ridges (EPR, Figures 1 and 3) [*Hey*, 1977; *Barckhausen et al*., 2001]. The crust to the southeast was created at the Cocos-Nazca Spreading Center (CNS, Figures 1 and 3) and contains several bathymetric features associated with passage over the Galápagos hot spot [*Lonsdale and Klitgord*, 1978; *von Huene et al*., 1995, 2000; *Ranero and von Huene*, 2000; *Ranero et al*., 2008]. Some of the largest of these features are the Fisher Seamount Chain and the Quepos Plateau, which both lie >1000 m above the adjacent seafloor and are approximately 15 and 25 km wide, respectively (FS, QP, Figure 1) [*von Huene et al*., 1995, 2000; *Ranero and von Huene*, 2000]. The north-east-trending transition between this "seamount domain" (SMD, Figure 1) and smoother crust to its northwest is referred to as the "rough-smooth boundary" (RSB, Figure 1) [*Hey*, 1977]. Located to the southeast of the seamount domain is the aseismic Cocos Ridge, a 200 km wide and 1000 km long trail of the Galápagos hot spot [*Johnson and Lowrie*, 1972; *Werner et al*., 2003] that is 1500 m

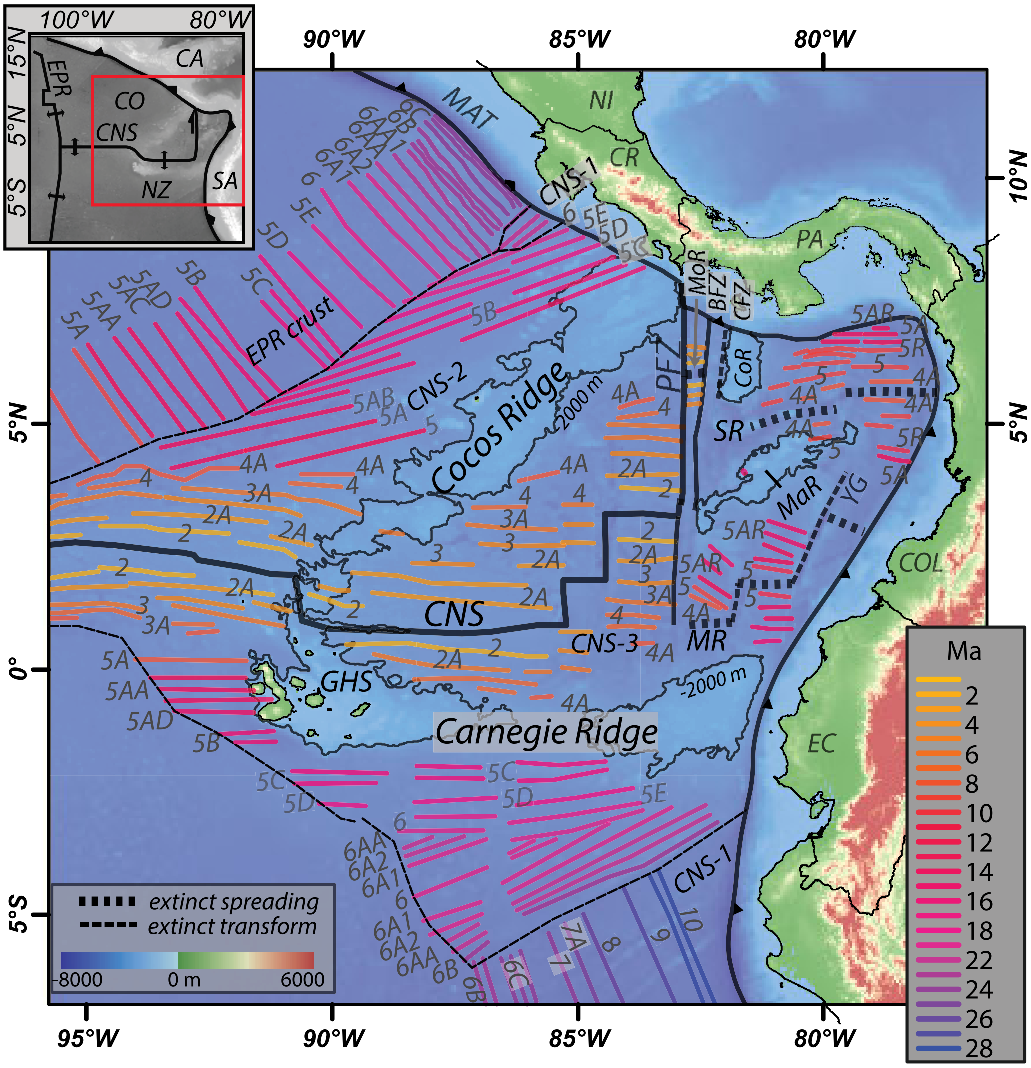


Figure 3. Digital elevation model [*Smith and Sandwell*, 1997; *Amante and Eakins*, 2009] showing Panama Basin and seafloor magnetic anomaly data surrounding the southern Central America subduction zone [*Lonsdale and Klitgord*, 1978; *Wilson and Hey*, 1995; *Barckhausen et al.*, 2001; *Lonsdale*, 2005] based on chron time scale of *Cande and Kent* [1995]. The −2000 m contour is shown for prominent bathymetric features in the region, including Malpelo Ridge (MaR) and Coiba Ridge (CoR). BFZ, Balboa Fracture Zone; CFZ, Coiba Fracture Zone; CNS, Cocos-Nazca spreading center; COL, Colombia; CR, Costa Rica; EC, Ecuador; GHS, Galápagos hot spot; MR, Malpelo Rift; MAT, Middle America Trench; MoR, Morgan Rift; NI, Nicaragua; PA, Panama; PFZ, Panama Fracture Zone; SR, Sandra Rift; YG, Yaquina Graben. Inset: Present day plate boundaries of Cocos (CO), Nazca (NZ), Caribbean (CA), and South American (SA) plates. East Pacific Rise (EPR) and Cocos-Nazca Spreading Center (CNS) are also shown.

tall and contains >20 km thick crust along its axis (Figures 1 and 3) [*Sallarès et al.*, 2003; *Walther*, 2003]. The Cocos Ridge is truncated on the east by the Panama Fracture Zone, which exhibits a 2 km bathymetric scarp (PFZ, Figure 1) [*Smith and Sandwell*, 1997].

2.2.2. Magnetic Anomalies

The Cocos plate crust produced at the East Pacific Rise exhibits a relatively simple pattern of magnetic anomalies: seafloor age increases with distance from the spreading center, with the oldest (~24 Ma) crust nearest the trench (Figure 3) [*Lonsdale and Klitgord*, 1978; *Barckhausen et al.*, 2001]. Crust produced at the Cocos-Nazca Spreading Center reveals a much more complicated history, however. Magnetic anomaly patterns show at least three discrete clockwise rotations in the orientation of Cocos-Nazca spreading since the Paleogene, resulting in seafloor that is labeled CNS-1, CNS-2, and CNS-3, for each change in spreading axis (Figure 3) [*Meschede et al.*, 1998; *Barckhausen et al.*, 2001]. CNS-1 refers to the oldest seafloor, spanning 22.7–19.5 Ma [*Meschede et al.*, 1998]. Only a small (8000 km^2) region of CNS-1 crust remains on the Cocos plate to the southeast of East Pacific Rise crust along the trench.

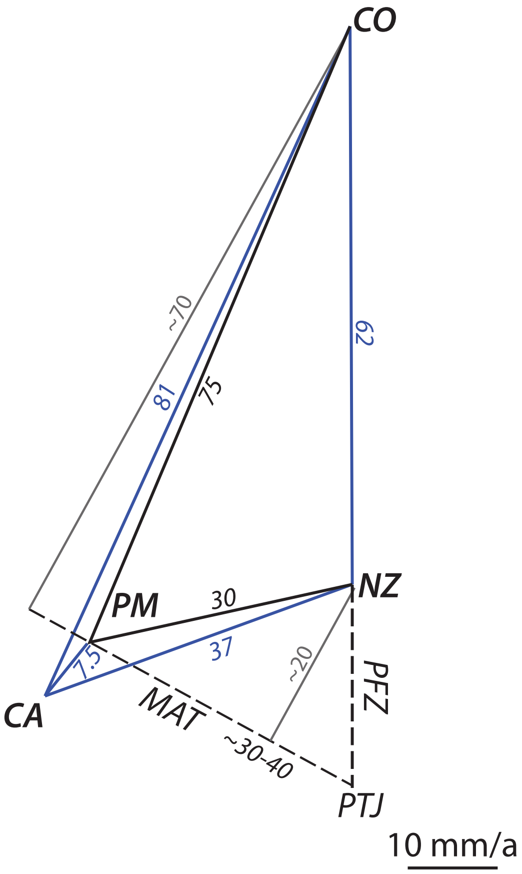


Figure 4. Velocity diagram for the Panama Triple Junction (PTJ) based on MORVEL data set [*DeMets et al.*, 2010; *Argus et al.*, 2011] showing Cocos (CO), Nazca (NZ), and Caribbean (CA) plates. Panama microplate (PM) velocity relative to the CA plate from *Kobayashi et al.* [2014]. Rates shown in mm/a. Black vectors show motion relative to the Panama microplate. Trench-orthogonal convergence rates are shown in gray. MAT, Middle America Trench; PFZ, Panama Fracture Zone. The triple junction migration rate of 30–40 mm/a is slower than previously reported studies based on the NUVEL-1 model, which were based on faster rates of CO-CA motion [e.g., *Gardner et al.*, 1987, 1992; *McIntosh et al.*, 1993; *Sitchler et al.*, 2007; *Morell et al.*, 2008].

