Constraints on inner forearc deformation from balanced cross sections, Fila Costeña thrust belt, Costa Rica

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[1] The Fila Costeña thrust belt in the forearc of Costa Rica is accommodating a significant portion of the convergence of the Cocos plate and Panama microplate. Geologic mapping of the thrust belt depicts a duplex with three horses that incorporate Eocene limestones and Oligocene to early Miocene clastics inboard of the subducting Cocos Ridge axis. By constructing a cross section at this location along a NE–SW trending transect perpendicular to the thrust belt, we constrain a shortening rate of approximately 40 mm/a and propose that as much as 50% of the total plate convergence rate is taken up in the inner forearc. The Eocene limestones at the base of the thrust sheets pinch out in both directions away from the onland projection of the Cocos Ridge axis owing to decrease in slip on faults and a lateral ramp in the basal décollement. The thrust belt terminates near the Panama border at the onland projection of the subducting Panama Fracture Zone. These observations suggest that shortening is propagating to the east with the migration of the Panama triple junction and the onset of shallow subduction of the thickened edge of the Cocos plate. The absence of similar features in the Nicaraguan forearc, where the subducting crust is older, subducts more steeply, and lacks incoming ridges and seamounts, indicates that deformation of the forearc basin in Costa Rica reflects greater coupling between the converging plates inboard of the Cocos Ridge. **Citation:** Sitchler, J. C., D. M. Fisher, T. W. Gardner, and M. Protti (2007), Constraints on inner forearc deformation from balanced cross sections, Fila Costeña thrust belt, Costa Rica, *Tectonics*, *26*, TC6012, doi:10.1029/2006TC001949.

1. Introduction

[2] Convergent plate boundaries show a range of behavior with attributes bounded by two end-members: accretionary margins with seaward growth of an accretionary wedge and erosive margins with basal erosion of a margin wedge and trench retreat [*von Huene and Scholl*, 1991; *Shreve and Cloos*, 1986]. Accretionary margins occur in areas with a thick incoming sediment pile, whereas erosive margins are typically characterized by relatively little sediment input at the trench [*Clift and Vannucchi*, 2004]. These erosive margins are also found in conjunction with convergence rates greater than 6 cm/a [*Clift and Vannucchi*, 2004] and recently subducted seamounts and ridges that increase the degree of coupling between the converging plates [*Norabuena et al.*, 2004; *Yáñez and Cembrano*, 2004] resulting in forearc deformation, i.e., the subducting Cocos Ridge beneath the Osa Peninsula in Costa Rica [*Corrigan et al.*, 1990; *Gardner et al.*, 1992; *Sak et al.*, 2004], and the New Hebrides and Solomon arcs in the South Pacific [*Mann et al.*, 1998; *Taylor et al.*, 2005]. In these cases, the outer forearc experiences transient uplift and subsidence in response to subducting bathymetric features.

[3] This study focuses on the southeastern end of the Middle America Trench (MAT) along the Pacific coast of Costa Rica (Figure 1), a region that is considered to be a classic example of an erosive margin [*Meschede et al.*, 1999a, 1999b; *Vannucchi et al.*, 2001; *Meschede*, 2003]. The interpretation of basal erosion along this margin is supported in the outer forearc by analysis of slope strata, and benthic foraminifera offshore of the Nicoya Peninsula to the northwest [*Kimura et al.*, 1997; *Vannucchi et al.*, 2001; *Meschede et al.*, 2002] (Figure 2), seismic data [*Hinz et al.*, 1996; *Ye et al.*, 1996], high-resolution bathymetry [*von Huene et al.*, 1995], and experimental sandbox models for seamount subduction [*Dominguez et al.*, 1998]. These studies collectively show active subsidence of the upper slope and arcward retreat of the trench axis.

[4] In contrast with the outer part of the forearc, the inner forearc in central and southern Costa Rica is thickened and telescoped by an active thrust system, located along an arc-parallel mountain range and regional drainage divide (henceforth referred to as the Fila Costeña) [*Fisher et al.*, 1998, 2004a]. Additionally, high-angle faults, oriented perpendicular to the trench, allow lateral variations in uplift along the forearc. The areas where the inner forearc exhibits the most shortening, uplift, and unroofing, lie directly inboard of the areas of greatest scarring and subsidence related to seamount subduction on the outer forearc [*Fisher et al.*, 1998]. Thus, there is a strong dichotomy between the inner forearc and outer forearc in the Costa Rican segment of the MAT that directly corresponds with bathymetric features on the subducting plate. Such a dichotomy between inner forearc shortening, uplift, and erosion, and outer forearc extension, subsidence, and trench retreat has been

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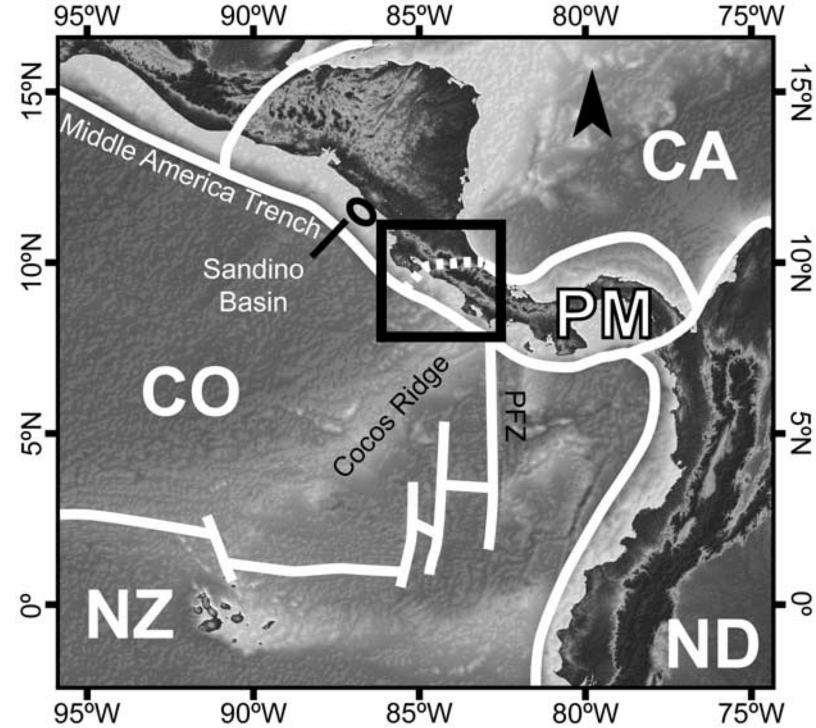

Figure 1. Hill-shaded DEM of Central America superimposed with tectonic boundaries and major bathymetric features. CA, Caribbean plate; PM, Panama microplate; CO, Cocos Plate; NZ, Nazca plate; ND, North Andes plate; PFZ, Panama Fracture Zone. Black box indicates boundary of Figure 2. Topographic data from the SRTM30 data set (source for this data set is the Jet Propulsion Laboratory, 3 arc second SRTM elevation data, Shuttle Radar Topography Mission (SRTM), v. 1.0, available at http://www2.jpl.nasa.gov/srtm/). Bathymetric data are from *Smith and Sandwell* [1997].

observed along other convergent margins with subducting rough crust such as the New Hebrides and Solomon island arcs [*Mann et al.*, 1998; *Meffre and Crawford*, 2001; *Taylor et al.*, 2005], Japan [*Kodaira et al.*, 2000], and central Chile [*Fisher et al.*, 2004b; *Kay et al.*, 2005; *Encinas et al.*, 2006].

[5] This raises an important question: What is the mass balance between outer forearc subsidence and inner forearc uplift? The answer to this question bears on whether margins such as the Costa Rica MAT experience a transfer of material from the outer to the inner forearc, or whether they are truly erosional, where material removed from the margin bypasses the inner forearc. There are two potential mechanisms of inner forearc thickening along an erosive margin: (1) underplating of eroded outer forearc material or incoming seamounts [*Sak et al.*, 2004] and (2) shortening and duplication by thrusting. Outer forearc erosion has been constrained offshore Nicoya Peninsula with estimates of subsidence rates related to Late Tertiary to recent erosion [*Vannucchi et al.*, 2001]. The subsidence rates offshore can be compared with an extensive onland record of Holocene and Late Quaternary uplift rates and incision rates [*Gardner et al.*, 1992; *Bullard*, 1995; *Marshall et al.*, 2000; *Gardner et al.*, 2001; *Fisher et al.*, 2004a]. However, it is difficult to separate the relative contributions of underplating and shortening. Prior to this study, the inner forearc had been mapped both structurally and stratigraphically using a combination of aerial photographs and land-based surveys [*Mora*, 1979; *Lowery*, 1982; *Phillips*, 1983; *Kolarsky et al.*, 1995; *Fisher et al.*, 2004a]. To the best of our knowledge, there has been only one transect across the inner forearc, where the total crustal shortening due to thrusting is estimated (17 km) [*Fisher et al.*, 2004a], with no constraints on lateral variations in shortening along the margin.

