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Inner forearc response to subduction of the Panama Fracture Zone, southern Central America

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Abstract

Subduction of the right-lateral Panama Fracture Zone, along the convergent margin of Central America creates abrupt lateral variations in convergence rate, obliquity, and subducting crustal thickness at its intersection with the Middle America Trench. This intersection, known as the Panama (CO-NZ-CA) Triple Junction, is migrating to the southeast at a rate of 55 mm/yr, and currently coincides with the lateral termination of the Fila Costeña Thrust Belt in the inner forearc of the overriding plate. Mapping in the inner forearc in the area that straddles the subducting Panama Fracture Zone reveals that Cocos–Caribbean convergence west of the triple junction leads to the development of an inner forearc thrust belt inboard of the colliding Cocos Ridge, while little deformation is evident inboard of Nazca–Caribbean convergence, east of the triple junction. This results in the lateral termination of the Fila Costeña Thrust Belt in the region of the forearc that projects over the Panama Fracture Zone, where four out of five mapped thrust faults tip out and are buried by lahars. Three new balanced cross-sections indicate a steep gradient in shortening from the center of the thrust belt to its southeastern termination. The short-term history of the inner forearc recorded in the landscape and topography of the Fila Costeña is consistent with the southeastward migration of the thrust belt and the Panama Triple Junction throughout the past ~3 Ma, with evidence for the growth of a new topographic divide and reorganization of stream channel networks.

Keywords: Costa Rica; Panama; Panama Triple Junction; Fila Costeña Thrust Belt; Terraba Basin; Brito Formation; Terraba Formation; crustal shortening; thrust belt; Cocos Ridge; Baru volcano; Cocos Plate; Cocos Ridge; Nazca Plate; Panama Block; forearc basins; deformation; faults; active faulting; uplift; fold and thrust belts; Panama Fracture Zone; Talamanca Range; thrust faults; river morphology; basin asymmetry; triple junction migration; CO-NZ-CA Triple Junction

1. Introduction

The Neogene breakup of the Farallon plate into the Cocos and Nazca plates and formation of the Galapagos rift system (Stock and Lee, 1994) led to the development of a transform–trench–trench triple junction between the Cocos plate, the Nazca plate, and the overriding Panama block (Panama Triple Junction, PTJ, Fig. 1). Here, the Panama Fracture Zone (the common name for the transform plate boundary between the Cocos and Nazca plates) subducts beneath the Caribbean plate at the Middle America Trench (MAT, Fig. 1). This configuration leads to drastic lateral changes in the characteristics

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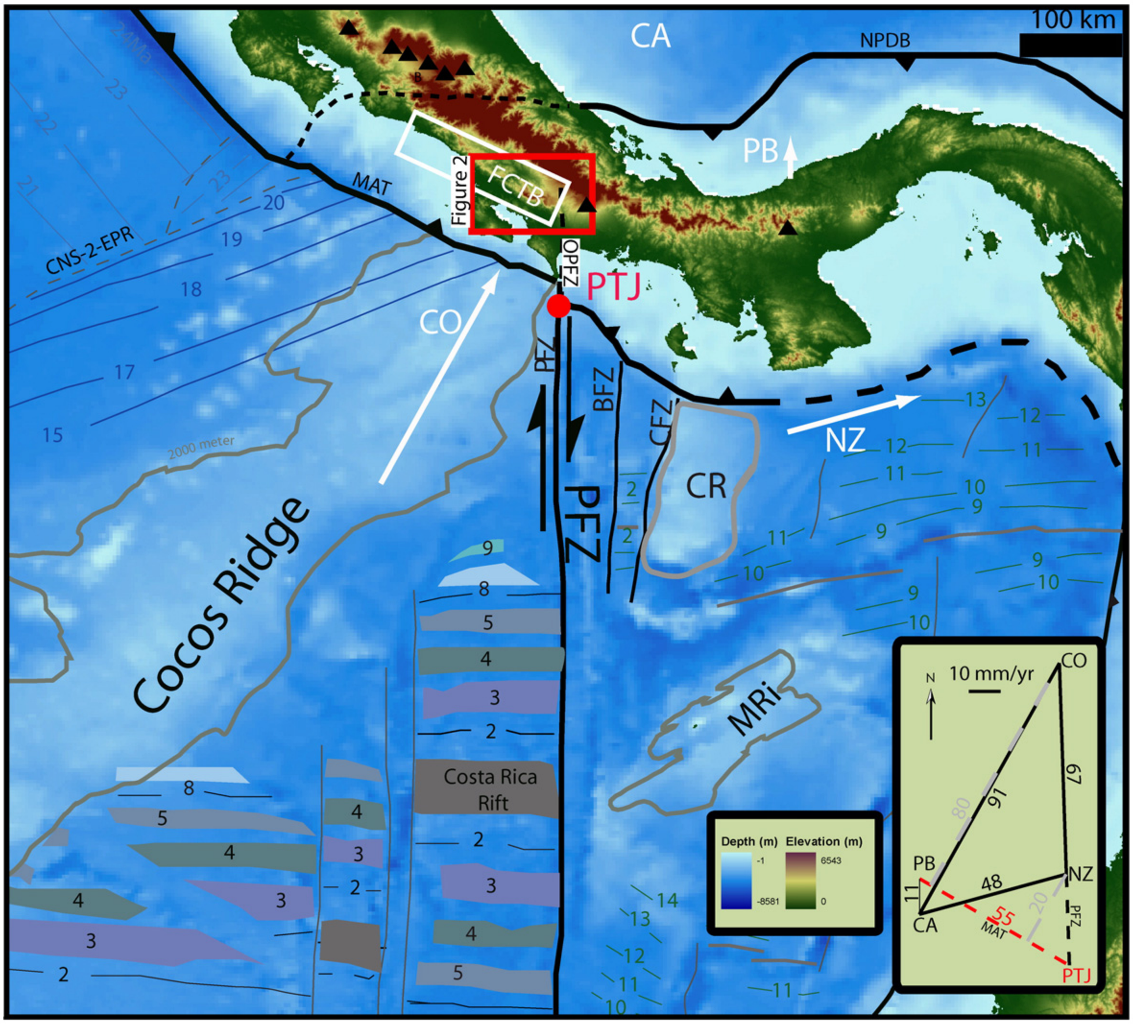