CNS-2 crust, which spans 19.5–14.5 Ma and is located south of CNS-1, contains the seamount domain and Cocos Ridge (Figure 3) [*Barckhausen et al.*, 2001]. Magnetic anomalies suggest that the subducting crust within the seamount domain decreases in age from northwest to southeast (~23–15 Ma) [*Barckhausen et al.*, 2001]. CNS-3 crust represents the youngest seafloor on the Cocos plate (14.5 Ma recent) and does not intersect the convergent margin (Figure 3) [*Wilson and Hey*, 1995; *Meschede et al.*, 1998; *Barckhausen et al.*, 2001].

2.3. The Nazca Plate

2.3.1. Bathymetry

The northern half of the Panama Basin contains the Balboa and Coiba Fracture Zones, transform faults that parallel the Panama Fracture Zone to its east and are spaced ~50 km apart (Figures 1 and 3) [*Hey*, 1977; *Lowrie et al.*, 1979; *van Andel et al.*, 1971; *Lonsdale and Klitgord*, 1978]. Both of these structures have ~2 km scarps, extend for more than 150 km in length, and intersect the margin offshore western Panama. Earthquake hypocenters suggest that the Balboa Fracture Zone is highly seismically active, whereas the Coiba Fracture Zone is largely inactive [*Cleveland and Ammon*, 2013]. There is a 25 km long fossil spreading center in between the Panama and Balboa Fracture Zones named the Morgan Rift (MoR, Figures 1 and 3) [*Lowrie et al.*, 1979]. The Coiba Fracture Zone marks the western edge of the Coiba Ridge, a >2 km high and 100 km wide elevated plateau (CoR, Figure 1).

The center of the Panama Basin contains the Malpelo and Sandra Ridges (Figures 1 and 3) [*Lonsdale and Klitgord*, 1978]. The Sandra Ridge extends for more than 400 km along strike (Figures 1 and 3) and although not currently spreading was host to several historic sinistral earthquakes [*de Boer et al.*, 1988; *Lonsdale*, 2005]. South of the Sandra Rift, the Malpelo Ridge exhibits bathymetry (>-2000 m) and crustal thickness (>20 km) similar to the Cocos Ridge [*Sallarès et al.*, 2003, 2005].

The southern half of the eastern Panama Basin contains the Malpelo Rift, Yaquina Graben, and Carnegie Ridge (Figure 3) [*Hardy*, 1991]. Although not well understood, the Malpelo Rift and Yaquina Graben are most likely part of an extinct spreading-transform system that could be related to the Sandra Rift system to the north [*Lonsdale*, 2005]. The southernmost eastern Panama basin is marked by the Carnegie Ridge, a >2 km tall trace of the Galápagos hot spot [*Johnson and Lowrie*, 1972; *Hey*, 1977; *Lonsdale and Klitgord*, 1978] with crust that is ~19 km thick [*Sallarès et al.*, 2005].

2.3.2. Magnetic Anomalies

Most of the magnetic anomalies in the Panama Basin were formed by the now-extinct Sandra and Malpelo Rifts [*Lonsdale*, 2005] and range in age from ~9 to 14 Ma (Figure 3) [*Lonsdale*, 2005]. There are also several magnetic anomalies between the Panama and Balboa Fracture Zones that were produced by the Morgan Rift that range in age from 5 to 2 Ma (MoR, Figure 3) [*Lowrie et al.*, 1979]. In this paper, I use the distribution of these lower plate features, together with the methods outlined below, to produce the reconstructions.

3. Plate Reconstruction Methods

Reconstructions are computed based on MORVEL Euler poles describing the relative motion for the Cocos-Caribbean and Nazca-Caribbean plate pairs averaged over the past 3.16 Ma [*DeMets et al.*, 2010; *Argus et al.*, 2011]. This procedure assumes that modern plate motions have remained constant for the past 10 Ma. This assumption has been regularly used in previous 0–10 Ma regional reconstructions in this study area [*Hey*, 1977; *Lonsdale and Klitgord*, 1978; *Gardner et al.*, 1992; *MacMillan et al.*, 2004] because quantifying reconstruction poles for time periods $\gtrsim$3 Ma [e.g., *Cox and Hart*, 2009] requires computation of a complex plate circuit involving the Caribbean-North America-Africa-Antarctica-Pacific-Cocos plates, which introduces uncertainties of a comparable order to the magnitude of plate motions. While it is unlikely that Cocos-Caribbean and Nazca-Caribbean plate motions have remained unchanged over the past 10 Ma, this assumption is necessary given the lack of constraints on the past plate motion between the relevant plate pairs for this time period. However, the distribution of magnetic anomalies on the Cocos and Nazca plates does not show appreciable changes in spreading over the past 10 Ma that would significantly affect the reconstructions [*Wilson and Hey*, 1995], and global plate velocity models suggest that the Caribbean plate has shown little movement relative to an Indo-Atlantic hot spot reference frame during this time period [*Pindell and Kennan*, 2009].

In this study, angular rotation calculations are based on a grid spacing of one degree latitude and longitude and exclude the motion of the Panama microplate relative to the Caribbean plate or any motion of the upper plate or trench. The Panama microplate is excluded from the calculations because of its slow geodetically determined rate of motion relative to the Caribbean plate ($<$10 mm/a) [*Kobayashi et al.*, 2014] and because the exact timing of microplate detachment remains ambiguous. In addition to the angular rotation calculations, the reconstructions incorporate constraints from: (1) seafloor magnetic anomaly data [*van Andel et al.*, 1971; *Hey*, 1977; *Lonsdale and Klitgord*, 1978; *Lowrie et al.*, 1979; *Lonsdale and Fornari*, 1980; *Hardy*, 1991; *Wilson and Hey*, 1995; *Wilson*, 1996; *Barckhausen et al.*, 2001; *Lonsdale*, 2005], (2) dating of seafloor crust [*Hoernle et al.*, 2002; *Lonsdale*, 2005], and (3) the distribution of bathymetric features [*Hey*, 1977; *Lonsdale and Klitgord*, 1978]. The Cocos Ridge is defined here as the crust of the Cocos Plate between the Quepos Plateau and the Panama Fracture Zone, while the seamount domain is defined by the region between the rough-smooth boundary and the Quepos Plateau (Figure 1).

The models presented here differ from previous plate reconstruction studies [i.e., *Gardner et al.*, 1992; *McIntosh et al.*, 1993; *Meschede and Barckhausen*, 2000, 2001; *Barckhausen et al.*, 2001; *Werner et al.*, 1999, 2003; *MacMillan et al.*, 2004; *Boschman et al.*, 2014] in a number of ways. First, they incorporate new interpretations of the magnetic anomalies on the Nazca plate by *Lonsdale* [2005] that provide important additional constraints on the late Miocene history that were unavailable in previous studies [e.g., *MacMillan et al.*, 2004]. Second, the calculations were performed using the MORVEL global plate model [*Argus et al.*, 2011; *DeMets et al.*, 2010], rather than the NUVEL-1A model [*DeMets et al.*, 1990, 1994] used in past publications [e.g., *MacMillan et al.*, 2004], resulting in plate rates that are slower overall. Finally, because this paper focuses on the effects of lower plate dynamics on the subduction zone system, the results emphasize the timing of subduction of the rough-smooth boundary, the Cocos Ridge, and the Panama Triple Junction relative to present-day geographic landmarks.

4. Results From Plate Reconstructions

The reconstructions depict a complex plate tectonic history (Figures 5 and 6), which I describe below via a sequence of times series, starting with 1 Ma and working backward in time to 10 Ma. In each time step, I describe the location of lower plate features at the trench, from northwest to southeast, that are important to regional tectonics.

4.1. 1 Ma

There are three notable differences in the plate reconstructions at 1 Ma compared to today. The 150 km long region experiencing rough crust subduction (seamount domain) is ~25 km farther to the southeast, the Cocos Ridge is subducting over a shorter distance along strike (~80 km at 1 Ma versus ~120 km at 0 Ma), and the Panama Triple Junction is located approximately 40 km to the northwest of its current location (Figure 5).