[6] In this paper, we quantify the crustal thickening from thrusting in the inner part of the Costa Rican forearc system in an area where there are stratigraphic constraints that allow restoration of thrust-related shortening and characterization of parameters such as shortening rate and the amount of erosional unroofing. The field area lies inboard of the subducting Cocos Ridge in the Fila Costeña, an area that is conjectured to be a region of strong plate coupling based upon inner forearc shortening, as measured along a transect near the Río Térraba gorge (Figures 3 and 4, A-A′) [*Fisher et al.*, 2004a], geodetic observations in the interseismic period [*Norabuena et al.*, 2004; *LaFemina et al.*, 2005], and repeated large subduction earthquakes [*Adamek et al.*, 1987; *Tajima and Kikuchi*, 1995]. We present a geologic map along a 100-km-long segment of the Fila Costeña and evaluate the lateral variations in shortening within the inner forearc in relation to the subducting Cocos Ridge by

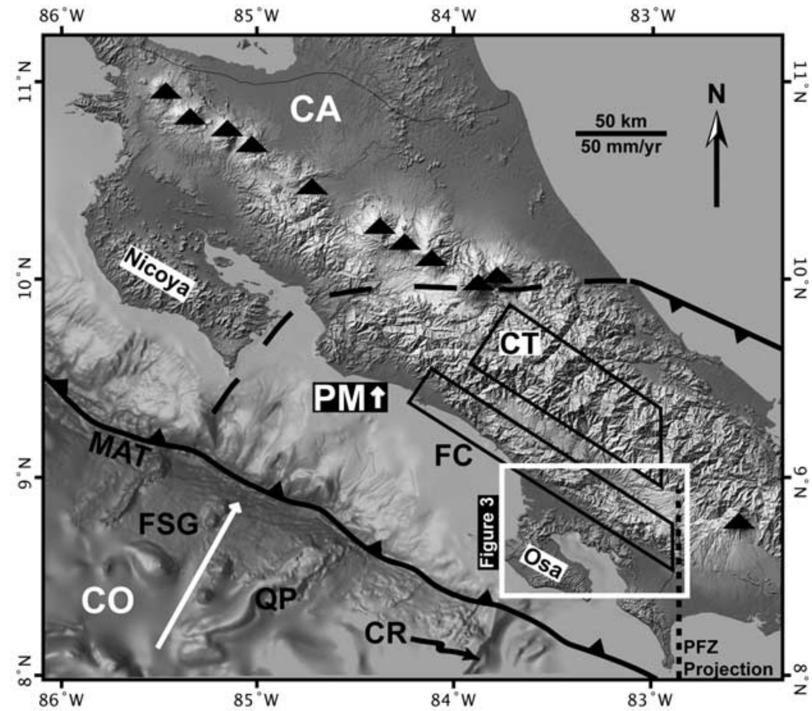

Figure 2. Hill-shaded DEM showing morphologic characteristics of Costa Rica and the adjacent Cocos plate. CA, Caribbean plate; PM, Panama microplate; CO, Cocos Plate; CR, Cocos Ridge; PFZ, Panama Fracture Zone; MAT, Middle America Trench; FSG, Fisher Seamount Group; QP, Quepos Plateau; FC, Fila Costeña (black-enclosed area); CT, Cordillera de Talamanca (black-enclosed area). Black triangles indicate active arc volcanoes. White arrows indicate plate motion vectors relative to a fixed CA based on NNR-NUVEL-1B plate velocity model [*DeMets et al.*, 1990; *Silver et al.*, 1990; *Shuanggen and Zhu*, 2004]. Long-dashed line represents estimated Panama microplate–Caribbean plate boundary (i.e., central Costa Rica deformed belt [*Marshall et al.*, 2000]). Short-dashed line is northward projection of PFZ. White box shows location of Figure 3. Maximum elevation is ~3800 m. Bathymetric data are courtesy of GEOMAR.

constructing a new balanced cross section approximately 25 km east of the *Fisher et al.* [2004a] transect directly inboard of the axis of the ridge (Figures 3 and 4, B-B′).

2. Regional Tectonic Setting

[7] Costa Rica encompasses the forearc and magmatic arc associated with northeast subduction of the Cocos plate beneath the Panama microplate along the MAT (Figures 1 and 2). Offshore Nicaragua and western Costa Rica, the northwest domain of the Cocos crust is characterized by smooth bathymetry, created at the East Pacific Rise 22–24 Ma [*Barckhausen et al.*, 2001; *Protti et al.*, 1995; *von Huene et al.*, 1995]. Steep subduction has led to the formation of ridges at low angles to the trench on the outer rise offshore of Nicaragua [*Ranero et al.*, 2000]. At the Nicoya Peninsula in Costa Rica, rapid subduction of the smooth Cocos crust corresponds with an active arc system [*Alvarado et al.*, 1992; *Marshall et al.*, 2000, 2003; *MacMillan et al.*, 2004], and subduction of seafloor sediment [*Kimura et al.*, 1997]. The southeast domain, created at the Galapagos rift system 15–16 Ma, is predominately rough crust with a thin sediment cover and includes several prominent bathymetric features such as the Fisher Seamount Group (FSG), the Quepos Plateau (QP), and the most expressive feature in the rough segment of the Cocos plate, the Cocos Ridge (CR) (Figure 2) [*Protti et al.*, 1995; *von Huene et al.*, 1995]. Previous research has shown that subduction of this broad, aseismic ridge, which formed as a result of Galapagos Hot Spot volcanism [*Hey*, 1977; *Werner et al.*, 1999], is associated with decreased seismicity along the plate boundary [*Adamek et al.*, 1987; *Protti et al.*, 1995; *Tajima and Kikuchi*, 1995], scouring of the trench slope [*von Huene et al.*, 1995], and forearc thrusting and uplift in Costa Rica [*Corrigan et al.*, 1990; *Gardner et al.*, 1992; *Fisher et al.*, 2004a]. It is best described as a long-wavelength bulge with superposed short-wavelength roughness (e.g., FSG and QP) that subducts slightly obliquely to the trench and is cut by the subducting Panama Fracture Zone (PFZ).

[8] The Central America forearc in Costa Rica can be divided into distinct segments based on Wadati-Benioff zone geometries [*Protti et al.*, 1994], seismic potential [*von Huene et al.*, 2000], and deformation [*Marshall et al.*, 2000]. Segmentation of the overriding Panama and Caribbean plates corresponds with lateral variations in subducting bathymetry. The increase in thickness of sub-