Fig. 1. Regional digital elevation model of southern Central America showing the location of the Panama Triple Junction (PTJ, red dot) at the intersection of the Cocos (CO), Nazca (NZ) and Panama block (PB), part of the Caribbean (CA) plates. PB = Panama block, PFZ = Panama Fracture Zone, OPFZ = On-land projection of the Panama Fracture Zone, FCTB = Fila Costeña Thrust Belt outlined in white box, NPDB = North Panama Deformed Belt, MAT = Middle America Trench. Location of Fig. 2 in red box. White arrows indicate plate motion vectors relative to a fixed Caribbean plate. Black triangles denote active volcanoes. Map of identified magnetic anomalies on lower plate based on data by Barckhausen et al. (2001), Lonsdale and Klitgord (1978), Lonsdale (2005), Lowrie et al. (1979), and modified after MacMillan et al. (2004). Numbers show age in millions of years based on the chron time scale of Cande and Kent (1995). BFZ = Balboa Fracture Zone, CFZ = Coiba Fracture Zone, CR = Coiba Ridge, MRi = Malpelo Ridge, CNS-2-EPR = boundary between crust originated at Galapagos Hot Spot (CNS-2, south of boundary) and EPR (East Pacific Rise) crust (north of boundary). Bathymetry supplied by the USGS GTOPO30 dataset, and topography by NASA SRTM-3 90-m DEM. Inset. Plate vector diagram after Sitchler et al. (in press), relating Cocos, Nazca, Caribbean plates, and Panama Block. Solid lines denote relative plate velocity vectors based on velocity model NNR-NUVEL-1B derived from Bird (2003), DeMets et al. (1990), Shuanggen and Zhu (2004), and Silver et al. (1990). Bold dashed lines represent the location of the Middle America Trench (red), and Panama Fracture Zone, respectively. The intersection of these represents the Panama Triple Junction, which migrates to the SE along the Middle America Trench with respect to a fixed Panama Block at a rate of ~55 mm/yr (red dashed line). Panama Block–Nazca (PB-NZ) and Panama Block–Cocos (PB-CO) convergence are shown as dotted gray lines orthogonal to the Middle America Trench. Rates are shown in mm/yr. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of the subduction boundary, including subduction rate (Bird, 2003; DeMets, 2001; DeMets et al., 1990), subduction angle (Protti et al., 1994, 1995) and slab crustal thickness (Sallarès et al., 2003; von Huene et al., 1995; Walther, 2003). In Costa Rica, subduction of the aseismic Cocos Ridge produces the highest plate coupling (Norabuena et al., 2004; Sitchler et al., in press), the greatest forearc shortening (Sitchler et al., in press), a shallowing of the Benioff Zone (Protti et al., 1994, 1995) and a cessation of arc volcanism inboard of the ridge axis (de Boer et al., 1988). Subducting seafloor bathymetry also has profound effects on the distribution and style of deformation and seismicity in the upper plate of convergent margin systems (Fisher et al., 1998; Ranero and von Huene, 2000; Sak et al., 2004; Taylor et al., 2005; von Huene et al., 1995, 2000) and can affect forearc subsidence and uplift inboard of seamounts and ridges (Fisher et al., 1998; Gardner et al., 1992, 2001; Sak et al., 2004; Taylor et al., 2005).

In this paper, we characterize the inner forearc response of the upper plate to the abrupt changes in subduction angle, rate and direction that occur at the Panama Triple Junction. Because the subducting Panama Fracture Zone migrates to the southeast with the Panama Triple Junction, the upper plate of this system experiences an abrupt change from slow and oblique Nazca plate subduction to rapid and near-orthogonal Cocos plate subduction (Fig. 1). The upper plate of this system thus likely undergoes a rapid increase in convergence rate, plate coupling, and shortening rate through time as the subducting Panama Fracture Zone migrates to the southeast with the triple junction (Fig. 1, inset).

2. Tectonic setting

The Central American forearc-volcanic arc system along the western coast of Costa Rica and Panama is created as a result of the subduction of the Cocos and Nazca plates under the Caribbean plate at the Middle America Trench (MAT, Fig. 1). The upper plate of this system, the Panama Block (Fig. 1), is a microplate that is separated from the Caribbean plate along diffuse deformation zones to its north (Kellogg and Vega, 1995) and west (Marshall et al., 2000). The Panama Triple Junction is located at the intersection of the dextral Panama Fracture Zone with the Middle America Trench. At this point, the subducting Panama Fracture Zone juxtaposes Cocos subduction to its west against Nazca subduction to its east (Fig. 1), and creates an abrupt boundary for drastic along-strike variations in lower plate properties and behavior.

The Cocos plate subducts normal to the trench at a convergence rate of 91 mm/yr (Bird, 2003; DeMets, 2001; Shuanggen and Zhu, 2004), and exhibits significant lateral variations from NW to SE. In the northwest offshore Nicaragua, the Cocos Plate subducts steeply (slab dip of 84°), and consists of “smooth” crust that was created at the East Pacific Rise (EPR, Hey, 1977; van Andel et al., 1971). Farther to the SE in Costa Rica, the Cocos plate subducts more shallowly (19°, Protti et al., 1995), and consists of “rough” CSN-2 crust, which originated at the Galapagos Rift system (Hey, 1977; Werner et al., 2003). The lateral shallowing in slab dip across the Middle America Trench is attributed to subduction parameters dictated by the youth and buoyancy of the down-going Cocos plate, as both bathymetry (von Huene et al., 1995) and geodetically constrained interplate coupling (Norabuena et al., 2004) increases along the trench from northwest to southeast (Protti et al., 1994, 1995). The most prominent bathymetric feature on the subducting “rough” CNS-2 crust is the anomalously thick (~19 km crustal thickness) Cocos Ridge (Sallarès et al., 2003; von Huene et al., 1995; Walther, 2003) which subducts near-orthogonal to the trench offshore Osa Peninsula (Fig. 1). Subduction of this broad, aseismic feature induces increased forearc coupling (Norabuena et al., 2004) and deformation (Corrigan et al., 1990), leading to uplift of both the Osa Peninsula (Gardner et al., 1992) and the Fila Costeña Thrust Belt (Fisher et al., 2004; Sitchler et al., in press) inboard of the ridge axis.

East of the Panama Fracture Zone, the Nazca plate subducts obliquely (N70E) under western Panama at a rate of 48 mm/yr (Fig. 1, Bird, 2003; DeMets, 2001; Shuanggen and Zhu, 2004). Here, the Benioff zone is poorly imaged, but is documented to dip to the northeast by about 33° (Vergara Muñoz, 1988). Two distinct N–S striking transforms parallel the Panama Fracture Zone to its east: the Balboa and Coiba Fracture Zones, respectively (Fig. 1). A magnetic anomaly profile imaged along a N–S track line between the Coiba and Balboa Fracture Zones displays a 2 Ma-old extinct spreading ridge offshore of western Panama (Fig. 1, Lonsdale, 2005; Lowrie et al., 1979).

A triple junction velocity diagram indicates that in order for the triple junction to remain stable, it must migrate to the southeast at a rate of 55 mm/yr (Fig. 1 inset, Bird, 2003; DeMets et al., 1990; Gardner et al., 1992; Silver et al., 1990). Palinspastic plate reconstructions based on magnetic anomaly data (Barckhausen et al., 2001; Hey, 1977; Lonsdale and Klitgord, 1978; Lonsdale, 2005) and current plate motions suggest that the Panama Triple Junction has likely been migrating to the southeast along the Middle America Trench since the middle Pliocene (Gardner et al., 1992; MacMillan et al., 2004). The time at which the Cocos Ridge axis arrived at the Middle America Trench, however, is highly debated and ranges in the literature between 8 Ma (Abratis and Wörner, 2001) and 0.5 Ma (Gardner et al., 1992). Nonetheless, based on plate motions surrounding the CO-NZ-CA triple junction over the past 3 Ma, the upper plate of this system has experienced a sudden increase in convergence rate (20 mm/yr to 80 mm/yr) as the triple junction migrates to the southeast (Fig. 1, inset, Fisher et al., 2004; Sitchler et al., in press). We explore the effects this migration has on the upper plate of this system.

2.1. Outer forearc

The outer forearcs of Costa Rica and western Panama exhibit vastly differing characteristics due to the variations in subduction style that occur at the subducting Panama Fracture Zone. The Costa Rican outer forearc, inboard of Cocos subduction, records evidence of subsidence (Ranero and von Huene, 2000; Vannucchi et al., 2004), basal erosion (von Huene et al., 1995) and arcward retreat of the trench axis (von Huene et al., 2000). In contrast, the outer forearc offshore Panama, inboard of Nazca subduction, shows evidence for active accretion, with the development of an accretionary prism (Kolarsky et al., 1995; Moore and Sender, 1995).