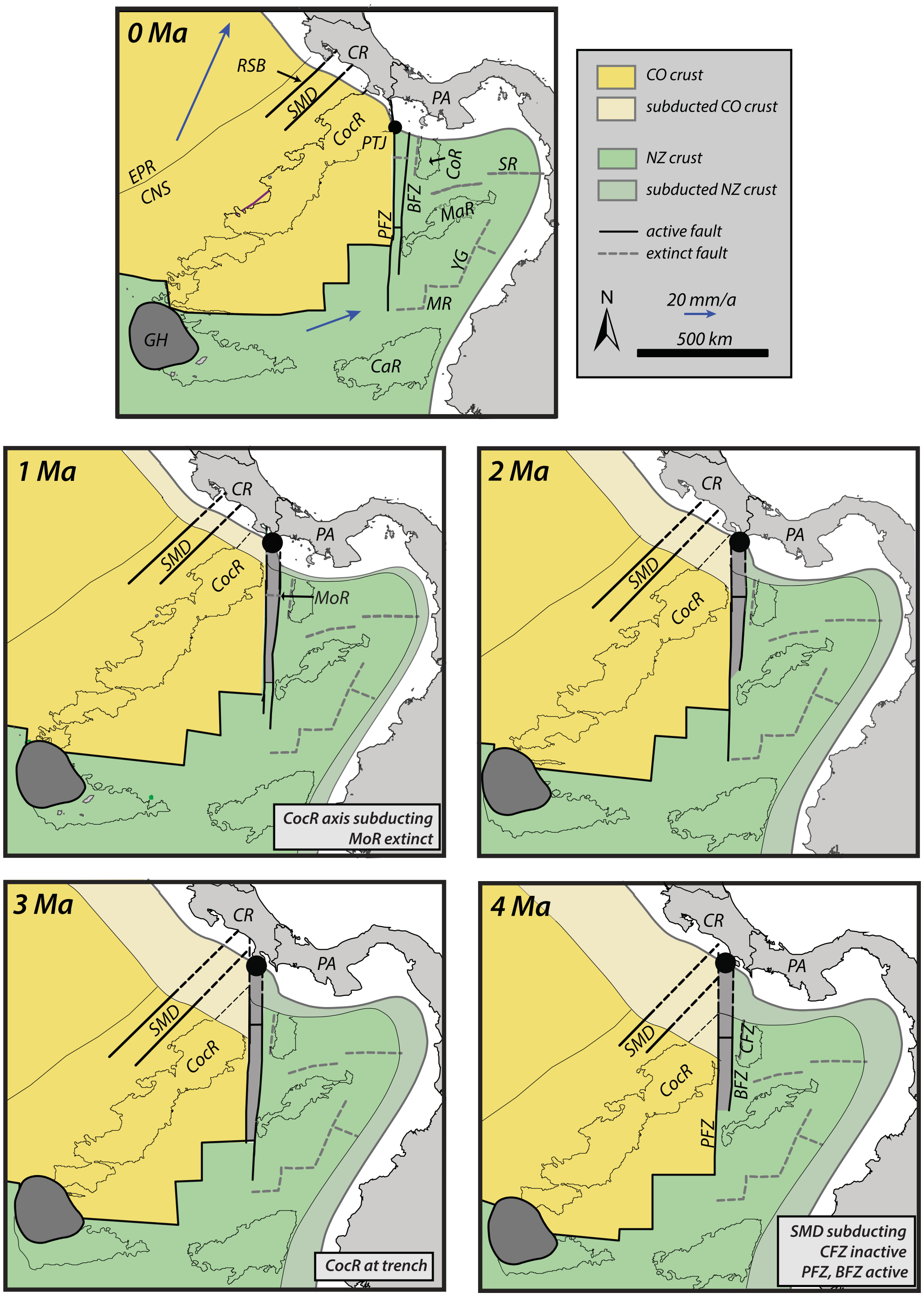


Figure 5. Plate reconstruction models for the Cocos (CO) and Nazca (NZ) plates relative to the Caribbean plate from 4 Ma to recent. BFZ, Balboa Fracture Zone; CaR, Carnegie Ridge; CFZ, Coiba Fracture Zone; CNS, crust derived from the Cocos-Nazca spreading center; CocR, Cocos Ridge; CoR, Coiba Ridge; CR, Costa Rica; EPR, crust derived from the East Pacific Rise; GH, Galápagos hot spot; MaR, Malpelo Ridge; MoR, Morgan Rift; MR, Malpelo Rift; PA, Panama; PFZ, Panama Fracture Zone; PTJ, Panama Triple Junction; RSB, rough-smooth boundary; SMD, seamount domain; SR, Sandra Ridge; YG, Yaquina Graben.

4.2. 2 Ma

By 2 Ma, the subduction of rough crust is restricted to south-central Costa Rica and the rough-smooth boundary subducts >50 km to the southeast of its present location (Figure 5). Cocos Ridge subduction is

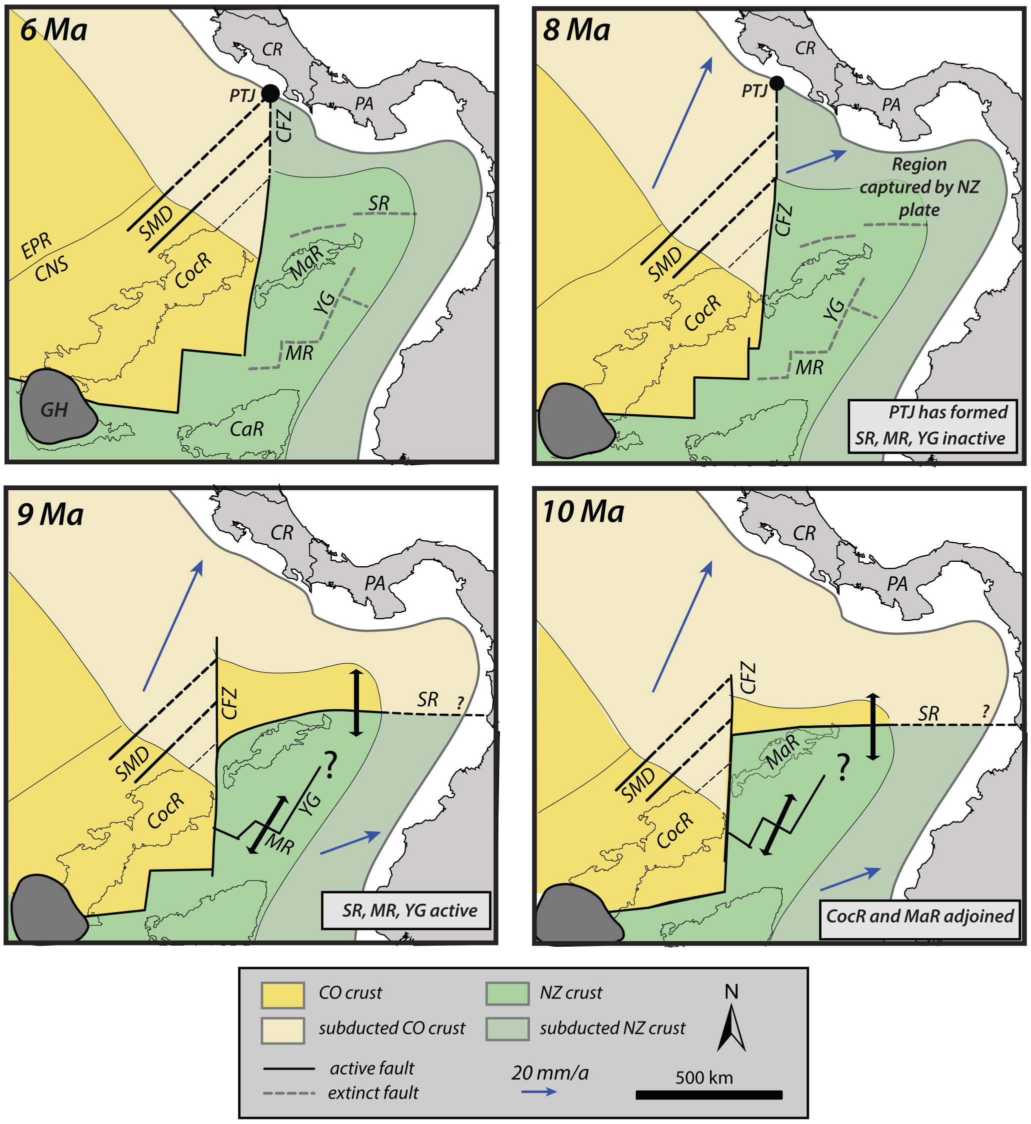


Figure 6. Plate reconstruction models for the Cocos and Nazca plates relative to the Caribbean plate from 6 to 10 Ma. CaR, Carnegie Ridge; CFZ, Coiba Fracture Zone; CNS, crust derived from the Cocos-Nazca spreading center; CocR, Cocos Ridge; CR, Costa Rica; EPR, crust derived from the East Pacific Rise; GH, Galápagos hot spot; MaR, Malpelo Ridge; MR, Malpelo Rift; PA, Panama; PFZ, Panama Fracture Zone; PTJ, Panama Triple Junction; SMD, seamount domain, SR, Sandra Ridge; YG, Yaquina Graben.

restricted to an 80 km width of southern Costa Rica. At this time, the Panama Triple Junction is located northwest of the Burica Peninsula, spreading is occurring on the Morgan Rift, and both the Panama and Balboa Fracture Zones are assumed to be active.