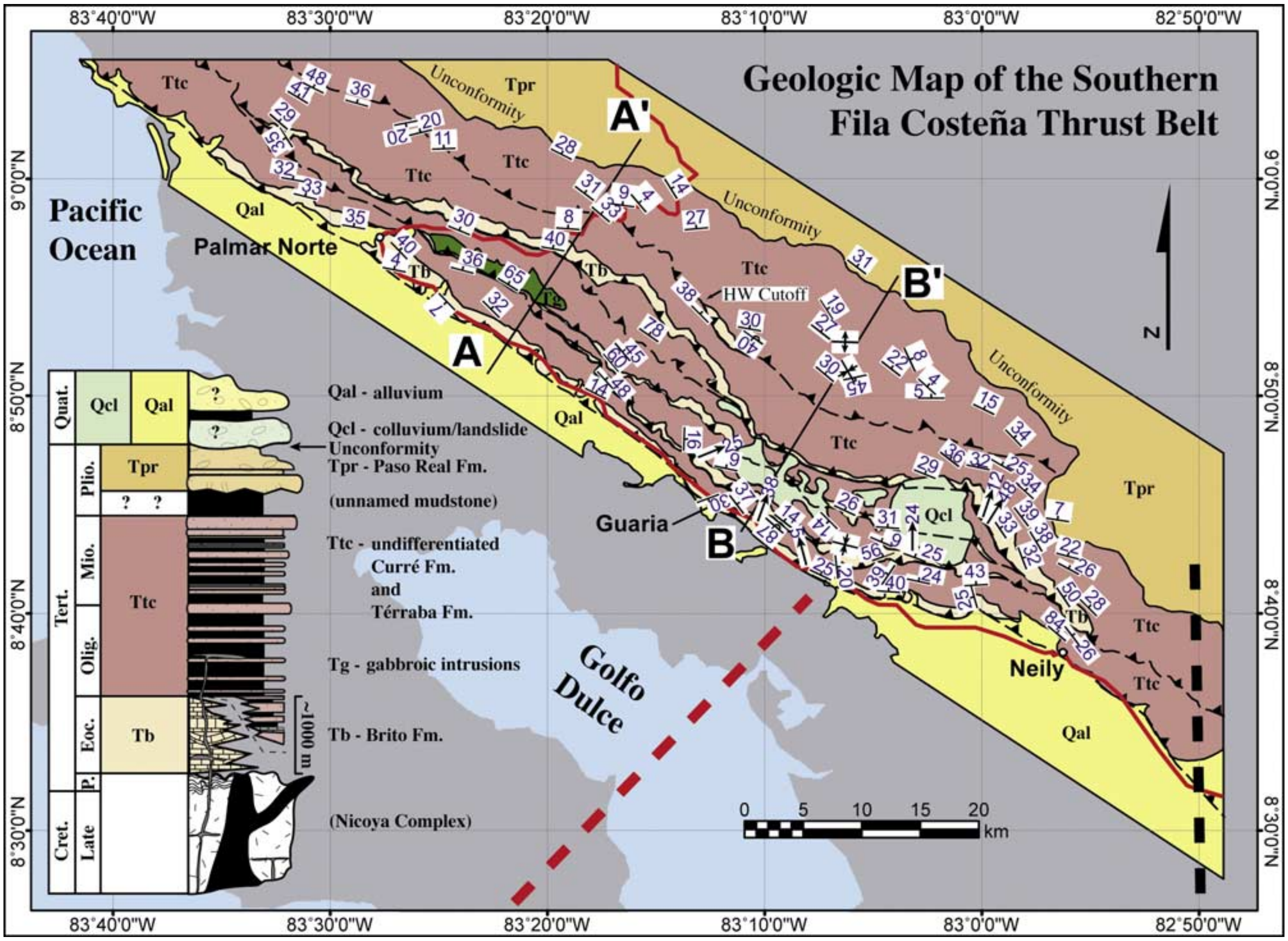

Figure 3. Simplified geologic map of the southern Fila Costeña showing fault traces, strike and dip, slickenline, and fold measurements. Stratigraphic column is modified from *Phillips* [1983] and *Fisher et al.* [2004a]. Solid red line denotes Pan American highway, towns labeled, transecting the thrust belt through the Río Térraba gorge; Dashed black line denotes northward projection of the Panama Fracture Zone, roughly coinciding with the eastern extent of the thrust belt and the Costa Rica–Panama border; Dashed red line denotes onland projection of the Cocos Ridge axis; A-A′ is location of the cross section completed by *Fisher et al.* [2004a]; B-B′ is position of the cross section completed during this study.

ducting crust toward the Cocos Ridge corresponds with a shift from steep to shallow subduction [*Protti et al.*, 1995, 2001]. In the northern segment, Wadati-Benioff zone earthquake foci delineate a slab dip of at least 43° whereas a similar section to the south indicates a roughly 19° dipping seismogenic zone directly inboard of the subducting Cocos Ridge [*Protti et al.*, 1995; *Norabuena et al.*, 2004]. This change in the dip of the Wadati-Benioff zone indicates a tear or sharp bend in the seismic slab at depths greater than 70 km, and has been referred to as the Quesada Sharp Contortion (QSC) [*Protti et al.*, 1994, 1995]. The QSC also coincides with the transition on the upper plate from active volcanism in northwestern Costa Rica to inactive volcanism to the southeast. This volcanic gap, known as the Cordillera de Talamanca, continues approximately 200 km to the southeast until crossing the onland projection of the subducting PFZ into western Panama where volcanic activity resumes [*de Boer et al.*, 1991].

[9] The focus of this study is in the region of the forearc that lies above the shallowly dipping slab between the Cordillera de Talamanca and the Osa Peninsula (Figure 2). The plate interface beneath this region is strongly coupled [*Adamek et al.*, 1987; *Norabuena et al.*, 2004], contributing to infrequent, large earthquakes [*Protti et al.*, 2001; *Norabuena et al.*, 2004], such as the April 3, 1983 (Ms = 7.3; depth = 30 km) plate boundary thrust event located beneath the forearc inboard of the Osa Peninsula [*Adamek et al.*, 1987], and the April 22, 1991 (Ms = 7.5; depth = 12 km) back-thrusting event, located about 100 km to the north beneath the backarc, related to interaction between the Panama microplate and Caribbean plate [*Tajima and Kikuchi*, 1995]. Segments of the plate interface adjacent to these coupled regions experience frequent, smaller earthquakes [*Protti et al.*, 2001; *Bilek et al.*, 2003; *Bilek and Lithgow-*

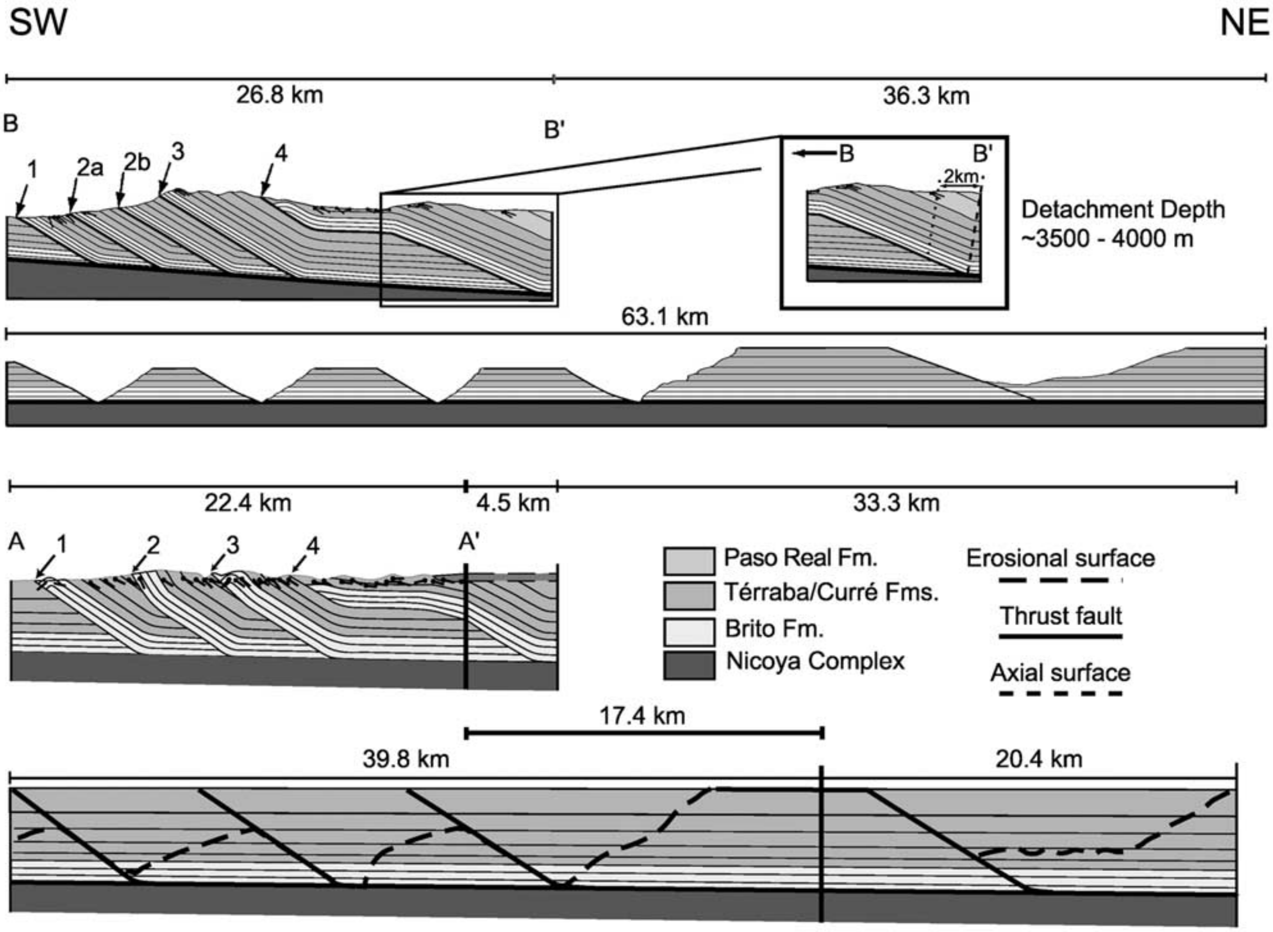

Figure 4. Balanced cross sections along two transects through the southern Fila Costeña (see Figure 3 for location of sections A-A′ and B-B′). Inset shows detachment depth 3500–4000 m. Minimum depth is determined by placing axial surface at rearmost dip measurement (dotted line). Short-dashed line shows probable axial surface location based on total data set. Fault ramps dip 15°–30° to the northeast. The décollement at the basement/cover contact dips 4° to the northeast. B-B′ (completed during this study) lies directly inboard of the subducting Cocos Ridge axis. Minimum shortening over the five thrusts in B-B′ is 36.3 km. The three frontal thrusts are horses in a duplex, and the roof thrust has been eroded. A-A′ (updated from *Fisher et al.* [2004a]) records 17.4 km of total shortening across three thrusts. Restorations were completed by minimizing the amount of possible slip when hanging wall cutoffs were eroded. Fault 4 (previously unreported by *Fisher et al.* [2004a]) has been estimated and added to A-A′, extending the shortened section 4.5 km and the restored section 17.4 km. There is no vertical exaggeration.