Net subsidence within the outer forearc of Costa Rica has occurred at variable rates since the Miocene, primarily as a consequence of subduction erosion (Vannucchi et al., 2003). The lower slope apron is “rough” and highly scarred directly inboard of subducting bathymetric highs, with embayments in the slope that mark areas of significant basal erosion (von Huene et al., 1995). Previous work suggests that the outer forearc experiences initial uplift in response to incoming bathymetric features, followed by subsidence as the feature passes (Dominguez et al., 1998). Seismic imaging within the upper slope exhibits a km-scale (~3900 m deep) reflector separating a low-velocity (~2–2.5 km/s) slope cover from a higher-velocity (4–4.5 km/s) margin wedge (Hinz et al., 1996; Ranero and von Huene, 2000; Vannucchi et al., 2004; von Huene et al., 2000). This so-called BOSS unconformity is correlated to the Mal Pais unconformity found onshore and suggests ~50 km of arcward migration of the trench axis since the Neogene (Vannucchi et al., 2004). Furthermore, the outer forearc shows evidence for net subsidence since Tertiary time as recorded in a deepening-upward sedimentary sequence (von Huene et al., 2004).

Seismic reflection profiles indicate that the outer forearc of western Panama contains an accretionary prism created primarily by offscraping and accretion of terrigenous trench sediment (Kolarsky and Mann, 1995; Moore and Sender, 1995). This prism is cut by arcward-dipping thrust faults and associated seaward-verging folds created by oblique convergence between the Cocos and Caribbean Plates. Oblique subduction between the Nazca and Caribbean plates causes eastward sweeping of the Balboa and Coiba Fracture zones, (BFZ, CFZ, Fig. 1) temporarily causing an over-steepened surface slope inboard of the ridge, followed by subsequent collapse (Moore and Sender, 1995).

2.2. Volcanic arc

The Central American volcanic arc continues unbroken from Nicaragua to Panama, although it varies significantly in character from NW to SE. Active volcanism is occurring throughout Nicaragua and northwestern Costa Rica (de Boer et al., 1988, 1995), where there are two margin-parallel arcs: an extinct Miocene arc, and a seaward Quaternary arc (Alvarado et al., 1993; Marshall et al., 2003). Volcanism becomes extinct coincident with the northern boundary of the Panama microplate and remains extinct for ~175 km to the southeast until volcanic activity resumes at Volcán Barú in western Panama (Fig. 1, de Boer et al., 1988, 1995; Defant et al., 1992; Defant and Drummond, 1990; Drummond et al., 1995). This extinct portion of the volcanic arc, the Cordillera de Talamanca, is the highest range on the Central American isthmus and is correlated with shallow subduction of the Cocos plate and a marked shallowing of the Benioff Zone in central and southern Costa Rica (Protti et al., 1994, 1995). Although volcanism within the Talamancas Range is currently extinct, the volcano immediately south of the Talamancas Range, Volcán Barú, is currently active, having experienced its most recent event within recent history (tremors reported in 1963, de Boer et al., 1988). This volcano, with a peak elevation of 3474 m, located east of the subducting Panama Fracture Zone, exhibits a ~40 km wide radial lahar fan that extends across the forearc of western Panama.

2.3. Inner forearc

The inner forearc of Costa Rica, by contrast to the outer forearc, is thickened and has experienced differential and rapid net uplift (Fisher et al., 1998, 2004; Gardner et al., 1992, 2001; Sitchler et al., in press) related to both short- and long-wavelength features on the subducting plate (Gardner et al., 1992, 2001; Sak et al., 2004). Inboard of bathymetric highs, active high-angle faults separate ~7 blocks that experience differential uplift and NW-down tilting along a 150 km segment of the central Pacific coast (Marshall et al., 2000). Uplift along the margin is reported between 1 and 8 m/kyr as seen in deformed marine terraces along the Pacific Coast of Costa Rica (Gardner et al., 2001), and is documented to be highest inboard of bathymetric highs on the down-going plate, directly arcward from regions with histories of the highest subsidence in the outer forearc (Fisher et al., 1998; Sak et al., 2004).

In southern Costa Rica the forearc is highly deformed and exhumed, where higher coupling has created the regionally extensive Fila Costeña Thrust Belt in southeastern Costa Rica (Figs. 1 and 2). The Fila Costeña is a