4.3. 3–4 Ma

At 3 Ma, the rough-smooth boundary is located offshore central Costa Rica and rough crust subduction extends for 100 km offshore southern Costa Rica (Figure 5). The Cocos Ridge has just arrived at the trench but has not yet subducted, and the Panama Triple Junction is located ~150 km to the northwest of its present location. By 4 Ma, the width of rough crust subduction is reduced to less than 50 km along strike in southern Costa Rica, the Panama Triple Junction is located to the northwest of the Osa Peninsula, and the Morgan Rift continues to spread.

4.4. 6–8 Ma

At 6 Ma, the subduction zone is dominated by smooth crust subduction, as rough crust subduction has just begun at a location offshore central Costa Rica (Figure 6). By this time, the Morgan Rift has not yet opened and the Panama Fracture Zone has not yet formed. By 8 Ma, the Panama Triple Junction is located offshore north-central Costa Rica, >300 km northwest of its present location.

4.5. 9–10 Ma

At 9 Ma, the Sandra and Malpelo Rifts are actively spreading and both spreading centers are adjoined with the Cocos-Nazca spreading center (Figure 6). The region north of the Sandra Rift is part of the Cocos plate and the length of the subduction zone from northern Costa Rica to Panama experiences near-orthogonal subduction. At 10 Ma, the Malpelo and Cocos Ridges are almost completely aligned. There could have been a small microplate in between the spreading Malpelo and Sandra Rift from 14 to 9 Ma but the history of this microplate, if it existed, remains unclear without additional age constraints or seafloor mapping.

4.6. Interpretations and Assumptions Inherent in Plate Reconstructions

In addition to the paleogeographic calculations, several important interpretations were necessary in the construction of the plate reconstructions, including the late Miocene capture of the Cocos plate by the Nazca plate, the timing of slip along the Panama, Balboa, and Coiba Fracture Zones, and the origin of the Coiba Ridge. Below, I provide a justification for each of these interpretations.

4.6.1. Nazca Plate Captures Part of the Cocos Plate in the Late Miocene

The reconstructions support the hypothesis that the Sandra Rift (SR, Figures 1 and 3) was connected to the Cocos-Nazca spreading center in the mid-Miocene, and therefore, the northeastern portion of the Panama basin was once part of the Cocos plate (Figures 5 and 6). This interpretation is based on several lines of reasoning. First, the youngest crust adjacent to the Sandra and Malpelo Rifts is ~9 Ma in age (Figure 3), an observation that implies that both were actively spreading until ~8.5 Ma. Second, the reconstructions show that the Sandra Rift was both similarly oriented and adjacent to the Cocos-Nazca spreading center in the late Miocene (Figure 6). Finally, using the distance between magnetic anomalies as a proxy for spreading rate (Figure 3), late Miocene rates of spreading on the Sandra Rift are nearly identical to rates of Cocos-Nazca spreading during the same time period (~30 mm/a half spreading rate). All of these observations are best explained by the hypothesis, supported by both *Lonsdale* [2005] and *Pindell and Kennan* [2009], that the northeastern portion of the Panama basin was captured by the Nazca plate in the late Miocene by lengthening of the Coiba Fracture Zone when the Sandra Rift ceased spreading at ~8.5 Ma.

4.6.2. Evolution of the Panama, Balboa, and Coiba Fracture Zones

An outstanding ambiguity involves the past activity of the Panama, Balboa, and Coiba Fracture Zones (PFZ, BFZ, CFZ, Figure 1). The timing and activation of these three transform faults are poorly constrained given existing data, but an interpretation of their activity is imperative for any viable reconstruction. Here I use the observation that there is no offset portion of the Cocos Ridge evident between these transforms (Figure 1) to imply that the crust between them was created by the Morgan Rift (MoR, Figures 1 and 3) and an along-strike equivalent. Given the age of the magnetic anomalies that parallel the Morgan Rift (Figure 3) [*Lowrie et al*., 1979], I assume that both the Panama and Balboa Fracture Zones were active from 5 to 2 Ma during the time of spreading of the Morgan Rift, and that prior to 5 Ma all plate boundary slip occurred on the Coiba Fracture Zone. Although this interpretation is not unique, any interpretation regarding the activity of these three fracture zones has no bearing on the timing of Cocos Ridge subduction because there are no remnants of the Cocos Ridge visible between these structures. Any interpretation does, however, impart ambiguity on the location of the Panama Triple Junction by 25–50 km.

4.6.3. Origin of the Malpelo and Coiba Ridges

There is strong evidence to suggest that the Malpelo and Cocos Ridges (Figures 1 and 3) are traces of the Galápagos hot spot that were adjoined in the late Miocene [e.g., *Lonsdale and Klitgord*, 1978; *Gardner et al*., 1992; *Lonsdale*, 2005]. The Malpelo and Cocos Ridge share a similar northeast trend [*Hey*, 1977], they have similar graben structures on their ridge crests [*Lonsdale and Klitgord*, 1978], and they have comparable bathymetry [*Lonsdale and Fornari*, 1980] and crustal thickness (Figure 1) [*Sallarès et al*., 2003, 2005]. Perhaps even more convincingly, the plate reconstructions (Figure 6), and a ^{40}Ar/^{39}Ar date of ~15–17 Ma [*Hoernle et al*., 2002] of the Malpelo Ridge, are consistent with a continuous Malpelo-Cocos Ridge at ~10 Ma that originated at the Galápagos hot spot (GHS, Figure 3) [*Lonsdale*, 2005].

While the origin of the Malpelo Ridge is reasonably well-constrained, the source of the Coiba Ridge (CoR, Figures 1 and 3) remains much less clear. Unambiguous magnetic anomalies are not visible on the Coiba Ridge [*Lonsdale*, 2005], so the only age constraints derive from sediments sampled above the ridge that are ~15 Ma old [*Lonsdale*, 2005]. Several authors use geochemical signatures to suggest that the Coiba Ridge could be Galápagos-hot-spot-related and may have once been connected to either the Malpelo or Carnegie Ridges before becoming rifted apart [*Meschede and Barckhausen*, 2001; *Werner et al*., 2003]. Here I take the approach of *Lonsdale* [2005] and suggest that the Coiba Plateau was produced by tectonic tilting, rather than by an interaction with the Galápagos hot spot. I make this interpretation for several reasons. One, neither of the proposed rifting hypotheses are easily compatible with the compelling evidence for the Miocene connection of the Malpelo and Cocos Ridges. In particular, the Malpelo Ridge roughly equals the width of the Cocos Ridge and does not appear to be broken apart. Two, as pointed out by *Lonsdale* [2005], the margins of the three ridges in question do not appear rifted.

If the Coiba Ridge was produced by tectonic tilting, a corollary question relates to how tilting was produced. Given that the Coiba Plateau dips to the northeast, the Coiba Plateau could have been produced by a component of dip-slip motion along the now-extinct Coiba Fracture Zone, which clearly cuts across the plateau's western margin (CFZ, Figures 1 and 3). Overall, the origin of the Coiba Ridge remains poorly constrained, but this issue could be easily resolved by testing for similarities in crustal thickness to the Malpelo, Carnegie, and Cocos Ridges, as all three exhibit crust that is $>$20 km thick due to passage over the hot spot (Figure 1, A-A′) [*Sallarès et al*., 2003; *Walther*, 2003].