Bertelloni, 2005] and outer forearc subsidence [*Vannucchi et al.*, 2001].

3. Tectonic Evolution

[10] Changes in subduction geometry, convergence rate and direction, and upper plate shortening occur at the Panama triple junction where the PFZ subducts beneath the Panama microplate near the Costa Rica-Panama border. There is an abrupt increase in subduction angle from west to east across the PFZ, with shallow subduction of the Cocos plate to the west and steep subduction of the Nazca plate to the east as evidenced by the presence of active arc volcanism in western Panama [*de Boer et al.*, 1991]. This coincides with a sudden change in convergence from nearly orthogonal to highly oblique subduction and a related decrease in trench-perpendicular convergence rate from ∼80 mm/a to ∼20 mm/a across the subducting PFZ (Figure 5) [*DeMets et al.*, 1990; *Silver et al.*, 1990; *Shuanggen and Zhu*, 2004]. Along the upper plate, the Fila Costeña abruptly dies out to the southeast, and there is a change from an inactive, exhumed arc in Costa Rica to an active arc in western Panama (Figure 2) [*Restrepo*, 1987; *de Boer et al.*, 1988, 1991; *MacMillan et al.*, 2004].

[11] Presently, the Panama triple junction migrates to the southeast along the MAT at a rate of ∼55 mm/a relative to a fixed Panama microplate (Figure 5) [*DeMets et al.*, 1990; *Silver et al.*, 1990; *Shuanggen and Zhu*, 2004]. This implies

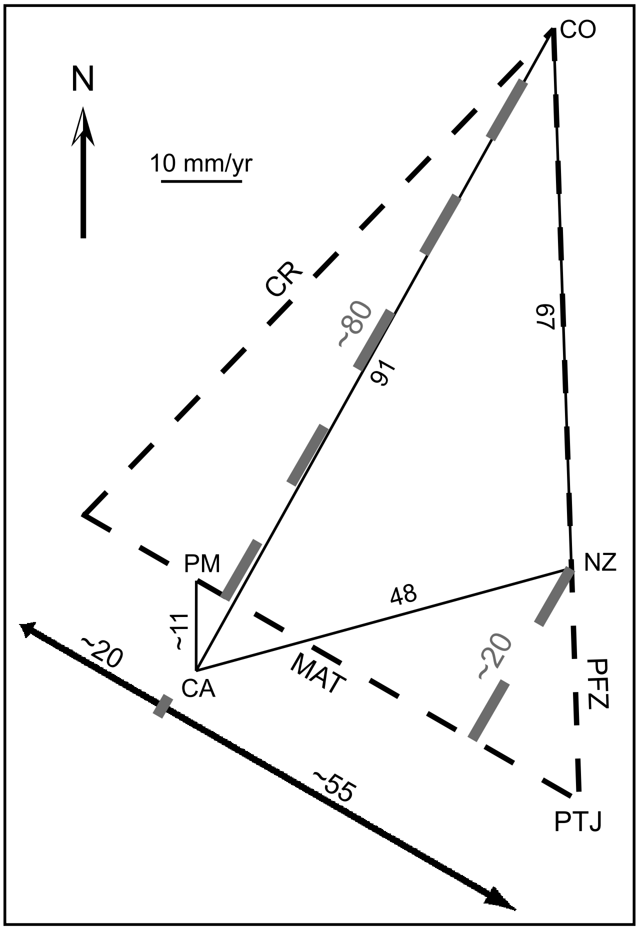

Figure 5. Vector diagram relating Caribbean plate (CA), Cocos plate (CO), Nazca plate (NZ), and Panama microplate (PM). Solid lines are relative plate motion vectors based on NNR-NUVEL-1B plate velocity model [*DeMets et al.*, 1990; *Silver et al.*, 1990; *Shuanggen and Zhu*, 2004]. PM velocity estimate from *Bird* [2003]. Dashed black lines represent the orientations of the Panama Fracture Zone (PFZ) and Middle America Trench (MAT) and Cocos Ridge axis (CR). Intersection of MAT and PFZ is Panama triple junction (PTJ). PTJ migrates ~55 mm/a southeast along MAT with respect to fixed PM. Intersection of MAT and CR migrates ~20 mm/a northwest along MAT. Thick, dashed grey lines indicate PM-NZ and PM-CO convergence rates of ~20 mm/a and ~80 mm/a, respectively.

that the upper plate in southeast Costa Rica experienced slow steep subduction of Nazca crust until the passage of the triple junction in the last million years. Therefore the abrupt changes that occur in the upper plate at the onland projection of the subducting PFZ must migrate eastward into Panama with eastward migration of the triple junction. There is potential for complication in this model if the Cocos-Nazca plate boundary jumped in the past 1 Ma owing to en echelon ridge transform steps associated with the Balboa and Coiba fracture zones. However, two studies of magnetic anomalies on the Nazca plate examined the history of these fracture zones (i.e., Miocene-Pliocene westward propagation of fracture zone activation [*Lonsdale and Klitgord*, 1978; *Lowrie et al.*, 1979]) and found that the PFZ has been the active Cocos-Nazca plate boundary for at least the past 1.5 Ma. On the basis of this assumption, the PFZ has migrated continuously during the past 1.5 Ma providing a time-for-space equivalence along the margin that can be used to determine the time since onset of deformation at both cross section locations discussed later in this paper. This is our primary method for determining shortening rates at any given position along the forearc.

[12] In this paper we focus our discussion on the collision of the Cocos Ridge axis, an event that does not occur until 1–2 Ma, according to plate reconstructions, when the triple junction related to the subducting PFZ migrates southeast past the present position of the ridge [*Lonsdale and Klitgord*, 1978; *Gardner et al.*, 1992; *MacMillan et al.*, 2004]. Given that the Cocos Ridge is oriented roughly N44°E and the relative convergence vector between the Cocos plate and the Panama block is oriented N30°E, the ridge will migrate to the northwest at a rate of 20 km/Ma (Figure 5). Thus the axis of the indenting ridge has not migrated more than 40 km since initial arrival at the MAT.

[13] Much of the deformation of the inner forearc in Costa Rica can be attributed to Cocos Ridge collision along the MAT. Estimates for the timing of arrival of the Cocos Ridge along the MAT range from 8 Ma [*Abratis and Wörner*, 2001] to 1 Ma [*Lonsdale and Klitgord*, 1978; *Gardner et al.*, 1992]. The earliest estimate of 8 Ma is based on cessation of "normal" calc-alkaline magmatism and occurrence of anomalous adakitic magmatism [*de Boer et al.*, 1991; *Drummond et al.*, 1995] distributed throughout southern Costa Rica and into Panama [*Abratis and Wörner*, 2001]. An arrival estimate of 5.5 Ma is derived from fission track ages that indicate rapid unroofing of the arc at this time [*Gräfe et al.*, 2002]. Benthic foraminifera assemblages suggest emergence of the forearc and backarc dated at 3.6 and 1.6 Ma, respectively [*Collins et al.*, 1995]. Stratigraphic, paleontological, and structural data on the exposed outer forearc in southern Costa Rica document Cocos Ridge effects around 1 Ma [*Corrigan et al.*, 1990], and oceanic crust magnetic anomaly data place the rough crust of the Cocos Ridge at the MAT 1 Ma in Neogene plate reconstructions [*Lonsdale and Klitgord*, 1978; *Gardner et al.*, 1992; *MacMillan et al.*, 2004]. We suggest that the range in estimates for Cocos Ridge arrival reflects differing definitions of the "ridge," with earliest estimates based on the arrival of anomalously thick oceanic crust along the northwest flank of the ridge that was created at the Galapagos rift system, and more recent estimates based on the arrival of the truncated ridge axis in a strict sense.

4. Térraba Trough

[14] The exposed Tertiary forearc basin in southern Costa Rica has been collectively referred to as the Térraba Trough [*Yuan*, 1984]. What was once an inner forearc depositional basin, similar to the present-day submerged, seismically imaged, deep Sandino basin of Nicaragua [*Ranero et al.*,

2000], is now a thrust faulted coastal mountain range (i.e., the Fila Costeña) (Figure 2). As in the case of the Sandino basin in Nicaragua, the strata of the forearc basin in Costa Rica record the depositional history inboard of the outer forearc rise. In this section, we summarize the mappable formations used in palinspastic reconstructions of the thrust belt.