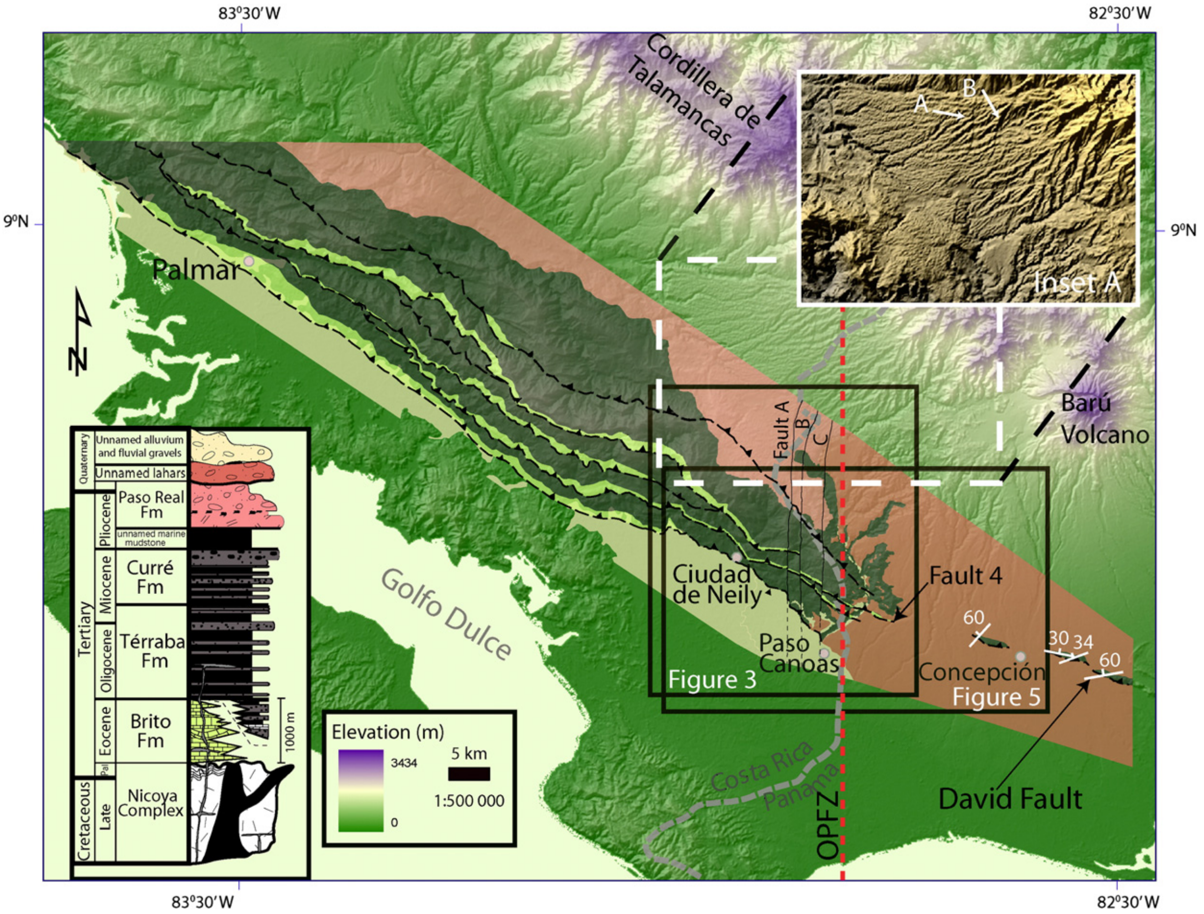

Fig. 2. Simplified geologic map of the southeast Fila Costeña Thrust Belt in the inner forearc of Costa Rica and western Panama (see Fig. 1 for location). Combined data from Sitchler et al. (in press) and this study, revised after Kolarsky and Mann (1995) and Mora (1979). Although the thrust belt continues to the northwest, we focus on the southeast termination. Black boxes indicate location of Figs. 3 and 5. OPFZ = On-land projection of the Panama Fracture Zone. Geology is draped on 90-m DEM supplied by NASA's SRTM-3 dataset. Stratigraphic column modified after Sitchler et al. (in press), Phillips (1983) and Fisher et al. (2004). Inset A shows shaded DEM of area in white dotted box denoting scarps visible for right-lateral faults A and B based on SRTM-3 dataset.

30-km-wide subaerial thrust belt in the inner forearc between the Cordillera de Talamancas and the Golfo Dulce. This thrust belt extends for ~250 km from central Costa Rica to western Panama (Fig. 2). Previous mapping of the Fila Costeña (Kolarsky et al., 1995; Mora, 1979; Sitchler et al., in press) found that the center of the thrust belt contains as many as 5 thrust faults rooted at or near the basement-cover contact that imbricate a Tertiary forearc basin sequence to the northeast (Fig. 2).

There is an abrupt lateral termination of the thrust belt near the on-land projection of the subducting Panama Fracture Zone near the Costa Rica–Panama border. Here, we report the results of recent mapping surrounding the thrust belt termination within the area from Ciudad de Neily, Costa Rica to Concepción, Panama (Fig. 2). Geologic units were drawn on 1:50,000 topographic maps acquired from the IGN in San Jose, Costa Rica and "Tommy Guardia" in Panama. Most exposures were limited to river and stream valleys perpendicular to the strike of the thrust belt, as well as road outcrops and active quarries.

2.3.1. Stratigraphy and sedimentology of the inner forearc

The main tectonostratigraphic units within the inner forearc of Central America include Cretaceous basement composed of oceanic crust of the Caribbean Large Igneous Province, forearc basin strata and a Pliocene–Quaternary sequence of volcanic flows, lahars, and fluvial terraces (Fig. 2, inset). The forearc basin strata are subdivided here into three formations based on lithofacies: the Eocene Brito Fm, the Oligocene–Miocene Térraba Fm. and the Miocene Curré Fm. The Brito Limestone Fm is a bioclastic limestone and turbidite sequence 1 kilometer thick (Phillips, 1983; Yuan, 1984), and was used as a key bed to generate line-length balanced cross-sections of the Fila