5. Implications for Central American Tectonics

The reconstructions illustrate a dynamic tectonic history that includes: (1) Cocos Ridge subduction at $\sim$2–3 Ma; (2) the initiation of seamount and rough crust subduction starting at $\sim$3–4 Ma; and (3) the capture of the Cocos plate together with the development of the Panama Triple Junction at $\sim$8.5 Ma (Figures 5 and 6). In addition to these timing constraints, the reconstructions illustrate how lower plate features have migrated laterally with respect to the edge of the Caribbean plate. For instance, the Cocos Ridge first began subducting offshore the southern Osa Peninsula (OP, Figures 1, 5, and 7), but its influence has since expanded both to the northwest and to the southeast. The rough-smooth boundary (RSB, Figure 1) initially entered the trench offshore southern Costa Rica, but this boundary subsequently migrated to the northwest to its present location. And finally, the Panama Fracture Zone sequence has migrated more than 300 km to the southeast along the trench at a rate of approximately 30–40 mm/a since the late Miocene. Given the well-documented links between lower plate properties and upper plate geology [e.g., *Sak et al*., 2009] (Table 1), these constraints on the timing and lateral migration of subducting features have several implications for the geologic, geodynamic, and volcanic history of this system, many of which are corroborated by independent data sets (Figure 7).

5.1. Cocos Ridge Subduction

Cocos Ridge subduction has significantly impacted the geologic evolution of the upper plate (Table 1), leading to: (1) trench embayment and increased sedimentation in the outermost fore arc [*Sak et al*., 2009; *Gardner et al*., 2013; *Vannucchi et al*., 2013]; (2) the emergence of both the Burica and Osa outer fore-arc peninsulas (BP, OP, Figure 1) [*Corrigan et al*., 1990; *Morell et al*., 2011; *Sak et al*., 2004; *Gardner et al*., 2013]; (3) increased shortening, and contraction related to the development of the Fila Costeña Thrust belt [*Fisher et al*., 2004; *Sitchler et al*., 2007]; (4) exhumation of the Cordillera de Talamanca (Figure 1) [*Gräfe et al*., 2002; *Morell et al*., 2012]; and finally (5) the development of a back arc thrust belt [Limón Thrust Belt, LTB, Figure 1; *Goes et al*., 1993; *Collins et al*., 1995]. Despite its widespread influence, the timing of Cocos Ridge subduction remains one of the most debated issues in Central American tectonics, with estimates ranging in the literature from as old as $\sim$8 Ma [e.g., *Abratis and Wörner*, 2001; *Gazel et al*., 2009] to as young as $\sim$0.5 Ma [e.g., *Gardner et al*., 1992]. The new reconstructions show that the Cocos Ridge (defined here by the region from the Quepos Plateau to the Panama Fracture Zone) began subducting no earlier than $\sim$2.5 Ma at a location offshore of the Osa Peninsula, and thereafter expanded laterally both to the northwest and to the southeast relative to the trench until the Cocos Ridge axis began to subduct at $\sim$1–2 Ma (Figure 5). Due to the wide-ranging effects of Cocos Ridge subduction (Table 1), these new results constrain the geologic history of the upper plate inboard of Cocos Ridge subduction in a number of ways.

First, Plio-Quaternary Cocos Ridge subduction agrees with the hypothesis that Cocos Ridge subduction led to embayment of the trench axis, subduction erosion, and increased sedimentation rates in the outermost fore arc since $\sim$2.5 Ma [*Sak et al*., 2009; *Gardner et al*., 2013; *Vannucchi et al*., 2013]. Pleistocene sedimentation rates calculated from core recovered by IODP drilling are as high as 1035 m/m yr within the region

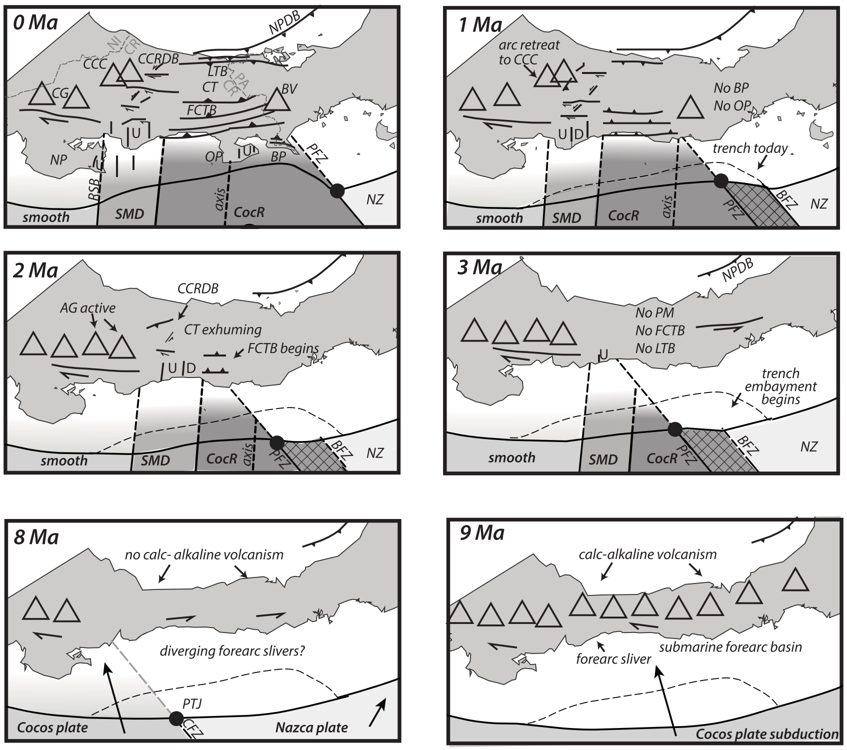


Figure 7. Cartoon showing relationship between lower plate evolution (Figures 5 and 6) and upper plate deformation and volcanism. Upper plate faults are simplified. "Axis" refers to the -2000 m contour of the Cocos Ridge. AG, Cordillera de Aguacate; BP, Burica Peninsula; BFZ, Balboa Fracture Zone; BV, Barú Volcano; CCC, Cordillera Central of Costa Rica; CCRDB, Central Costa Rica Deformed Belt; CFZ, Coiba Fracture Zone; CG, Cordillera de Guanacaste; CocR, Cocos Ridge; CR, Costa Rica; CT, Cordillera de Talamanca; FCTB, Fila Costeña Thrust Belt; LTB, Limón Thrust Belt; NI, Nicaragua; NP, Nicoya Peninsula; NPDB, North Panama Deformed Belt; NZ, Nazca plate; OP, Osa Peninsula; PA, Panama; PFZ, Panama Fracture Zone; PM, Panama microplate; PTJ, Panama Triple Junction; RSB, rough-smooth boundary; SMD, seamount domain; U and D refer to up and down motion of tectonic blocks. Vectors on lower plate show Cocos-Caribbean and Nazca-Caribbean relative motion.

directly inboard of the Cocos Ridge axis [*Vannucchi et al*., 2013]. Second, there is strong evidence to suggest that the rock uplift, deformation, and emergence of both the Osa and Burica Peninsulas (OP, BP, Figure 1) were produced by subduction of the crest of the Cocos Ridge and the short-wavelength bathymetry across it [*Corrigan et al*., 1990; *Gardner et al*., 1992; *Sak et al*., 2009; *Gardner et al*., 2013; *Morell et al*., 2011]. If so, the reconstructions predict that neither peninsula was emergent until at least 1 Ma, when the axis of the Cocos Ridge reached the trench (Figures 5 and 7). This timing is consistent with geomorphic, stratigraphic, and deformation data sets from both peninsulas, where late Quaternary marine deposits, now tens of meters above sea level, restrict emergence of these peninsulas to <1 Ma [*Corrigan et al*., 1990; *Sak et al*., 2009; *Gardner et al*., 2013; *Morell et al*., 2011].

Third, it is well established that Cocos Ridge subduction drives the growth of the Fila Costeña inner fore-arc thrust belt (FCTB, Figure 1), given the compelling relationship between the subducting Cocos Ridge and the distribution of topography, geologic units, coupling, and total shortening within the wedge [*Kolarsky et al*., 1995; *Fisher et al*., 2004; *Sitchler et al*., 2007; *Morell et al*., 2008, 2013; *Kobayashi et al*., 2014]. Based on these correlations, the evolution of Cocos Ridge subduction as shown in Figure 5 suggests that the Fila Costeña first developed in southern Costa Rica around 2.5 Ma, and has since grown laterally both to the northwest and to the southeast (Figure 7). Such an evolution is corroborated by a multitude of geologic and geomorphic evidence that confirms that not only is the Fila Costeña actively deforming today [*Sitchler et al*., 2007], but the thrusts of the Fila Costeña migrate laterally to the southeast with the Panama Fracture Zone and Panama Triple Junction (PFZ, PTJ, Figure 1), together with the eastern leading edge of the Cocos Ridge [*Morell et al*., 2008, 2013]. Pleistocene initiation of the Fila Costeña, as suggested by the reconstructions (Figures 5 and 7), also agrees with the observation of an unnamed Pliocene shallow-water mudstone capping sedimentary sequences within individual thrust stacks [*Kesel*, 1983]; this mudstone must have been deposited before imbrication began, and therefore constrains the initial development of the Fila Costeña to Pliocene or later [*Sitchler et al*., 2007].