[15] The Térraba River provides a natural transect through the central portion of this mountain range and has been a primary location for previous sedimentological [*Mora*, 1979; *Lowery*, 1982; *Phillips*, 1983], and structural [*Mora*, 1979; *Kolarsky et al.*, 1995; *Fisher et al.*, 2004a] surveys. Five distinctive stratigraphic units were identified in the Fila Costeña. These units, the Brito Formation, Térraba Formation, Curré Formation, an unnamed Pliocene unit and the Paso Real Formation, are described in terms of five margin-scale lithofacies: (1) carbonate-dominated turbidites, (2) mixed bioclastic and volcaniclastic turbidites to volcaniclastic-dominated turbidites, (3) volcaniclastic dominated conglomerate and breccia, (4) fossiliferous mudstone and (5) lahars, respectively (Figure 3, inset) [*Mora*, 1979; *Lowery*, 1982; *Phillips*, 1983]. The entire stratigraphic column, as measured in the thrust belt, constitutes more than 4 km of forearc basin sediments deposited in the last 55 Ma atop crystalline basement rock [*Phillips*, 1983; *Yuan*, 1984] of the Nicoya Complex, which is only exposed in basement highs related to outer forearc uplift [*Phillips*, 1983; *Yuan*, 1984]. The basement/cover contact is, therefore, a nonconformity or a faulted unconformity [*Phillips*, 1983; *Yuan*, 1984].

[16] The Brito Formation is the oldest sedimentary unit exposed in the Fila Costeña. Although the lower contact is not exposed in the thrust belt, it is presumed that the carbonate sequence in southeastern Costa Rica is approximately 600 m thick and rests atop the Nicoya Complex [*Phillips*, 1983]. The Térraba Formation, named after the type locality along the Río Térraba of Costa Rica, conformably overlies the Brito Formation. This Oligocene to Lower Middle Miocene mixed bioclastic/volcaniclastic turbidite sequence consists of approximately 1000 m of black shale, marl, sandstone, and conglomerate. The formation, in a broad sense, becomes increasingly coarse and volcaniclastic toward the top, suggesting a regional shoaling during this time period associated with the development of the Central American arc complex [*Phillips*, 1983]. Gabbroic intrusions, dated by K-Ar at 15–11 Ma, intrude both the Brito Formation and Térraba Formation [*de Boer et al.*, 1995; *MacMillan et al.*, 2004].

[17] As the depositional environment shoaled adjacent to the volcanic arc during the Middle and Late Miocene, the deposits became progressively more conglomeratic. This gradation into a shallow marine and terrestrial environment marks the base of the Curré Formation, which generally coarsens upward and includes approximately 830 m of volcaniclastic sediment. The top of the formation is poorly exposed, but in at least two locations in the central and northwest Fila Costeña, an unnamed Pliocene mudstone, up to 200 m thick and dated using fossil evidence, rests unconformably upon the terrestrial sediments of the Upper Curré Formation [*Kesel*, 1983], indicating a final marine inundation before inner forearc basin deformation and exhumation [*Kesel*, 1983]. Terrestrial alluvial deposits (i.e., lahars, pyroclastics, and lava flows) of the Pliocene Paso Real Formation were subsequently shed off of the Cordillera de Talamanca into the forearc, forming another regional unconformity [*Kesel*, 1983; *Phillips*, 1983]. The unnamed marine mudstone was not found in our mapping area and was likely eroded prior to deposition of the Paso Real Formation [*Kesel*, 1983]. Therefore the unconformity between the Curré and Paso Real formations and the correlative unconformity between the unnamed Pliocene mudstone and the Paso Real Formation provides a maximum age for the onset of exhumation in the Fila Costeña. Consequently, we can calculate an absolute minimum long-term shortening rate for the thrust belt.

[18] The Quaternary deposits found in the vicinity of the Fila Costeña are regionally unconformable and can broadly be divided into the mid-Pleistocene to Holocene Brujo Formation [*Phillips*, 1983] (located outside of our map area) and unnamed recent terrace gravels. The Brujo Formation is composed of alluvial fan and debris flow deposits shed off of the Cordillera de Talamanca into the valley between the Cordillera de Talamanca and the Fila Costeña [*Kesel*, 1983] to the northwest of our map area. In the 1970s, Richard Kesel identified several features indicative of active, ongoing uplift and exhumation of the Cordillera de Talamanca and inner forearc. These include faulted and back-tilted alluvial fans, lacustrine deposits formed from stream reversals, radiocarbon dated at 9 and 13 ka, and the appearance and increase in relative abundance of Cordillera de Talamanca–sourced plutonic clasts in the middle and upper Brujo Formation, above a 26.5 ka radiocarbon dated sample [*Kesel*, 1983].

[19] Incised fluvial terraces are preserved along rivers that cross the thrust belt, and the elevation of Late Quaternary terraces near the thrust front requires uplift along the frontal thrust [*Bullard*, 1995; *Murphy*, 2002; *Fisher et al.*, 2004a]. Dated marine terraces are also observed along the frontal thrust in the central Fila Costeña [*Fisher et al.*, 2004a]. In the region of the thrust belt directly inboard of the Cocos Ridge axis, extensive landslides have been shed off of the topographic divide (Figures 3 and 6). An individual slide in this region has an area of 39 square kilometers (Figure 3). Today, these deposits are identified by vegetated, hummocky topography that extends at least 4 km from the steep divide and contains limestone boulders in excess of several meters in diameter.

5. Geologic and Structural Mapping of the Fila Costeña

[20] The Fila Costeña is a 20- to 30-km-wide thrust belt that extends approximately 250 km from the Golfo de Nicoya to the Panama border. The geology of the southern $\sim$2000 km^2 was mapped using 1:50,000 topographic base maps (Figure 3). The mapped area encompasses the southeastern portion of the deformed Tertiary forearc basin inboard of the Cocos Ridge. Outcrops are generally limited to coastal headlands, numerous valley walls and streambeds

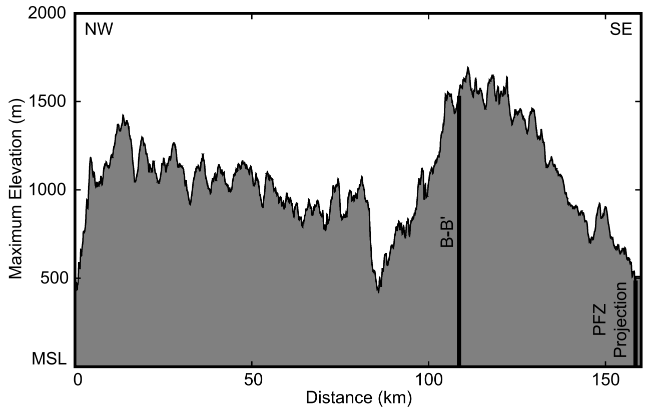

Figure 6. Topographic divide elevations along the Fila Costeña plotted parallel to the margin and extending the length of the thrust belt inboard of the Cocos Ridge (~160 km). The topographic minimum in the center of the plot is the Río Térraba gorge, which transects the thrust belt. B-B′ indicates position of the cross section completed in this paper (Figure 4, B-B′). Slightly southeast of this location the maximum elevation in the Fila Costeña is inboard of the subducting Cocos Ridge axis. Elevation of the divide decreases rapidly toward the onland projection of the Panama Fracture Zone.

oriented perpendicular to the structure, and quarries. The thrust belt in this area comprises three to five continuous thrust slices that imbricate the Térraba Trough. Strata within imbricate thrust slices strike parallel to the MAT (WNW–ESE) and dip ~15°–35° to the northeast. Mesoscale folds associated with southwest-directed thrusts in the thrust belt verge seaward with subhorizontal axes parallel to thrust traces. Overturned beds are rare but can be locally observed in the footwalls of major thrusts.

[21] The major thrusts are most easily recognized in our map area where they place carbonates of the Brito Formation on top of turbidites of the Térraba Formation. The Brito Formation, therefore, provides a key bed that is used to line length balance cross sections (Figure 4). To the northwest of our map area, the central Fila Costeña lies inboard of relatively smooth subducting bathymetry on the northwest flank of the subducting Cocos Ridge. Here the frontal thrust steps offshore, parallels the coastline, and returns landward along a lateral ramp [*Fisher et al.*, 2004a]. No limestone is exposed at the base of the thrust faults in this region, indicating a décollement above the Brito Formation at the northwest extent of the mapped area in this study (Figure 3).

[22] As the thrust belt nears the onland projection of the Cocos Ridge axis to the southeast, the basal décollement deepens stratigraphically toward the basement/cover contact, as indicated by the presence of Brito Formation limestone at the base of the individual thrusts. Slightly off-axis to the west, three thrusts expose hanging wall flats within the limestone and a fourth thrust at the rear of the thrust belt exposes a hanging wall flat stratigraphically higher in the Térraba Formation (Figure 4, A-A′). Directly inboard of the subducting Cocos Ridge axis, the total number of thrust sheets increases to five (Figure 4, B-B′). This imbricate fault system could be described as either an imbricate fan or a duplex. The observation that the frontal three thrust sheets are thinner than the total thickness of the Térraba Trough as defined by the depth-to-detachment (Figure 4, inset) at the rear of the thrust belt requires that either (1) the Térraba Trough was significantly thinner to the southwest in the case of an imbricate fan or (2) the frontal thrust slices involve only the deeper strata of the Térraba Trough and the roof thrust of a duplex is eroded away. We favor a duplex model because the basal limestones on thrust faults 2a and 2b terminate laterally at hanging wall cutoffs before merging at leading branch lines (Figure 3).