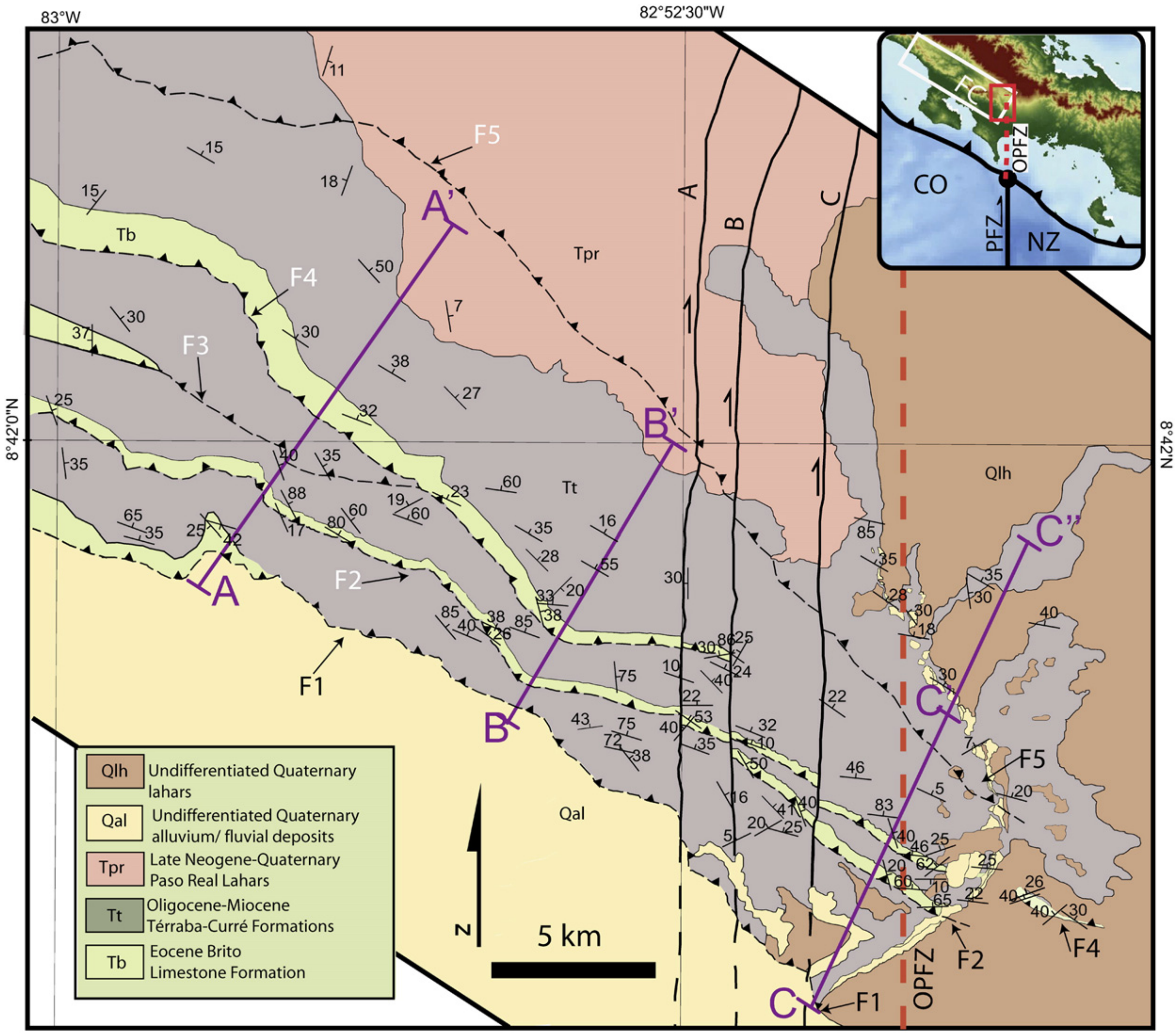

Fig. 3. Bedrock geologic map of the southeastern termination of the Fila Costeña Thrust Belt showing strike and dip measurements within thrust sheets that dip to the northeast. The southeastern termination of the thrust belt roughly coincides with the on-land projection of the Panama Fracture Zone (OPFZ, red dashed line), which is migrating to the southeast with the Panama Triple Junction. F1, F2, F3, F4, and F5 refer to thrust faults 1, 2, 3, 4 and 5, respectively. Cross-sections show locations of balanced cross-sections in Fig. 4. All fault traces and contacts are approximated. Inset index map shows figure location in red box relative to the on-land projection of the Panama Fracture Zone. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Costeña. The Térraba Fm, conformably overlying the Brito Fm (Fig. 3, inset), is a bioclastic/volcaniclastic turbidite sequence composed primarily of inter-bedded mudstone and volcaniclastic sandstone with minor black shales, marls and conglomerates (Phillips, 1983; Yuan, 1984). The Curré Formation, defined by a thin, coarsening upwards volcaniclastic sandstone and conglomerate (Lowery, 1982; Yuan, 1984), is grouped here with the Térraba Fm as the Térraba–Curré Fm, which is ~2 km thick. Both the Brito and the Térraba Formations are intruded locally by 15–11 Ma-aged gabbros (de Boer et al., 1995). A 200-m thick Pliocene unnamed marine mudstone lies unconformably atop the Térraba–Curré Formations, but is found only in the central and northwest portions of the thrust belt. In the current study area, the Pliocene Paso Real Formation unconformably drapes the Térraba basin sedimentary package and consists of ~900 m-thick andesitic volcanic flows, breccias and lahars (Lowery, 1982; Phillips, 1983). These lahars that originated from the Cordillera de Talamanca range in age from 4.3 to 1.2 Ma (de Boer et al., 1995).

3. Results

Geologic mapping along the southeastern termination of the Fila Costeña Thrust Belt delineates structural and landscape features that change significantly along-strike (Figs. 2 and 3). For example, all individual thrusts of the Fila Costeña exhibit progressive along-strike decreases in slip from NW to SE, until four out of five thrusts abruptly die out or link along leading branch lines into a single fault. Likewise there is a transition in geomorphic features, where the drainage divide within the elevated and dissected portion of the thrust belt reorganizes and the relief of the thrust belt dissipates to the southeast and is replaced by a relatively undeformed lahar fan. Interestingly, these changes occur abruptly in the forearc region that overrides the Panama Fracture zone. This region, near the Costa Rica–Panama border, divides the area into two zones with contrasting structural and landscape characteristics.

Northwest of this region, the Fila Costeña is dominated by as many as five continuous thrust faults that strike NW–SE across the belt (Figs. 2 and 3). Here, the landscape is rugged, dominated by NW-trending limestone ridges, and exhibits a local drainage divide that follows peak elevations of ~1500 m (Fig. 2). The northern, backside of the thrust belt in this area is covered unconformably by lahars of the Paso Real Fm that are backtilted to the northeast by as much as 11° (Fig. 3). By contrast, east of the on-shore projection of the Panama Fracture Zone, only one thrust fault is evident, and the region is dominated by an extensive lahar fan that slopes gently to the south–southwest and radiates from Volcán Barú (Fig. 2). The lahar deposits radiating from Barú vary widely in texture, composition and thickness, yet most contain basaltic–andesitic clasts that ranged in size from pebbles to boulders within a largely mud matrix. The following sections provide details of the changing structure and landscape features evident across this critical region in more detail.

3.1. Structure of the inner forearc

In the Fila Costeña west of the on-land projection of the Panama Fracture Zone, five NW-striking thrust faults rooted at the base of the Eocene Brito Limestone Fm imbricate the Térraba Fm along a detachment at the basement-cover contact (Fig. 3). Thrusts are continuous along-strike and oriented parallel to the margin (NW–SE), with dips that range from 20° to 60° to the NE. Where no predominant limestone ridge is exposed, thrusts are commonly recognized by the presence of Brito limestone overlying Térraba Fm in transverse streams and traced along-strike from stream valley to stream valley. Mapping confirms that the overall number of thrusts decreases from NW to SE and the aerial thickness of limestone exposures decreases both laterally and longitudinally from NW to SE, and N to S, respectively. Thrust 3 merges laterally into thrust 4 along leading branch lines. Thrusts 1, 2 and 5 decrease in slip to the southeast where they are buried by lahar near the termination of the Fila Costeña (Fig. 3). No pronounced topographic expression or outcrops of Eocene Brito Limestone Fm are immediately evident to the southeast. However, thrust 4 (Figs. 2 and 3), which exposes the thickest section of the Brito Fm and produces the most predominate limestone ridge in the Fila Costeña proper, continues east across the lahar fan from Volcán Barú for as much as ~30 km, labeled here as the David Fault. This fault, identified by some as left-lateral (Kolarsky and Mann, 1995; Mann and Corrigan, 1990) produces 3 fault-related anticlines (Térraba Fm dips NW–NE, see David Fault, Fig. 2) within the Térraba Fm that deforms the base of the relatively continuous and undeformed lahar fan.

We quantify the termination of the Fila Costeña Thrust Belt by constructing balanced cross-sections along three transects (Fig. 3). Previous cross-sections based on line-length balances of the Brito Fm (Fisher et al., 2004; Sitchler et al., in press) provide minimum shortening estimates along two transects across the Fila Costeña near the center of the thrust belt. A cross-section directly inboard of the subducting Cocos Ridge, where there are five thrust faults, provides a minimum total shortening of 36 km, or a minimum 58% decrease in length (Sitchler et al., in press). A cross-section northwest of the Cocos Ridge axis where three thrust faults are located, shows a smaller value of minimum shortening, approximately 33 km, or 55% total (Fisher et al., 2004; Sitchler et al., in press). These cross-sections indicate that the highest value of minimum shortening is concentrated near the axis of the Cocos Ridge, where interseismic coupling is greatest (Norabuena et al., 2004).

Line-length balancing of three new cross-sections reveals that minimum shortening decreases progressively and rapidly from northwest to southeast (Fig. 4). The westernmost line of section (line A–A′, Fig. 3) exhibits 10 km of shortening, or a 42% decrease in length. Only 10 kilometers to the east, along line B–B′, we calculate ~6.5 km of shortening. Line C–C′ exhibits the least amount of shortening (4 km), along the easternmost line of section. Thrust five is excluded from the shortening calculations since it is significantly underconstrained for most areas of the thrust belt, except along line C–C″, where thrust 5 exhibits ~7.5 km of slip. If we compare the amounts of shortening across strike in the Fila Costeña based on thrusts that are well constrained (1, 2, 3 and 4, Fig. 4), we calculate a ~6 km drop in minimum shortening over a lateral distance of 24 km.

The Brito Fm acts as a key-bed for thrust belt reconstructions and line-length balancing, since it is

