Constraints on Inner Forearc Deformation From Balanced Cross Sections, Fila Costeña Thrust Belt, Costa Rica

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ABSTRACT

The Fila Costeña thrust belt in the forearc basin 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-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/yr 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 due to decrease in slip on faults and a lateral ramp in the basal decollément. 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 rapidly to the east with the migration of the Panama triple junction and the onset of rapid, shallow subduction of thickened 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 inboard of the Cocos Ridge.

Introduction

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]. Erosive margins are typically characterized by rapid convergence with relatively little sediment input at the trench [*Clift and Vannucchi,* 2004]. They are found in conjunction with 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.

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.*, 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.

In contrast with the outer part of the forearc, the inner forearc basin in central and southern Costa Rica is thickened and telescoped by an active thrust system [*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 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].

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 thickening and exhumation due to thrusting is estimated [*Fisher, et al.*, 2004a], with no constraints on lateral variations in shortening along the margin.

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 like shortening rate and the amount of erosional unroofing. The field area lies inboard of the subducting Cocos Ridge in the Fila Costeña thrust belt, 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 thrust belt and evaluate the lateral variations in shortening within the inner forearc in relation to the subducting Cocos Ridge by constructing a new balanced cross section approximately 25 km east of the Fisher, et al., [2004] transect directly inboard of the axis of the ridge (Figures 3 and 4, B-B').

Regional Tectonic Setting

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 [*Barkhausen, 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 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; *Marshall, et al.*, 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 this broad, aseismic ridge, which formed as a result of Galapagos Hot Spot volcanism [*Hey*, 1977; *Werner, et al.,* 1999], affects the seismicity [*Adamek, et al.*, 1987; *Protti, et al.*, 1995; *Tajima and Kikuchi*, 1995], trench-slope morphology [*von Huene, et al.*, 1995], and the style of forearc deformation 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).

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 subducting 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; *Protti, et al.*, 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].

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

Tectonic Evolution

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/yr to ~20 mm/yr across the subducting PFZ (Figure 5) [*DeMets, et al.,* 1990; *Silver, et al.,* 1990; *Shuanggen, et al.,* 2004]. From NW to SE, the upper plate of 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; *de Boer, et al.*, 1991; *MacMillan, et al.*, 2004].

Presently, the Panama triple junction migrates to the southeast along the MAT at a rate of ~55 mm/yr relative to a fixed Panama microplate (Figure 5) [*DeMets, et al.,* 1990; *Silver, et al.,* 1990; *Shuanggen, et al.,* 2004]. This implies 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 m.y. due 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 m.y. Based on this assumption, the PFZ has migrated continuously during the past 1.5 m.y. 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.

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 N44E and the relative convergence vector between the Cocos plate and the Panama block is oriented N30E, 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.

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 *sensu strictu*.

The Térraba Trough

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.

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, respective, 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 (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 m.y. 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].

The Brito Fm. 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 Fm., named after the type locality along the Río Térraba of Costa Rica, conformably overlies the Brito Fm. 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 Fm. and Térraba Fm. [*de Boer, et al.*, 1995; *MacMillan, et al.*, 2004].

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 Fm., 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 Fm, [*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 Fm. 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 is assumed to have largely been removed prior to deposition of the Paso Real Formation [*Kesel,* 1983]. Therefore, the unconformity between the Curré and Paso Real Fms. and the correlative unconformity between the unnamed Pliocene mudstone and the Paso Real Fm. 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.

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 Fm. [*Phillips*, 1983] (located outside of our map area) and unnamed recent terrace gravels. The Brujo Fm. 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 1970's, Richard Kesel identified several features indicative of active, ongoing uplift and exhumation of the Cordillera de Talamanca and inner fore arc. 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 Fm., above a 26.5 ka radiocarbon dated sample [*Kesel,* 1983].

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.

Geologic and Structural Mapping of the Fila Costeña

The Fila Costeña is a 20-30 km wide thrust belt that extends approximately 250 km from the Golfo de Nicoya to the Panama border. The geology of the southern ~2,000 sq. km 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 oriented perpendicular to the structure, and quarries. The thrust belt in this area is comprised of 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 ~15º – 35º 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 footwall of major thrusts.

The major thrusts are most easily recognized in our map area where they place carbonates of the Brito Fm. on top of turbidites of the Térraba Fm. The Brito Fm., 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 decollément above the Brito Fm. at the northwest extent of the mapped area in this study (Figure 3).

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 Fm. 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 Fm. (Figure 4, A-A'). Directly inboard of the subducting Cocos Ridge axis, the total number of thrust sheets increases from three 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).

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 uplifted by thrust fault #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.