[23] In the area where thrust shortening is greatest, the topographic divide is roughly 1,700 m high, at least 200 m higher than the top of the divide along strike (Figure 6). This divide is supported by massive limestones along the base of thrust sheet 3 (Figures 3 and 4, B-B′). Recent landslides scour the unstable southwest-facing slope. Hummocky topography extends approximately four kilometers to the southwest away from the divide between fault 3 and fault 2b (Figure 3). This is the only location within the southeastern Fila Costeña where there is evidence of extensive landslides on the order of tens of square kilometers.

[24] Total shortening decreases northwest and southeast of this region as individual thrusts merge at leading branch-lines with the roof thrust. Farther to the east, the thrust belt terminates, or shortening is greatly reduced, across north–south trending tear faults that extend to the north into Pleistocene deposits [*Cowan et al.*, 1997; *Morell et al.*, 2007]. These right-lateral faults coincide with the updip projection of the PFZ and have been interpreted as indentation faults that are deeply rooted in the crust of the Panama microplate [*Kolarsky et al.*, 1995].

[25] The overall regional pattern within the thrust belt is a lenticular culmination that exposes basal limestones in a series of laterally tapering thrust slices centered over the axis of the subducting ridge (Figure 3). This trend of decreasing shortening to the northwest is also suggested by the absence of Brito Formation in thrusts (i.e., stepping up of the décollement into younger strata). To quantify this relationship, two balanced cross sections were constructed: one along the Térraba gorge along a transect described by *Fisher et al.* [2004a] and another within the culmination inboard of the Cocos Ridge axis where the shortening is inferred to be the greatest (Figure 4). To the southeast of both of these transects, the thrust belt ends abruptly near the Costa Rica–Panama border at the updip projection of the subducting PFZ (Figures 2 and 3).

[26] Balanced cross sections were constructed using structural data collected in the field throughout the Tertiary and Quaternary deposits in the southeast Fila Costeña. Toward the rear of the thrust belt, the axial surface related to the closing bend at the base of frontal footwall ramps is placed behind the rearmost observation of steeply dipping strata in order to both minimize shortening and satisfy dip data at the surface. This axial surface is projected to the intersection with the rearmost thrust that exposes Brito

Formation along the base. This fault in cross section is constrained by the surface trace and the dip of beds in the hanging wall. On the basis of these assumptions, the décollement depth is at approximately 3500 and 4000 m below the surface, a depth that is in agreement with previous structural and stratigraphic studies in the nearby Térraba gorge [*Phillips*, 1983; *Fisher et al.*, 2004a].

[27] The Fila Costeña is depicted in these cross sections as a thin-skinned thrust belt with imbricate faults that are rooted at the basement-cover contact. We base this interpretation on the observation that, for most exposed thrusts within the area, the hanging wall consists of a flat at or near the base of the Brito limestone. In one such case we measured downdip slickenlines on a northeast dipping regional fault surface that places Brito Formation atop Térraba Formation. In six other cases we measured less extensive faults with strikes ranging from N79°W to N24°W (average = N52°W) and dips from 19° to 54° NE (average = 40°). Slickenlines measured on these six fault surfaces plunge an average of 25°, a vergence of S21°W, indicating primarily dip slip motion. Fold trends at five locations range from N88°W to N15°W (average = N64°W). These observations, coupled with the absence of any exposed basement in the mapping area, are consistent with northeast-directed underthrusting of the outer forearc basement beneath the forearc sedimentary basin.

[28] On the basis of a line-length balance of the Brito Formation on a cross section located above the subducting axis of the Cocos Ridge, the minimum slip is 4.5 km, 5.5 km, 6.3 km, 8.1 km, and 12 km for faults 1, 2a, 2b, 3, and 4, respectively, representing a minimum shortening of approximately 36 km, a 58% decrease in line length (Figure 4, B-B′). Using the distance from the onland projection of the PFZ (~50 km) as a proxy for time since the onset of deformation (~1 Ma), this indicates a shortening rate of nearly 40 mm/a, roughly half of the Cocos-Panama plate convergence rate of ~80 mm/a (Figure 5). The lateral equivalent of fault 4 in section B-B′ was not included in the cross section from *Fisher et al.* [2004a], because this fault does not expose the Brito Formation in the Térraba gorge. On the map, the fault is required by the exposure of a Brito Formation hanging wall cutoff along the fault just to the southeast of the gorge (Figure 3, "HW Cutoff"). To the east of this exposure, shallow dip measurements in the Térraba Formation indicate a hanging wall flat. Therefore the addition of this fault in that section increases the overall shortening from 17 km to approximately 33 km, or 55% total shortening (Figure 4, A-A′). Although both reconstructions minimize the shortening, the cross section near the Térraba gorge exposes hanging wall cutoffs in two of the thrust sheets (Figure 4, A-A′). Therefore the potential to underestimate the shortening is less likely at that location than at the center of the culmination where most of the Brito cutoffs are eroded (Figure 4, B-B′).

6. Discussion

[29] The observations we present in this paper illustrate that accommodation of active convergence occurring at a convergent plate boundary may rapidly shift from the trench to the inner forearc in response to increased outer forearc coupling, such as shallow subduction of thickened crust [*von Huene et al.*, 1995]. In the case of southeastern Costa Rica, the inner forearc is accommodating upper plate shortening between the extinct arc and the MAT. The deformation is localized in the region affected by the colliding Cocos Ridge, with rates of shortening roughly 50% of the total Cocos-Panama convergence rate. This increase in coupling in conjunction with relatively fast subduction of young oceanic crust is contrary to model results for quasistatic equilibrium [*Yáñez and Cembrano*, 2004], indicating that the features we observe represent a transient response to Cocos Ridge subduction.

[30] The Fila Costeña of Costa Rica records a minimum of 36 km of slip on five major thrust faults directly inboard of the axis of the subducting Cocos Ridge. Tear faults in the thrust belt are restricted to lateral ramps as the décollement cuts up section to the northwest [*Fisher et al.*, 2004a] and to the southeast above the onland projection of the subducting PFZ. For estimates of shortening, we assume that the thrust faults record primarily dip slip, an observation that is consistent with measured slickenlines along the exposed faults in the area, including one major fault.

[31] It should be noted that we were not able to locate any observable outcrop of the Curré Formation in the frontal portion of the Fila Costeña southeast of the Térraba gorge. The depositional facies associated with the Curré Formation must have been confined to the region proximal to the volcanic arc and paleoshoreline. We speculate that this depositional environment did not exist at the restored location of the front of the thrust belt, some 80 km away from the volcanic arc, during the time of deposition of the Curré Formation. The correlative facies at that distal location would be more similar to that of the Térraba Formation, and a Curré-type sequence may never have been deposited there. This would imply that the undeformed basin had trenchward variations in lithofacies and would display significant disparities in postcompaction thicknesses, a conjecture that is consistent with seismic reflection data landward of the outer forearc rise in the deep Sandino basin of Nicaragua [*Ranero et al.*, 2000], with seaward thinning of sedimentary packages relative to a forearc basin depocenter. Given the discontinuous nature of exposure in the thrust belt, we employ the simplest case for structural reconstruction, which is to consolidate the Térraba Formation and Curré Formation on the maps and cross sections, and assume a constant basin-wide thickness for each sedimentary unit based on measurements made in the Térraba gorge during previous studies [*Phillips*, 1983]. This is a simplification that bears no relevance on our minimum shortening estimate that is based on conservation of line length for the base of the Brito Formation. Nevertheless, seaward thinning of units would have a large effect on the geometry of the thrust system in cross sections and the position of the roof thrust in reconstructions.

[32] Radiocarbon dated volcaniclastics of the Brujo Formation that are faulted and back-tilted, and lacustrine deposits formed from stream reversals as a result of this

tilting [*Kesel*, 1983] as well as incised Quaternary river terraces [*Bullard*, 1995; *Murphy*, 2002; *Fisher et al.*, 2004a] indicate that the Fila Costeña is actively deforming. Where the thrust belt extends offshore, there is a regionally extensive marine platform that indicates uplift rates of 0.34 mm/a and 1.5 mm/a [*Fisher et al.*, 2004a]. The map and cross sections of the Fila Costeña show that shortening in the inner forearc is greatest inboard of the Cocos Ridge axis, where the thrust belt assembles into a duplex, and decreases along strike. This unique structural feature within the thrust belt lies directly in front of the highest and sharpest topographic divide in the Fila Costeña (Figures 3 and 6), a ridge that is supported by resistant limestones that comprise the rear thrust in the duplex. Landslides are shed off of the divide and bury strata on the backside of the adjacent thrust sheet to the south (Figure 3). Major thrusts inboard of the Cocos Ridge axis detach at the contact between the crystalline basement rock and the overlying Tertiary forearc basin sequence, producing a duplex that imbricates the lower strata of the Térraba basin. Several of the fault traces merge laterally, away from the onland projection of the ridge axis, as the duplex terminates to the northwest and southeast at leading branch lines. As the overall number of faults decrease, they step upsection from the basement/cover contact into the Térraba Formation. These observations support conjectures that shallow subduction of the Cocos Ridge has caused arching of the Panama microplate parallel to the plate convergence vector [*Corrigan et al.*, 1990; *Kolarsky et al.*, 1995]. If this is the case, the depth of the basal detachment beneath the thrust belt relative to some horizontal datum may be constant, while shallowing stratigraphically to the east and west owing to basement arching above the Cocos Ridge axis [*Kolarsky et al.*, 1995].