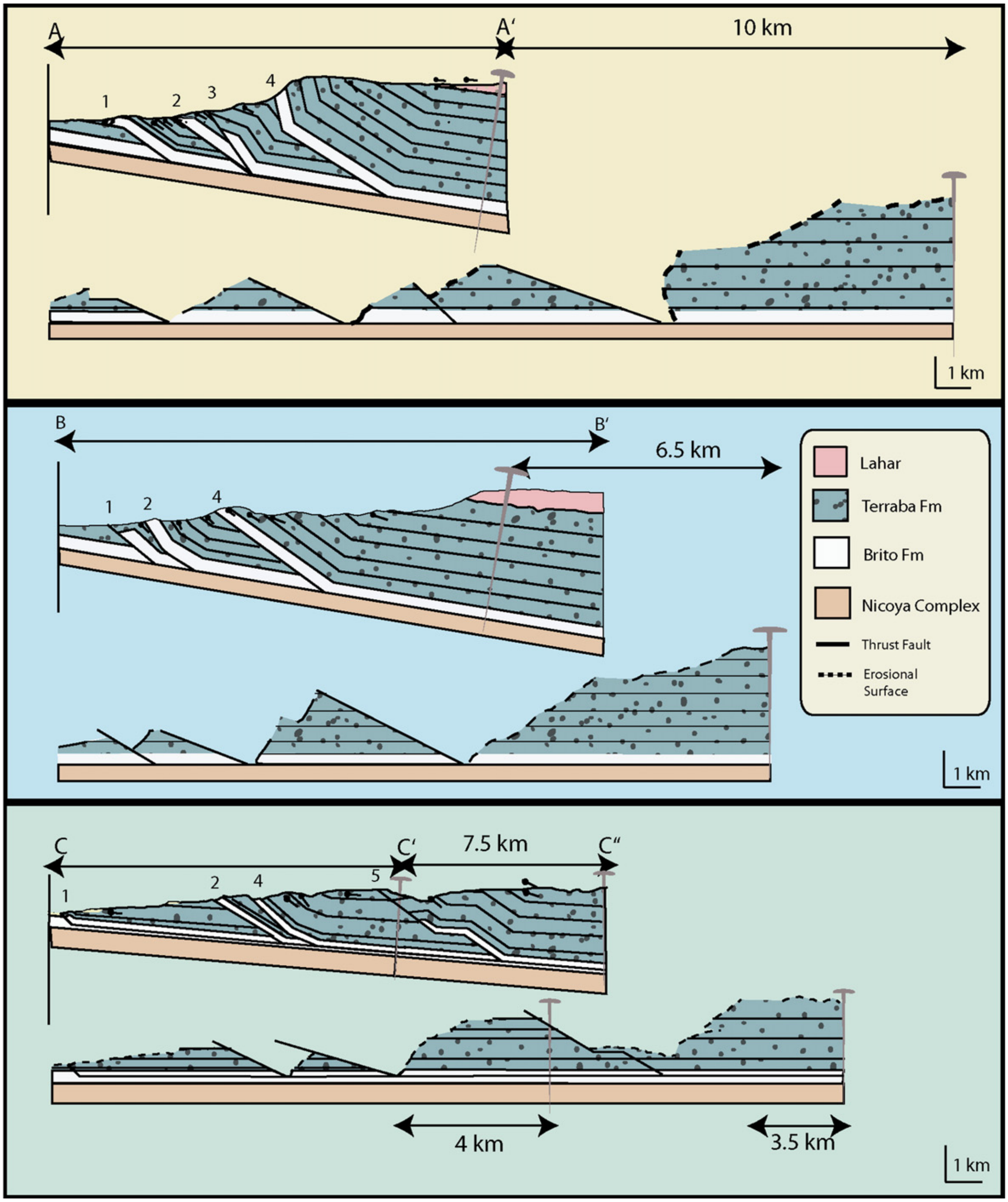

Fig. 4. Balanced cross-sections of the Fila Costeña Thrust Belt (See Fig. 3 for location). Minimum shortening estimates are based on a line-length balanced restoration of the Brito Fm. Décollement depth is calculated from extrapolation of the axial plane associated with the rear-most thrust based on surficial data. Décollement at the basement-cover contact dips approximately 10° to the northeast. Where no hanging wall cutoffs were exposed, they were placed at the erosional surface to maintain a conservative estimate of shortening.

competent, exhibits little internal strain, and is easily recognized and mapped. Hanging wall cut-offs are rare, and are assumed to be eroded, but some crop out locally. For example, a seaward verging fault-related anticline is exposed near Paso Canoas, Panama (Fig. 2) as slip decreases on an individual thrust to the southeast. At this location, sheared Quaternary lahars are incorporated and deformed by an emergent thrust 4. Where no hanging wall cutoff was observed, a cutoff was placed directly above the current erosional surface in order to minimize an estimate of shortening for each cross section. Because hanging wall cut-offs were rare, minimum shortening estimates are reported here. A depth to décollement is extrapolated by projection of the axial surface of the rear-most anticline constrained by surficial dips after décollement calculations by Sitchler et al. (in press). Our shortening calculations assume constant line lengths, unit thickness and décollement dip within individual thrust sheets. These assumptions are valid given that no internal deformation is apparent within the thrust belt, no cleavage is present, and slip indicators (Fisher et al., 2004) are parallel to plate convergence. We approximate a décollement depth of 2.5 km along line A–A′, yet it shallows progressively to the southeast (~2 km at line C–C″). Likewise, the basement-cover contact in the NW near line A–A′ dips approximately 8° to the northeast, and decreases dip to ~5° near line C–C″ (Fig. 4).

At least three N–S striking, right-lateral, strike-slip faults cut the thrusts of the Fila Costeña near the easternmost termination of the thrust belt (Fig. 2, inset A). Right-lateral faults of this type were first identified by Cowan et al. (1997) and correlated with subduction of the right-lateral Panama Fracture Zone, yet we identify two faults (A, B, Fig. 3) that were previously unrecognized. In addition to displacing thrusts of the Fila Costeña by as much as 2 km, these faults cut the western flank of the lahar slope of Barú tens of kilometers north of thrust 5, and can be traced for as much as 30 km along strike (Fig. 2 inset A). These faults are recognized to accommodate right-lateral motion both by spatial relationships within the thrust belt, and also by a cataclastic shear zone (slickenlines oriented 325°/45°) evident within imbricated sections of the Térraba Formation. The strike of these faults parallels the strike of the Panama Fracture Zone (N–S orientation) and they are localized between lines B–B′ and C′–C″ (Fig. 3).

3.2. Landscape in the inner forearc

Along-strike changes in landscape features and drainage behavior are evident across the termination of