Fourth, the evolution of Cocos Ridge subduction as shown in Figures 5 and 7 is supported by data from incisional histories in fluvial systems draining the Cordillera de Talamanca (CT, Figure 1), which argue for ~2 km of rock uplift and exhumation of the Cordillera de Talamanca within the past 1–3 Ma [*Gräfe et al*., 2002; *Morell et al*., 2012]. Exhumation of the Cordillera de Talamanca is most likely related to Cocos Ridge subduction, given that the heightened topography and range width of this mountain belt nearly exactly coincide with the present-day width of Cocos Ridge subduction (CT, Figure 1) [*Weyl*, 1980; *Kolarsky et al*., 1995]. Finally, the exhumation of the Cordillera de Talamanca is further linked to the back thrusts associated with the Limón back arc thrust belt, as they bound the Cordillera de Talamanca to its north and facilitate its exhumation (LTB, Figure 1) [*Fisher et al*., 2004]. Benthic foraminifera constrain the inversion of shallow-water back-arc basins by the Limón back arc thrust belt (Limón and Bocas del Toro basins) to 1.6 Ma [*Collins et al*., 1995], a timing that is consistent with the timing of Cocos Ridge subduction revealed by the reconstructions (Figures 5 and 7). *Collins et al*. [1995] suggest that this slightly younger timing (i.e., 1.6 Ma) for development of the Limón back arc thrust belt compared to older arrival times documented from the outer fore arc (i.e., ~2.5 Ma) [*Vannucchi et al*., 2013] could relate to the time required for the effects of Cocos Ridge subduction to reach the back arc.

In summary, the chronology of Cocos Ridge subduction provided by the reconstructions and the links between lower plate kinematics and upper plate geology suggest the following sequence of events: the Osa and Burica Peninsulas become emergent at 1 Ma, the Fila Costeña begins to develop at ~2.5 Ma and grows laterally starting from southern Costa Rica. The growth of the Fila Costeña at ~2.5 Ma also coincides with the uplift of the Cordillera de Talamanca and is followed by growth of the Limón back arc thrust belt (Figure 7). This sequence of tectonic events is corroborated by a large number of independent stratigraphic, structural, geomorphic, and exhumational constraints, all of which are consistent with the hypothesis that Cocos Ridge subduction began at a time no earlier than 2.5 Ma.

5.2. Cocos Ridge Subduction and Cessation of Calc-Alkaline Volcanism in the Cordillera de Talamanca

The only published data sets that do not agree with a Plio-Quaternary Cocos Ridge arrival relate to the hypothesis that the cessation of mantle-wedge-derived volcanism in the Cordillera de Talamanca was induced by Cocos Ridge subduction [e.g., *McGeary et al*., 1985; *de Boer et al*., 1995; *Kolarsky et al*., 1995]. Based on dating of range plutons and arc products, several authors suggest that late Miocene Cocos Ridge subduction is responsible for mantle wedge removal and the termination of calc-alkaline volcanism in the Cordillera de Talamanca at ~5–8 Ma [*de Boer et al*., 1995; *Abratis and Wörner*, 2001]. Given the wealth of data sets mentioned above that argue for Plio-Quaternary Cocos Ridge subduction, I suggest that the late Miocene shut-off of calc-alkaline volcanism in the Cordillera de Talamanca is unrelated to Cocos Ridge subduction and is instead linked to the plate tectonic reorganization of the Panama basin that also occurred at that time. There are several lines of evidence that support this idea.

First, late Miocene arc extinction is not restricted to the Cordillera de Talamanca (CT, Figure 1). Rather, the adjacent Cordillera Central of Panama likewise exhibits ~7–8 Ma plutons that core abandoned arc edifices (CCP, Figure 1) [*Wegner et al*., 2010]. While Quaternary adakitic volcanism is documented among a few isolated volcanoes in the Cordillera Central of Panama [*Hidalgo and Rooney*, 2010; *Hidalgo et al*., 2011; *Hidalgo and Rooney*, 2014], calc-alkaline products associated with this range are no younger than ~7–8 Ma [*Wegner et al*., 2010]. Therefore, calc-alkaline volcanism within both the Cordillera Central of Panama and the Cordillera de Talamanca went extinct at the same time during the late Miocene (CCP, CT, Figure 1). This coincidence in timing suggests that both ranges likely shut-off due to the same mechanism at the same time, yet Cocos Ridge subduction occurs too far west to explain the extinction of the Cordillera Central of Panama (Figure 1).

Second, the reconstructions suggest that the termination of calc-alkaline volcanism for both the Cordillera de Talamanca and the Cordillera Central of Panama are contemporaneous with cessation of spreading on the Sandra Rift (SR, Figure 6). The reconstructions show that as spreading ceased along the Sandra Rift at ~8.5 Ma, lengthening of the Coiba Fracture Zone created the Panama Triple Junction offshore northern Costa Rica, which captured the northeastern Panama basin as part of the Nazca plate. Therefore, around 8.5

Ma, ∼700 km of the subduction zone underwent a relatively abrupt change from near-orthogonal to highly oblique subduction. This relatively sudden increase in subduction obliquity could have significantly decreased the flux of water and volatiles responsible for partial melting of the mantle wedge, thereby effectively terminating calc-alkaline volcanism (Figure 7) [*Morell et al*., 2012]. If correct, this hypothesis suggests that the exhumation and current absence of volcanism in the Cordillera de Talamanca could be related to Cocos Ridge subduction [*Gräfe et al*., 2002], but the late Miocene cessation of calc-alkaline volcanism in the Cordillera de Talamanca was instead caused by the initiation of oblique Nazca plate subduction (Figure 7).

In short, the reconstructions agree with all of the existing evidence that suggests that Cocos Ridge subduction began no earlier than the late Pliocene and had a significant impact on a wide number of processes extending from the outermost fore arc to the back arc (Table 1 and Figure 7). The reconstructions also suggest that Cocos Ridge subduction was not responsible for the shut-off of calc-alkaline volcanism in the Cordillera de Talamanca [*Abratis and Wörner*, 2001]; the shut-off could instead be due to oblique Nazca plate subduction starting at ∼8.5 Ma.

5.3. Seamount and Rough Crust Subduction

The subduction of rough crust on the Cocos plate (seamount domain, SMD, Figure 1) is also shown to strongly impact upper plate deformation and volcanism in southern Central America (Table 1). Some of these effects include: (1) embayment of the trench axis and thinning of the margin wedge [*Ranero and von Huene*, 2000]; (2) an increase in fore-arc vertical tectonism [e.g., *Fisher et al*., 1998; *von Huene et al*., 2000]; (3) the detachment of the western margin of the Panama microplate (Central Costa Rica Deformed Belt, CCRDB) [*Marshall et al*., 2000]; and (4) a northward shift of the volcanic front [e.g., *Marshall et al*., 2003]. The reconstructions show that the seamount domain began to subduct around 3–4 Ma near south-central Costa Rica, and it then drifted northwestward relative to the trench until its present location (SMD, Figure 5). Because of the large number of processes controlled by seamount subduction (Table 1) [*Sak et al*., 2009], this timing has several consequences for the tectonic and volcanic evolution of southern Central America.

One, given the coincidence between trench embayment, thinning of the margin wedge, and the present location of the rough-smooth boundary (RSB, Figure 1) [*Ranero and von Huene*, 2000; *Ranero et al*., 2008; *Gardner et al*., 2013; *Vannucchi et al*., 2013], the reconstructions predict that trench embayment likely began at 3–4 Ma offshore south-central Costa Rica, and then expanded laterally to its modern extent (Figure 7). If so, there has been ∼50 km of trench embayment since the middle Pliocene. Two, the reconstructions suggest that the southeastern tip of the Nicoya Peninsula (NP, Figures 1 and 7) has only experienced seamount subduction since <1 Ma. This implication is supported by geomorphic and stratigraphic data that constrain the rapid vertical tectonics on the Nicoya Peninsula to less than ∼500 ka [*Hare and Gardner*, 1985; *Gardner et al*., 2001; *Marshall*, 2008; *Sak et al*., 2009]. Third, a number of seismic, geologic, and geomorphic data sets show that seamount subduction created the Central Costa Rica Deformed Belt (CCRDB, Figure 1), characterized by vertical faults that bound small (10 km) blocks in the fore arc, and diffuse deformation in the arc [*von Huene et al*., 1995; *Ranero and von Huene*, 2000; *von Huene et al*., 2000; *Ranero et al*., 2008; *Marshall et al*., 2000; *Sak et al*., 2009; *Montero et al*., 2013]. Given the evolution of seamount subduction depicted in Figure 5, the reconstructions imply that faults analogous to those in the present-day Central Costa Rica Deformed Belt could have first developed in the Pliocene and then expanded along-strike and across-strike as the influence of rough crust subduction continued to increase (Figure 7).