[33] Current geodetic observations using a limited GPS array can be used to infer the coupling between the Cocos plate and the Panama microplate [*Norabuena et al.*, 2004]. However, these tools typically measure displacements related to elastic strains that accumulate during the interseismic part of the seismic cycle rather than long-term, time-averaged deformation rates. *Norabuena et al.* [2004] describe GPS displacements from a regional network in Costa Rica that depict greater coupling in the area inboard of the subducting Cocos Ridge than in other parts of the thrust belt. A single site within the area of the thrust culmination of the Fila Costeña records an arcward velocity of ~35 mm/a relative to a stable Caribbean plate [*Norabuena et al.*, 2004], a value that is very close to our estimate for long-term shortening rates. The map and cross sections of this study indicate that the increased plate boundary coupling inferred for the interseismic time period are matched by greater amounts of long-term upper plate shortening in the inner forearc.

7. Conclusions

[34] There is an active thrust belt along the Central American convergent margin that uplifts the inner forearc basin in Costa Rica. Geologic maps and cross sections lead to several conclusions about the relationship between the Cocos plate and Panama microplate at the MAT in southeastern Costa Rica. (1) Deformation is concentrated inboard of the Cocos Ridge where a culmination is reached by an imbricate stack with an eroded roof thrust. (2) This region coincides with a relative increase in interseismic coupling based on geodetics [*Norabuena et al.*, 2004]. (3) The total number of thrusts decreases to the northwest and southeast of the onland projection of the Cocos Ridge axis where they join adjacent thrusts at leading branch lines, indicating erosion through the roof thrust in the area of greatest shortening. Away from the Cocos Ridge axis, the décollement of the Fila Costeña steps up laterally into the Térraba Formation. (4) To the southeast, the topographic expression of the thrust belt ends abruptly at the onland projection of the subducting PFZ, suggesting that the thrust belt may be actively propagating to the southeast with the Panama triple junction. (5) Minimum shortening within the thrust belt since the middle Pliocene is 36 km, representing more than 58% shortening in the inner forearc. (6) The calculated minimum shortening rate of ~40 mm/a inboard of the Cocos Ridge axis represents nearly 50% of the total plate convergence rate. (7) Given shortening rates of tens of millimeters per year along the Fila Costeña, much of the trench retreat estimated for the outer forearc [e.g., *Vannucchi et al.*, 2004] can be accounted for by increased plate boundary coupling and underthrusting of the outer forearc wedge beneath the inner forearc.

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References

Abratis, M., and G. Wörner (2001), Ridge collision, slab-window formation, and the flux of Pacific asthenosphere into the Caribbean realm, *Geology*, *29*, 127–130.

Adamek, S., F. Tajima, and D. A. Wiens (1987), Seismic rupture associated with subduction of the Cocos Ridge, *Tectonics*, *6*, 757–774.

Alvarado, G. E., et al. (1992), Chronostratigraphy of Costa Rican igneous rocks based on radiometric dating, *J. S. Am. Earth Sci.*, *6*, 151–168.

Barckhausen, U., et al. (2001), Revised tectonic boundaries in the Cocos Plate off Costa Rica: Implications for the segmentation of the convergent margin and for plate tectonic models, *J. Geophys. Res.*, *106*, 19,207–19,220.

Bilek, S. L., and C. Lithgow-Bertelloni (2005), Stress changes in the Costa Rica subduction zone due to the 1999 Mw = 6.9 Quepos earthquake, *Earth Planet. Sci. Let.*, *230*, 97–112.

Bilek, S. L., et al. (2003), Control of seafloor roughness on earthquake rupture behavior, *Geology*, *31*, 455–458.

Bird, P. (2003), An updated digital model of plate boundaries, *Geochem. Geophys. Geosyst.*, *4*(3), 1027, doi:10.1029/2001GC000252.

Bullard, T. F. (1995), Neotectonics, geomorphology, and late Quaternary geology across a forearc region impacted by the subduction of the aseismic Cocos Ridge, Pacific coast of Costa Rica, Ph.D., 775 pp., Univ. of N. M., Albuquerque.

Clift, P., and P. Vannucchi (2004), Controls on tectonic accretion versus erosion in subduction zones: Implications for the origin and recycling of the continental crust, *Rev. Geophys.*, *42*, RG2001, doi:10.1029/2003RG000127.

Collins, L. S., et al. (1995), Timing and rates of emergence of the Límon and Bocas del Toro basins: Caribbean effects of Cocos Ridge subduction?, *Spec. Pap. Geol. Soc. Am.*, *295*, 263–289.