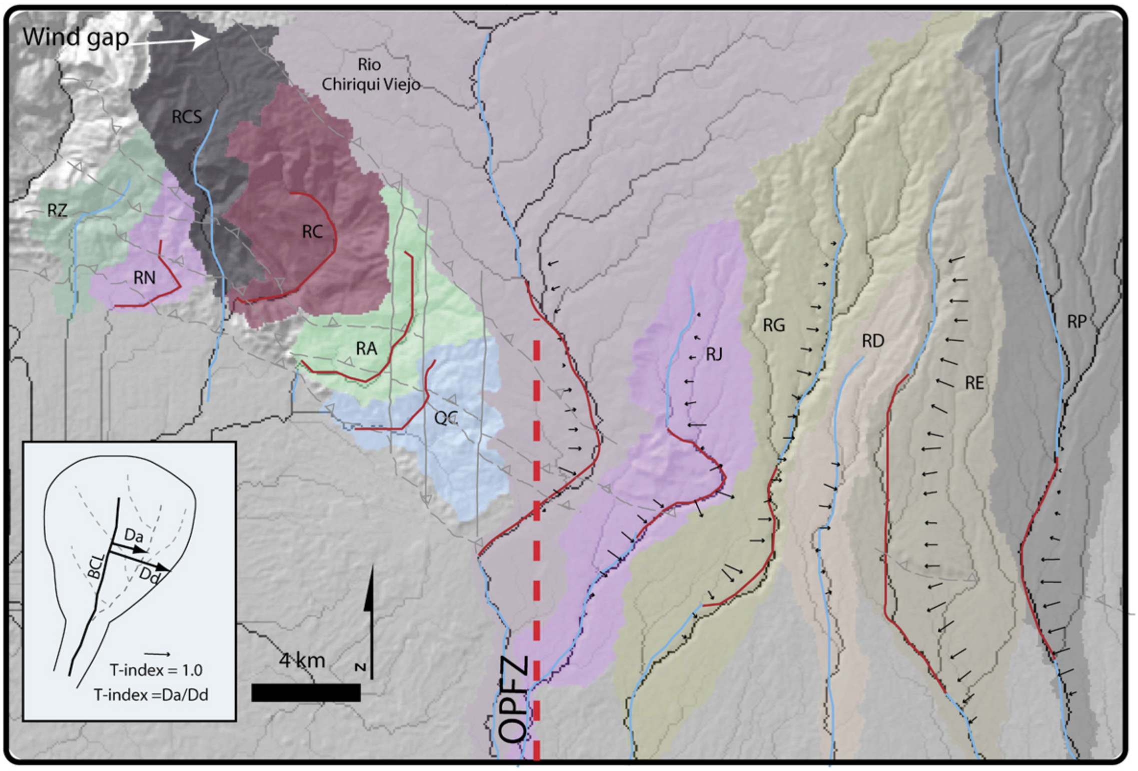

Fig. 5. Regional shaded relief map outlining local drainages derived from and draped on a 90-m SRTM DEM. Trunk segments of streams are outlined and color-coded as consequent (blue) or subsequent (red) reaches. For six easternmost rivers, asymmetry vectors (calculated by methods of Cox (1994) and Garrote et al. (2006)) are placed at the basin center line (BCL). Red dotted line (OPFZ) indicates the location of the on-land projection of the Panama Fracture Zone. RZ = Río Zumbada, RN = Río Nuevo, RC = Río Corredor, RA = Río Abrojo, QC = Quebrada Callejonuda, RJ = Río Jacú, RG = Río Gariche, RD = Río Davila, RE = Río Escarrea, RP = Río Piedra. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

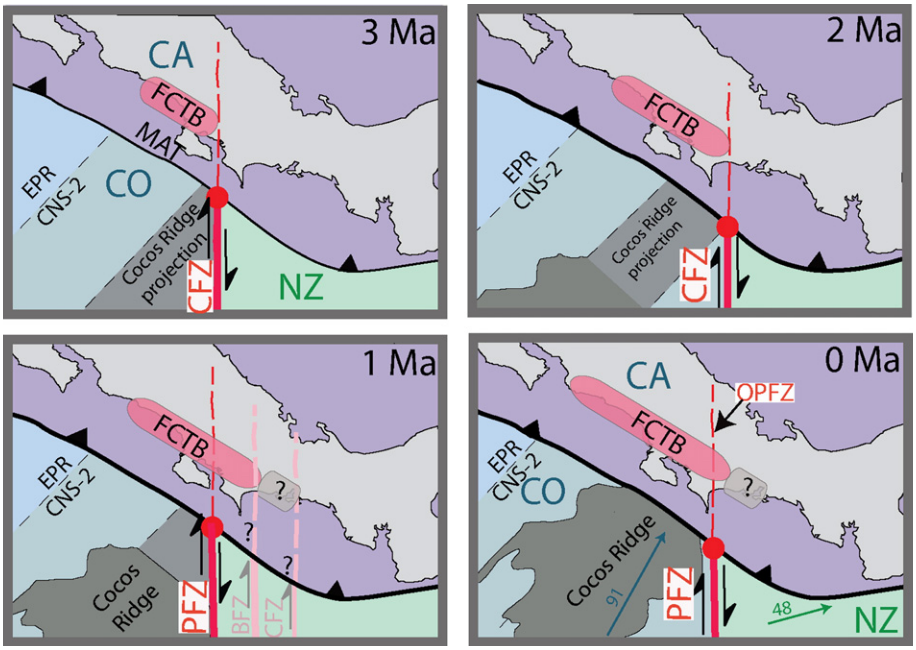

Fig. 6. Schematic plate tectonic reconstruction of the Cocos (CO, blue/green) and Nazca (NZ, green) plates with respect to a stable Caribbean (CA, purple) plate and its relation to the development and growth of the Fila Costeña Thrust Belt for the past 3 Ma after Gardner et al. (1992), Lowrie et al. (1979), and MacMillan et al. (2004). Red dot indicates location of the Panama Triple Junction, which migrates to the SE along the Middle America Trench at a rate of 55 mm/yr (see Fig. 1, inset). PFZ = Panama Fracture Zone, CFZ = Coiba Fracture Zone, BFZ = Balboa Fracture Zone, OPFZ = on-land projection of the Panama Fracture Zone. CNS-2 crust shown in dark green, EPR crust in light blue. Red text and dark red line denotes fracture zone occupying CO-NZ boundary. Dotted red line shows on-land projection of this boundary. Pink boxes denote extent of Fila Costeña Thrust Belt (FCTB) which migrates with the triple junction. Transform step occurs between 2 Ma and 1 Ma, based on magnetic anomaly data by Lowrie et al. (1979). Depending on the timing of this jump, possible locations of Balboa Fracture Zone and Coiba Fracture Zone are shown in pink, with possible extent of Fila Costeña Thrust Belt shown in gray box. Plate motions based on DeMets et al. (1990) and Wilson and Hey (1995) are indicated in mm/yr. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the Fila Costeña Thrust Belt. To the northwest, the peaks of the Fila Costeña create a NW-trending local drainage divide with trunk streams that generally flow perpendicular to strike and incise siliciclastics of the Térraba Fm (Fig. 5). Many of the streams draining the front of the Fila Costeña in this area exhibit hook-shaped segments within their upper reaches (Fig. 5, red) although tributaries branching from these sections often follow the structural grain. Also, wind gaps are evident along the current local drainage divide, suggesting flow reversal for beheaded streams on the northern side of the local divide (Fig. 5). Conversely, to the southeast of the on-land projection of the Panama Fracture Zone, streams source from the high peaks of volcán Barú, drain to the south, and incise lahars. Streams in this area exhibit both hooked-shaped, subsequent segments (Fig. 5, red) and straight, mostly consequent courses (Fig. 5, blue) that radiate from the central cone of Volcán Barú.

Many local drainage basins along the termination of the Fila Costeña are transversely asymmetric where the trunk section of the stream is displaced from the basin center line (Fig. 5). We quantify stream deflection for five streams along 1-km segments using a T-index factor (Cox, 1994), where a given asymmetry vector indicates a direction and relative magnitude of basin asymmetry (Garrote et al., 2006). The bearing and magnitude of basin asymmetry vectors (T-index) was calculated from the equation $T\text{-index} = \text{Da}/\text{Dd}$, where Da is the orthogonal distance from the basin center line to the trunk stream, and Dd is the distance from the basin center line to the drainage edge (Cox, 1994; Garrote et al., 2006). The Río Chiriquí Viejo, Río Jacú and Río Gariche (RJ, GR, Fig. 5) nearest the on-shore projection of the Panama Fracture Zone exhibit basin asymmetry vectors that point to the east and southeast for the reaches that cross the Fila Costeña. However, the two easternmost rivers, Río Escarrea and Río Piedra (RE and RP, Fig. 5) exhibit asymmetry vectors that point to the west and southwest. Thus, there are major changes in the drainage networks in the study area that vary with location relative to the termination of the Fila Costeña Thrust Belt.

4. Discussion

Lateral changes in shortening occur in the upper plate straddling the subducting Panama Fracture Zone with a relative ~6 km decrease in shortening over a lateral distance of 24 km (Fig. 4). Incorporating these findings with previous cross-sections of the thrust belt by Sitchler et al. (in press), the Fila Costeña exhibits a ~14 km relative drop in shortening (combined slip on faults 1–4) over a 45 km lateral distance. These observations indicate that the subducting Panama Fracture Zone affects upper plate deformation, with inner forearc deformation restricted to areas experiencing Cocos plate subduction. Given that the thrust belt terminates at the on-land projection of the Panama Fracture Zone, and plate motions indicate that the Panama Fracture Zone is migrating to the southeast, we propose that lateral southeasterly growth of the Fila Costeña is ongoing and has been continuous for at least the past 3 Ma. Support for this conjecture is evident in both the landscape and structure of the area, which provide both short- and long-term records.