Finally, the timing of rough crust subduction shown in Figure 5 also has implications for the evolution of the volcanic arc. ^{40}Ar/^{39}Ar dating and geologic mapping suggest that the Cordillera de Aguacate (CAg, Figure 1) was active between ∼5 and 2 Ma [*Marshall et al*., 2003; *MacMillan et al*., 2004], but became inactive at approximately 1.5 Ma, when the arc shifted northward. The reconstructions corroborate the hypothesis posed by *Marshall et al*. [2003], who suggest that Neogene arc migration was induced by rough crust subduction; the reconstructions show that smooth crust was subducting offshore the Cordillera de Aguacate while it was active between 5 and 2 Ma, whereas rough crust subduction began at 1.5 Ma at the location of the Cordillera de Aguacate (Figures 5 and 7).

All of these analyses collectively suggest that rough crust subduction caused embayment of the trench axis, thinning of the margin wedge, a shift of the volcanic arc, and coeval development of the Central Costa Rica Deformed Belt (Figure 7). Each of these effects evolved in concert with the position of the subducting seamount domain along the trench, which began to subduct offshore southern Costa Rica at 3–4 Ma and then migrated to the northwest until reaching its present position (Figure 7).

5.4. Plio-Quaternary Detachment of the Panama Microplate

The results regarding the timing of subduction of Galápagos hot spot crust also place several constraints on the timing of detachment of the Panama microplate, which is bound to the west by the Central Costa Rica Deformed Belt, the north by the Limón Thrust Belt (LTB, Figure 1), and the northeast by the North Panama Deformed Belt offshore central Panama (Figure 1). The reconstructions suggest that the Central Costa Rica Deformed Belt became fully developed no earlier than ~2–3 Ma, while the uplift of back arc basins occurred between 1 and 2 Ma (Figure 7). Given published estimates on the development of the North Panama Deformed Belt ranging between ~10 and 25 Ma [*Silver et al*., 1990; *Coates et al*., 2003, 2004; *Pindell and Kennan*, 2009], the detachment of the Panama microplate must have occurred sometime between 1 and 3 Ma, as the Central Costa Rica Deformed Belt and the Limón back arc thrust belt connected the North Panama Deformed Belt to the Middle America Trench (Figure 7). This sequence of events agrees with observations of an east-west decrease in the amount of accretion in the North Panama Deformed Belt [*Silver et al*., 1990]. Because the Central Costa Rica Deformed Belt and Limón belt were created by the combined effects of seamount and Cocos Ridge subduction, the detachment of the Panama microplate from the Caribbean plate therefore occurred primarily due to the Plio-Pleistocene subduction of crust generated at the Galápagos hot spot (Figure 7).

5.5. Tectonic Reorganization at 10 Ma and Development of the Panama Triple Junction

One of the most significant events revealed by the reconstructions is the tectonic reorganization that led to the development of the Panama Triple Junction in the late Miocene (Figures 6 and 7). Given the ~9 Ma magnetic anomalies currently adjacent to the now-extinct Sandra Ridge (Figure 3) [*Lonsdale*, 2005], the development of the Panama Triple Junction occurred no earlier than ~8.5 Ma. This tectonic rearrangement was more than 15 Ma later than the breakup of the Farallon plates into the Cocos and Nazca plates at ~27 Ma [*Lonsdale and Klitgord*, 1978; *Barckhausen et al*., 2001].

The reconstructions show that prior to ~8.5 Ma, near-orthogonal smooth Cocos plate subduction was occurring from north-central Costa Rica to eastern Panama, at a time when calc-alkaline volcanism was occurring across much of southern Central America (Figures 6 and 7) [*de Boer et al*., 1995]. While not well-constrained, several observations suggest that this Miocene tectonic configuration could have also resulted in dextral fore-arc sliver transport within the upper plate. Facies depths associated with fore arc (Térraba) and back arc (Limón and Bocas de toro Basins) basins suggest that a large majority of the isthmus was submarine and therefore probably not undergoing rapid rock uplift [*Phillips*, 1983; *Collins et al*., 1995]. Moreover, sliver transport is observed in analogous regions today, such as northern Costa Rica, which is currently experiencing near-normal, smooth Cocos plate subduction [*Kobayashi et al*., 2014]. Therefore, prior to the initiation of the Panama Triple Junction in the late Miocene, the Central American subduction zone was experiencing pervasive calc-alkaline volcanism and perhaps could have also been undergoing right-lateral fore-arc sliver transport (Figure 7).

After shut-off of the Sandra Ridge at ~8.5 Ma, the northeastern Panama Basin was captured by the Nazca plate and the Panama Triple Junction initiated offshore northern Costa Rica (Figure 7). Therefore, a ~700 km length of the subduction zone suddenly began to experience oblique subduction (Figures 6 and 7). Based on this hypothesis, the marked decrease in convergence rate (~50%) that accompanied this tectonic reconfiguration is likely responsible for the shut-off of calc-alkaline volcanism of the Cordillera de Talamanca and Cordillera Central of Panama, by causing a decrease in the flux of water and/or volatiles required to produce mantle-wedge volcanism [*Morell et al*., 2012].

In addition to this impact on volcanism, this tectonic change likely had other implications for the geologic evolution of the region. For instance, both the outer fore arc (Azuero Peninsula) and arc (central Panama canal zone) exhibit active sinistral faulting inboard of oblique Nazca plate subduction in Panama (Figure 1) [*Rockwell et al*., 2010a, 2010b]. Left-lateral faulting in Panama could be a consequence of either the obliquity of subduction (Figures 1 and 4), bending of the isthmus due to collision with South America [*Kolarsky and Mann*, 1995; *Mann and Kolarsky*, 1995], or escape away from Cocos Ridge collision [*Kobayashi et al*., 2014]. If either of the former two hypotheses are correct, then the late Miocene Panama Triple Junction could have separated diverging fore-arc slivers, with right-lateral sliver transport inboard of Cocos plate subduction, and left-lateral motion inboard of oblique Nazca plate subduction (Figure 7). While this hypothesis remains conjectural, a similar style of deformation is observed in the northern Andes, 400 km south of the Carnegie Ridge, where an along-strike change in the sense of subduction obliquity produces adjacent fore-arc slivers with opposing senses of motion [*Nocquet et al*., 2014].

The reconstructions also constrain the location of the Panama Triple Junction at its initiation to a position offshore the southeastern tip of the Nicoya Peninsula (Figures 6 and 7). This location implies that the uplift of the majority of the Nicoya peninsula, excluding the southeasternmost tip, was apparently not created by the same mechanisms responsible for the Osa and Burica Peninsulas (OP, BP, Figure 1), both of which were uplifted by the combined effects of Cocos Ridge subduction and Panama Triple Junction migration [*Corrigan et al*., 1990; *Gardner et al*., 1992]. The Miocene capture of the northeastern portion of the Cocos plate by the Nazca plate should have also influenced the northern South American subduction zone, such that the 200 km long portion of the subduction zone north of the Sandra Ridge underwent a period of highly oblique subduction in the Miocene. This result implies that near-orthogonal subduction was not continuous from Miocene to recent in northernmost South America, which could have affected magmatic activity and/or the geochemistry of arc products associated with the northern Colombian volcanic arc.

This Neogene plate tectonic rearrangement also coincides with a proposed ~15° rotation in the Caribbean plate's azimuth of motion relative to the North and South American plates [*Pindell et al*., 1998]. *Pindell and Kennan* [2009] postulate that this rotation could be coeval with a reorganization of active fault networks in Hispañola, Trinidad, Venezuela and other parts of the Caribbean. Thus, in addition to its effects on tectonics and volcanism in southern Central America, the late Miocene tectonic event that created the Panama Triple Junction could be part of a regional tectonic phenomenon that affected the greater Caribbean and South American regions.

6. Implications for the Geometry of the Cocos and Nazca Slabs

In addition to informing the tectonic and volcanic evolution of southern Central America, the reconstructions also provide constraints on the present-day geometry of the subducting Cocos and Nazca plates.