Corrigan, J., et al. (1990), Fore-arc response to subduction of the Cocos Ridge, Panama Costa-Rica, *Geol. Soc. Am. Bull.*, *102*, 628–652.
Cowan, H., et al. (1997), Active faulting at the Cocos-Nazca-Caribbean Plate triple junction, southern Costa Rica and western Panama, *Geol. Soc. Am. Abstr. Programs*, *29*, 442.
de Boer, J. Z., et al. (1988), Quaternary calc-alkaline volcanism in western Panama: Regional variation and implication for the plate tectonic framework, *J. S. Am. Earth Sci.*, *1*, 275–293.
de Boer, J. Z., et al. (1991), Evidence For active subduction below western Panama, *Geology*, *19*, 649–652.
de Boer, J. Z., et al. (1995), Cenozoic magmatic phases of the Costa Rican island arc (Cordillera de Talamanca), *Spec. Pap. Geol. Soc. Am.*, *295*, 35–55.
DeMets, C., et al. (1990), Current plate motions, *Geophys. J. Int.*, *101*, 425–478.
Dominguez, S., et al. (1998), Upper plate deformation associated with seamount subduction, *Tectonophysics*, *293*, 207–224.
Drummond, M., et al. (1995), Igneous petrogenesis and tectonic setting of Plutonic and volcanic rocks of the Cordillera de Talamanca, Costa Rica—Panama, Central American Arc, *Am. J. Sci.*, *295*, 875–919.
Encinas, A., et al. (2006), Finding of a Holocene marine layer in Algarrobo (33°22′S), central Chile: Implications for coastal uplift, *Rev. Geol. Chile*, *33*(2), 339–345.
Fisher, D. M., et al. (1998), Effect of subducting seafloor roughness on fore-arc kinematics Pacific coast, Costa Rica, *Geology*, *26*, 467–470.
Fisher, D. M., T. W. Gardner, P. B. Sak, J. D. Sanchez, K. Murphy, and P. Vannucchi (2004a), Active thrusting in the inner forearc of an erosive convergent margin, Pacific coast, Costa Rica, *Tectonics*, *23*, TC2007, doi:10.1029/2002TC001464.
Fisher, D. M., S. H. Kirby, and S. W. David (2004b), In the footsteps of Charles Darwin: Patterns of coastal subsidence and uplift associated with seamount subduction, basal fore-arc erosion and seamount accretion in Latin America, *Eos Trans. AGU*, *85*(47), Fall Meet. Suppl., Abstract T23B-0585.
Gardner, T. W., et al. (1992), Quaternary uplift astride the aseismic Cocos Ridge, Pacific Coast, Costa-Rica, *Geol. Soc. Am. Bull.*, *104*, 219–232.
Gardner, T. W., et al. (2001), Holocene fore arc deformation in response to seamount subduction, Peninsula de Nicoya, Costa Rica, *Geology*, *29*, 151–154.
Gräfe, K., et al. (2002), Geodynamic evolution of southern Costa Rica related to low-angle subduction of the Cocos Ridge: Constraints from thermochronology, *Tectonophysics*, *348*, 187–204.
Hey, R. N. (1977), Tectonic evolution of the Cocos-Nazca spreading center, *Geol. Soc. Am. Bull.*, *88*, 1404–1420.
Hinz, K., R. von Huene, C. R. Ranero, and PACOMAR Working Group (1996), Tectonic structure of the convergent Pacific margin offshore Costa Rica from multichannel seismic reflection data, *Tectonics*, *15*, 54–66.
Kay, S. M., et al. (2005), Episodic arc migration, crustal thickening, subduction erosion, and magmatism in the south-central Andes, *Geol. Soc. Am. Bull.*, *117*, 67–88.
Kesel, R. H. (1983), Quaternary history of the Rio General Valley, Costa Rica, *Res. Rep. 15*, pp. 339–358, Natl. Geogr. Soc., Washington, D. C.
Kimura, G., et al. (1997), *Proceedings of the Ocean Drilling Program, Initial Reports: Costa Rica Accretionary Wedge, Covering Leg 170 of the Cruises of the Drilling Vessel JOIDES Resolution, San Diego, California, to Balboa, Panama, Sites 1039-1043, 16 October-17 December 1996*, 458 pp., Ocean Drill. Program, Tex. A & M Univ., College Station.
Kodaira, S., et al. (2000), Subducted seamount imaged in the rupture zone of the 1946 Nankaido earthquake, *Science*, *289*, 104–106.
Kolarsky, R. A., et al. (1995), Island arc response to shallow subduction of the Cocos Ridge, Costa Rica, *Spec. Pap. Geol. Soc. Am.*, *295*, 235–262.
LaFemina, P. C., T. H. Dixon, S. Schwartz, M. Protti, and V. Gonzalez (2005), Subduction of an aseismic Ridge: Interseismic deformation above the Cocos Ridge, Costa Rica, *Eos Trans. AGU*, *86*(52), Fall Meet. Suppl., Abstract T42A-07.
Lonsdale, P., and K. D. Klitgord (1978), Structure and tectonic history of the eastern Panama Basin, *Geol. Soc. Am. Bull.*, *89*, 981–999.
Lowery, B. J. (1982), Sedimentology and tectonic implications of the middle to upper Miocene Curre formation, southwestern Costa Rica, B. S., La. State Univ., Baton Rouge.
Lowrie, A., et al. (1979), Fossil spreading center and faults within the Panama fracture zone, *Mar. Geophys. Res.*, *4*, 153–166.
MacMillan, I., et al. (2004), Middle Miocene to present plate tectonic history of the southern Central American Volcanic Arc, *Tectonophysics*, *392*, 325–348.
Mann, P., et al. (1998), Accelerating late Quaternary uplift of the New Georgia Island Group (Solomon island arc) in response to subduction of the recently active Woodlark spreading center and Coleman seamount, *Tectonophysics*, *295*, 259–306.
Marshall, J. S., D. M. Fisher, and T. W. Gardner (2000), Central Costa Rica deformed belt: Kinematics of diffuse faulting across the western Panama block, *Tectonics*, *19*, 468–492.
Marshall, J. S., et al. (2003), Landscape evolution within a retreating volcanic arc, Costa Rica, Central America, *Geology*, *31*, 419–422.
Meffre, S., and A. J. Crawford (2001), Collision tectonics in the New Hebrides arc (Vanuatu), *Island Arc*, *10*, 33–50.
Meschede, M. (2003), The Costa Rica convergent margin: A textbook example for the process of subduction erosion, *Neues Jahrb. Geol. Palaontol. Abh.*, *230*, 409–428.
Meschede, M., et al. (1999a), Subsidence and extension at a convergent plate margin: Evidence for subduction erosion off Costa Rica, *Terra Nova*, *11*, 112–117.
Meschede, M., et al. (1999b), Melange formation by subduction erosion: The case of the Osa melange in southern Costa Rica, *Terra Nova*, *11*, 141–148.
Meschede, M., et al. (2002), Benthic foraminiferal distribution and sedimentary structures suggest tectonic erosion oat the Coast Rica convergent plate margin, *Terra Nova*, *14*, 388–396.
Mora, S. (1979), Estudio geologico de una parte de la region sureste del Valle del General, Provincia Puntarenas, Costa Rica, undergraduate thesis, 185 pp., Univ. de Costa Rica, San Pedro, Costa Rica.
Morell, K. D., et al. (2007), Inner forearc response to subduction of the Panama Fracture Zone, southern Central America, *Earth. Planet. Sci. Lett.*, doi:10.1016/j.epsl.2007.09.039, in press.
Murphy, K. (2002), Use of weathering rinds in fluvial terrace correlation along the coastal forearc, Pacific coast, Costa Rica, B. S., 70 pp., Trinity Univ., San Antonio, Tex.
Norabuena, E., et al. (2004), Geodetic and seismic constraints on some seismogenic zone processes in Costa Rica, *J. Geophys. Res.*, *109*, B11403, doi:10.1029/2003JB002931.
Phillips, P. J. (1983), Stratigraphy, sedimentology, and petrologic evolution of tertiary sediments in southwestern Costa Rica, B. S., La. State Univ., Baton Rouge.
Protti, M., et al. (1994), The geometry of the Wadati-Benioff Zone under southern Central-America and its tectonic significance—Results from a high-resolution local seismographic network, *Phys. Earth Planet. Inter.*, *84*, 271–287.
Protti, M., et al. (1995), Correlation between the age of the subducting Cocos plate and the geometry of the Wadati-Benioff zone under Nicaragua and Costa Rica, *Spec. Pap. Geol. Soc. Am.*, *295*, 309–326.
Protti, M., et al. (2001), *Evaluación del Potencial Sísmíco de la Península de Nicoya*, 1st ed., 144 pp., Fund. Univ. Nac., Heredia, Costa Rica.
Ranero, C. R., R. von Huene, E. Flueh, M. Duarte, D. Baca, and K. McIntosh (2000), A cross section of the convergent Pacific margin of Nicaragua, *Tectonics*, *19*, 335–357.
Restrepo, J. F. (1987), A geochemical investigation of Pleistocene to recent calc-alkaline volcanism in western Panama, M.S., 103 pp., Univ. of S. Fla., Tampa.
Sak, P., D. M. Fisher, and T. W. Gardner (2004), Effects of subducting seafloor roughness on upper plate vertical tectonism: Osa Peninsula, Costa Rica, *Tectonics*, *23*, TC1017, doi:10.1029/2002TC001474.
Shreve, R. L., and M. Cloos (1986), Dynamics of sediment subduction, mélange formation, and prism accretion, *J. Geophys. Res.*, *91*, 229–245.
Shuanggen, J., and W. Zhu (2004), A revision of the parameters of the NNR-NUVEL-1A plate velocity model, *J. Geodyn.*, *38*, 85–92.
Silver, E. A., D. L. Reed, J. E. Tagudin, and D. J. Heil (1990), Implications of the north and south Panama thrust belts for the origin of the Panama orocline, *Tectonics*, *9*, 261–281.
Smith, W. H. F., and D. T. Sandwell (1997), Global seafloor topography from satellite altimetry and ship depth soundings, *Science*, *277*, 1957–1962.
Tajima, F., and M. Kikuchi (1995), Tectonic implications of the seismic ruptures associated with the 1983 and 1991 Costa Rica earthquakes, *Spec. Pap. Geol. Soc. Am.*, *295*, 327–340.
Taylor, F. W., et al. (2005), Rapid forearc uplift and subsidence caused by impinging bathymetric features: Examples from the New Hebrides and Solomon arcs, *Tectonics*, *24*, TC6005, doi:10.1029/2004TC001650.
Vannucchi, P., D. W. Scholl, M. Meschede, and K. McDougall-Reid (2001), Tectonic erosion and consequent collapse of the Pacific margin of Costa Rica: Combined implications from ODP Leg 170, seismic offshore data, and regional geology of the Nicoya Peninsula, *Tectonics*, *20*, 649–668.
Vannucchi, P., et al. (2004), Long-term subduction-erosion along the Guatemalan margin of the middle America trench, *Geology*, *32*, 617–620.
von Huene, R., and D. W. Scholl (1991), Observations at convergent margins concerning sediment subduction, subduction erosion, and the growth of continental crust, *Rev. Geophys.*, *29*, 279–316.
von Huene, R., et al. (1995), Morphotectonics of the Pacific convergent margin of Costa Rica, *Spec. Pap. Geol. Soc. Am.*, *295*, 291–307.
von Huene, R., C. R. Ranero, W. Weinrebe, and K. Hinz (2000), Quaternary convergent margin tectonics of Costa Rica, segmentation of the Cocos plate, and Central American volcanism, *Tectonics*, *19*, 314–334.
Werner, R., et al. (1999), Drowned 14-m.y.-old Galapagos archipelago off the coast of Costa Rica: Implications for tectonic and evolutionary models, *Geology*, *27*, 499–502.
Yáñez, G., and J. Cembrano (2004), Role of viscous plate coupling in the late Tertiary Andean tectonics, *J. Geophys. Res.*, *109*, B02407, doi:10.1029/2003JB002494.
Ye, S., J. Bialas, E. R. Flueh, A. Stavenhagen, R. von Huene, G. Leandro, and K. Hinz (1996), Crustal structure of the Middle America Trench off Costa Rica from wide-angle seismic data, *Tectonics*, *15*, 1006–1021.
Yuan, P. B. (1984), Stratigraphy, sedimentology, and geologic evolution of Eastern Terraba Trough, southwestern Costa Rica, Ph.D., La. State Univ., Baton Rouge.

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