We postulate that the Cocos Ridge entered the trench at ~2–3 Ma (Fig. 6), since plate reconstruction models constrain this as the earliest time in which the Panama Triple Junction had migrated sufficiently SE in order for the ridge axis to subduct offshore Costa Rica (MacMillan et al., 2004). The exact timing of Cocos Ridge collision, however, is highly dependent upon the evolution of the Cocos–Nazca plate boundary, which in addition to migrating to the southeast through time, also probably experienced a left-stepping (NW) en echelon ridge transform step at approximately 3 Ma (Lonsdale and Klitgord, 1978; Lowrie et al., 1979). A magnetic anomaly 2 between the Coiba and Balboa Fracture Zones (Fig. 1, CFZ, BFZ), suggests that the Coiba Fracture Zone must have become inactive circa 2 Ma, at which time slip was transferred to the Panama Fracture Zone (Fig. 2, Lonsdale, 2005; Lowrie et al., 1979). The time at which this jump occurred has important implications for the both the arrival of the Cocos Ridge axis at the Middle America Trench, as well as the time of onset of deformation within the Fila Costeña. For example, if the Cocos–Nazca ridge jump occurred at or prior to 2 or 1 Ma, western Panama has yet to experience the affects of Cocos-style subduction (Fig. 6). Conversely, if the Cocos–Nazca jump occurred later (between 2 and 1 Ma), then western Panama may have experienced Cocos subduction just prior to the ridge jump (Fig. 6, gray box, timestep 2 Ma). Irrespective of these complications, the upper plate of this system has experienced an abrupt increase in convergence rate with migration of the triple junction, leading to the southeast propagation of the Fila Costeña through time, and the steep shortening gradient recognized near the thrust belt's termination.

The right-lateral faults that strike NS across the Fila Costeña (Fig. 2 inset, Fig. 3) could be accommodating the pronounced shortening gradient evident near the thrust belt's termination. In this sense, these faults could be considered tear faults that are typically oriented perpendicular to the strike of thrust belts, so as to re-distribute strain in areas experiencing high gradients in lateral shortening. The right-lateral faults identified here, however, are not oriented perpendicular to strike, rather they strike NS, which is inconsistent both with slip indicators within the thrust belt (Fisher et al., 2004; Sitchler et al., in press), and the direction of plate convergence. In addition, these faults are not located at the Fila Costeña termination, the area that is currently experiencing the highest shortening gradient (Fig. 3), and are instead located tens of kilometers west of that location. The NS orientation of these strike slip faults does, however, parallel the strike of the Panama Fracture Zone (Figs. 3 and 2 inset). These faults therefore are interpreted here to be deeply rooted in the crust of the Caribbean upper plate, and represent a tearing of the entire upper plate in response to basal tractions arising from the subducting Panama Fracture Zone.

The three EW striking ridges exposing Térraba Fm within lahars along the David Fault (Fig. 2) are recognized here as fault-related anticlines produced in the hanging wall of the lateral equivalent of thrust 4 (Fig. 2). This fault (David Fault, Fig. 2) is the only structural expression of the thrust belt well east of the on-land projection of the Panama Fracture Zone, and was first interpreted to accommodate right-lateral strike slip motion (Mann and Corrigan, 1990). Strike slip motion, however, is inconsistent with dip slip indicators in southeastern Costa Rica (Fisher et al., 2004; Sitchler et al., in press), which verify that thrust 4 is a thrust fault. Depending on the timing of the left-stepping transform jump in the Pliocene, this area of Panama could have experienced increased coupling and convergence associated with Cocos subduction if the Coiba Fracture Zone were still active at 1 Ma (Fig. 6, time 1 Ma). Alternatively, the transform step could have occurred before this area of Panama experienced Cocos-style subduction (Fig. 6, red box). In either case, this structure may represent the incipient and on-going propagation of the thrust belt to the southeast. If this on-going propagation is a correct interpretation, then the David Fault is accommodating strain generated as the upper plate of this system undergoes an increase in convergence rate as the triple junction migrates to the southeast.

Evidence for the active SE-migration of the Fila Costeña is most clearly recorded in modern drainage patterns of fluvial systems. Current river courses record deflection and adjustment to a SE-growing thrust belt. Most trunk sections of streams incising bedrock within the Fila Costeña west of the on-land projection of the Panama Fracture Zone exhibit hook-shaped courses, as do the two streams that incise lahars closest to the thrust belt's termination (Fig. 5). We propose that the hook-shaped reaches of these streams represent stream deflection as a consequence of topography arising from a migrating thrust belt. These hook-shaped courses are subsequent stream reaches (Fig. 5, red), since they are modified sections from the stream's original, consequent path (Fig. 5, blue) that followed initial topography (Davis, 1899). By this nomenclature, most streams east of the structural divide follow consequent paths that follow the topography of the gently-sloping lahar fan, whereas those streams that have experienced uplift and warping from thrusting develop subsequent reaches (Fig. 5). Moreover, the wind gaps evident along the current structural divide (Fig. 5) support the notion of a growing topographic divide, as streams become beheaded due to increasing elevation from uplift of the Fila Costeña.

Streams near the thrust belt termination may be recording a more diffuse termination of the thrust belt than is apparent from exposed structures. For example, Río Gariche contains a ~6 km long subsequent section (Fig. 5), even though it is located ~5 km east of the Fila Costeña termination, yet there is no obvious topographic expression of uplift (Fig. 2). This suggests that subtle amounts of uplift or warping may be occurring ahead of an eastward propagating thrust 4 tip. It is possible that lahars cover evidence of Pliocene forearc deformation created when the Cocos–Nazca boundary was subducting east of the current plate boundary (Fig. 6, 1 Ma).

Observations of landscape features confirm that deformation is active in the southeastern portion of the Fila Costeña. The right-lateral faults that cut the thrusts of the Fila Costeña also cut Quaternary lahars (Fig. 2, inset A). The asymmetry observed among several of the easternmost drainages in the study area points to active southeast tilting in the area on-land of the subducting Panama Fracture Zone (Fig. 5). This asymmetry suggests that this region may be experiencing S- or SE-directed tectonic tilting (Fig. 5), a notion that is consistent with the upper plate's response to subduction of the bathymetric step evident between the Cocos and Nazca plates at the Panama Fracture Zone.

5. Conclusions

Geologic mapping and structural cross-sections indicate that the Fila Costeña Thrust Belt terminates laterally near the on-land projection of the Panama Fracture Zone suggesting that the Fila Costeña is migrating to the southeast with the on-land projection of the Panama Fracture Zone. We see evidence for this in the following: 1.) Rapid, orthogonal and thick Cocos plate subduction leads to the development of the Fila Costeña, while oblique, and thinner Nazca plate subduction does not. 2.) The number of thrusts and amount of total shortening progressively decreases from NW to SE until the thrust belt terminates at the on-land projection of the Panama Fracture Zone. 3.) Newly recognized right-lateral faults in the upper plate represent a tearing of the upper plate in response to tractions arising from the tear in the down-going plate. 4.) The Fila Costeña Thrust Belt migrates with the Panama Triple Junction deflecting river drainage lines to hooked subsequent reaches and asymmetric basin shapes.

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