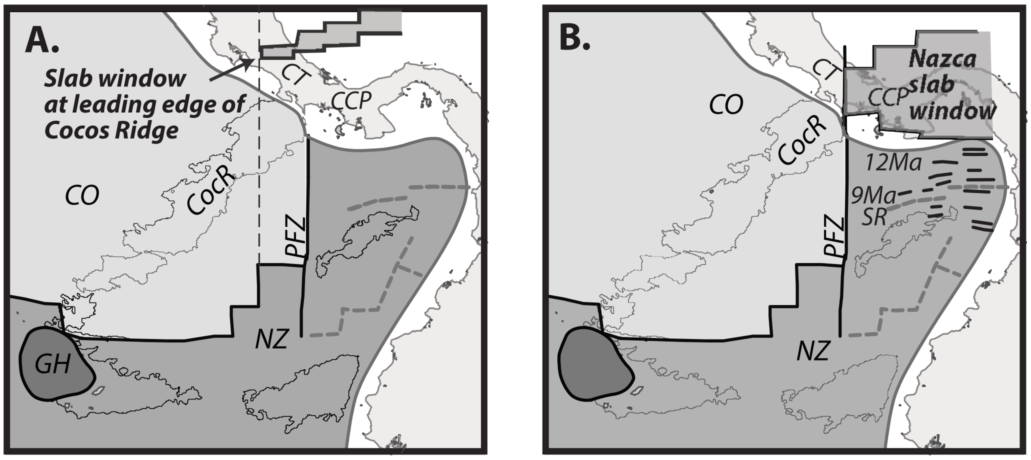
6.1. Cocos Slab Geometry

The southeastward increase in the crustal thickness of the Cocos plate roughly correlates with decreases in dip of the Cocos slab. The Wadati-Benioff zone progressively shallows from $>60°$ for the northwestern portion of the Cocos plate [*Güendel et al*., 1989; *Protti et al*., 1995; *Ranero and von Huene*, 2000; *Syracuse et al*., 2008] to near-horizontal along the axis of the Cocos Ridge (Figure 2) [*Protti et al*., 1994, 1995; *Husen et al*., 2003; *Linkimer et al*., 2010]. Although this pattern of along-strike shallowing is well-established within ~100 km of the trench, the downdip slab geometry remains poorly constrained for the region surrounding the Cocos Ridge. Receiver function and tomographic analyses along a transect inboard of the northwest flank of the Cocos Ridge suggest that the slab remains relatively shallow for ~75 km from the trench, but potentially steepens sharply to 80° below a depth of ~50 km (Figure 2b) [*Dinc et al*., 2010; *Dzierma et al*., 2010, 2011].

While the geometry of the slab downdip of the Cocos Ridge remains poorly constrained without more geophysical data, the reconstructions show that Cocos Ridge subduction began no earlier than 2–3 Ma, while the axis of the ridge subducted later, between 1 and 2 Ma (Figures 5 and 7). The complex three-dimensionality of the slab and the lack of dense geophysical data make it difficult to accurately predict slab geometry with increasing depth, but the transition from shallow to steep subduction evident in the geophysical images (Figure 2b) could represent the northwest-leading edge of a Cocos Ridge that has only recently subducted, with the steeper section representing the dip of the Cocos plate prior to Cocos Ridge subduction [*Dzierma et al*., 2011]. Several authors have also used the presence of young adakitic arc products (<10 Ma) to argue for a slab window at the leading edge of the Cocos Ridge, created by slab break-off (Figure 8a) [*Abratis*, 1998; *Abratis and Wörner*, 2001; *Gazel et al*., 2011]. Because of its location (Figure 2a), the *Dzierma et al*. [2011] transect unfortunately does not address the geometry of the Cocos slab directly downdip of the Cocos Ridge.

6.2. Nazca Slab Geometry

The geometry of the Nazca plate beneath Panama is poorly defined and debate remains over whether there is a subducting slab in this region. Unlike Cocos plate subduction to its west, the subducting Nazca plate



Abratis and Wörner, 2001

Johnston and Thorkelson, 1997

Figure 8. Proposed models for a present-day slab window beneath Central America based on (a) *Abratis and Wörner* [2001] and (b) *Johnston and Thorkelson* [1997]. Black lines on Nazca plate (NZ) show magnetic anomalies from *Lonsdale* [2005] with ages labeled. CCP, Cordillera Central of Panama; CT, Cordillera de Talamanca; GH, Galápagos hot spot; SR, Sandra Rift; CO, Cocos plate; CocR, Cocos Ridge; NZ, Nazca plate; PFZ, Panama Fracture Zone. Gray dashed lines indicate inactive structures on the Nazca plate. Area shown in each plot is the same area as in Figures 5 and 6.

does not show a well-defined Wadati-Benioff zone and instead exhibits remarkably little seismicity [*Adamek et al.*, 1988]. This lack of seismicity, along with evidence for young adakitic volcanics [*Defant et al.*, 1991; *de Boer et al.*, 1991; *Defant et al.*, 1992; *Leeman and Carr*, 1995], is used as evidence for a slab window beneath Panama (Figure 8b) [*Johnston and Thorkelson*, 1997]. Tomographic images support this view, in that they show an absence of a positive seismic velocity anomaly in the crust and upper mantle to 700 km depth beneath Panama [*van Benthem et al.*, 2013]. *Johnston and Thorkelson* [1997] suggest that this subduction window was produced by subduction of an ancient spreading ridge once connected to the Panama Fracture Zone (Figure 8b).

Despite the evidence for a slab window, others have argued for an actively subducting slab beneath western Panama. A deforming offshore accretionary prism spanning ∼150 km to the east of the Panama Fracture Zone is interpreted to reflect oblique convergence [*Heil*, 1988; *MacKay and Moore*, 1990; *Moore and Sender*, 1995] and some argue that isolated centers of active adakitic arc volcanism across Panama could be related to a downgoing Nazca slab [*de Boer et al.*, 1988, 1991; *Defant et al.*, 1992]. While not directly imaged, if there is a subducting Nazca slab in this region, it is most likely more steeply dipping than the shallowly subducting Cocos plate to its west (Figure 2). If so, this configuration could result in a slab tear between the Cocos and Nazca plates [*Morell et al.*, 2013].

While a slab window produced by the subduction of a spreading ridge beneath Panama cannot be unequivocally ruled out without more geophysical data, several observations argue against this model. First, there are no northward-younging magnetic anomalies imaged on the Nazca plate offshore Panama as would be expected if a spreading ridge had recently subducted (Figures 3 and 8b). Second, the slab window hypothesis of *Johnston and Thorkelson* [1997] requires a window within the Nazca plate only (Figure 8b), yet similar-aged Quaternary adakites in the Cordillera de Talamanca (CT, Figure 8b) [*Abratis and Wörner*, 2001] demonstrate that adakitic volcanism is not restricted to the arc above the Nazca plate (Cordillera Central of Panama, CCP, Figure 8b) but also extends to the region above the Cocos plate. Clearly more geophysical analyses are needed to address the geodynamics of the Nazca plate beneath Panama, with a model that explains: (1) the lack of seismicity in Panama, (2) the absence of a positive seismic anomaly for 700 km depth, and (3) the cause of adakitic volcanism from ∼10 Ma to recent in both the Cordillera de Talamanca and Cordillera Central of Panama.

7. Conclusions

New plate reconstructions constrain several Neogene tectonic events that affected the southern Central American convergent margin. The reconstructions show that Cocos Ridge subduction occurred from ∼2 to

3 Ma to recent, beginning in southern Costa Rica and then expanding laterally relative to the Caribbean plate. This event caused trench retreat, emergence of the Burica and Osa outer fore-arc peninsulas, growth of the Fila Costeña inner fore-arc thrust belt, uplift and exhumation of the Cordillera de Talamanca, and inversion of the Limón and Bocas del Toro back arc basins. The plate reconstructions also show that subduction of rough crust within the seamount domain began at ∼3–4 Ma and migrated to the northwest with respect to the trench. This chronology resulted in: (1) further embayment of the trench axis; (2) a diffuse zone of deformation from the fore arc to arc (Central Costa Rica Deformed Belt); and (3) a northward shift of the active volcanic arc. The final detachment of the Panama microplate from the Caribbean plate occurred between 1 and 3 Ma, when the Central Costa Rica Deformed Belt and Limón Thrust Belt connected with the North Panama Deformed Belt.

One of the most significant events revealed by the reconstructions is the tectonic reorganization that led to the development of the Panama Triple Junction in the late Miocene (∼8.5 Ma). This event was coeval with: (1) cessation of spreading on the Sandra Rift; (2) lengthening of the Coiba Fracture Zone; (3) capture of the northeastern Panama basin by the Nazca plate; and (4) initiation of oblique subduction along the northeast portion of the Nazca plate. This reconfiguration caused the cessation of mantle-wedge-derived volcanism within the Cordillera de Talamanca and Cordillera Central of Panama. The timing of this rearrangement is well-constrained by the youngest magnetic anomalies adjacent to the Sandra Ridge that are ∼9 Ma in age.

Acknowledgments
Thanks to Donald Fisher and Thomas Gardner for introducing me to Central America. Thanks also to Eduardo Camacho, Eric Chichaco, Eric Kirby, Pete LaFemina, Marino Protti, and Jeff Marshall for discussions about Central American tectonics. Paul Mann, Lucinda Leonard, and an anonymous reviewer provided helpful comments that improved the paper. The NSF Tectonics program and the Alfred P. Sloan Foundation are acknowledged for past funding in this area. All data used in this paper are available upon request to the author.

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