Total shortening decreases northwest and southeast of this region as individual thrusts merge at leading branchlines 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.*, 2005]. 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].

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 Fm. in thrusts (i.e. stepping-up of the decollément 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).

Balanced cross sections were constructed using structural data collected in the field throughout the Tertiary and Quaternary deposits in the southeast Fila Costeña thrust belt. 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 Fm. along the base. This fault in cross section is constrained by the surface trace and the dip of beds in the hanging wall. Based on these assumptions, the decollément 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].

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 have measured the orientation of a regional fault surface and associated slickenlines, a fault that places Brito Fm. atop Térraba Fm., and with dip slip on a surface that strikes N70W and dips 45 degrees to the northeast. In six other cases we measured less extensive faults with strikes ranging from N79W to N24W (average = N52W) and dips from 19 to 54 degrees NE (average = 40 degrees). Slickenlines measured on these six fault surfaces plunge an average of 25 degrees with vergence of S21W, indicating primarily dip slip motion. Fold trends at five locations range from N88W to N15W (average = N64W). These observations, coupled with the absence of any exposed basement in the mapping area, are consistent with low angle thrusting that detaches the sedimentary cover from the Nicoya Complex with southwestward vergence.

Based on a line-length balance of the Brito Fm. 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/yr, roughly half of the Cocos-Panama plate convergence rate of ~80 mm/yr (Figure 5). The lateral equivalent of fault #4 in section B-B' was not included in the cross section in *Fisher, et al.*, [2004a], because this fault does not expose the Brito Fm. in the Térraba gorge. On the map, the fault is required by the exposure of a Brito Fm. 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 Fm. 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').

Discussion

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 quasi-static equilibrium [*Yáñez and Cembrano*, 2004], indicating that the features we observe represent a transient response to Cocos Ridge subduction.

The Fila Costeña thrust belt 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 decollément 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.

It should be noted that we were not able to locate any observable outcrop of the Curré Fm. in the frontal portion of the Fila Costeña southeast of the Térraba gorge. The depositional facies associated with the Curré Fm. 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 Fm. The correlative facies at that distal location would be more similar to that of the Térraba Fm., 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 post-compaction 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 Fm. and Curré Fm. 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.

Radiocarbon dated volcaniclastics of the Brujo Fm. 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/yr and 1.5 mm/yr [*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 Fm. 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 due to basement arching above the Cocos Ridge axis [*Kolarsky, et al.*, 1995].

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/yr 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.

Conclusions

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 decollément of the Fila Costeña steps up laterally into the Térraba Fm. 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/yr inboard of the Cocos Ridge axis represents nearly 50% of the total plate convergence rate. 7) Given shortening rates of 10's of mm's 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

Adamek, S., et al. (1987), Seismic rupture associated with subduction of the Cocos Ridge, *Tectonics*, *6*, 757-774.

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.

Alvarado, G. E., et al. (1992), Chronostratigraphy of Costa Rican Igneous Rocks Based on Radiometric Dating, *J. South Am. Earth Sci., 6*, 151-168.

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 Plan. 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. Geosys.*, *4*.

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, N.M., USA.

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*.

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. Paper, Geol. Soc. Amer., 295*, Mann, P., 263-289.

Corrigan, J., et al. (1990), Fore-Arc Response To Subduction Of The Cocos Ridge, Panama Costa-Rica, *Geol. Soc. Amer. 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, *Abstracts with Programs, Annual Meeting, Geol. Soc. Amer., 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. South Amer. 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. Paper, Geol. Soc. Amer., 295*, Mann, P., 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.

Encinas, A., et al. (2006), Finding of a Holocene marine layer in Algarrobo (33˚22'S), central Chile. Implications for coastal uplift, *Revista Geológica de Chile, 33, 2*, 339-345.

Fisher, D. M., et al. (1998), Effect of subducting sea-floor roughness on fore-arc kinematics Pacific coast, Costa Rica, *Geology*, *26*, 467-470.

Fisher, D. M., et al. (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., et al. (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, paper presented at AGU, Fall Meeting, edited, AGU, San Francisco, Calif., USA.

Fisher, M. A., et al. (1991) Structure of the collision zone between Bougainville guyot and the accretionary wedge of the New-Hebrides island-arc, southwest Pacific, *Tectonics 10*, 887-903.

Gardner, T. W., et al. (1992), Quaternary Uplift Astride The Aseismic Cocos Ridge, Pacific Coast, Costa-Rica, *Geol. Soc. Amer. 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, 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.

Hare, Paul W. and T.W. Gardner (1985), Geomorphic indicators of vertical tectonism along converging plate margins, Nicoya Peninsula, Costa Rica, ch. 4, *in* Tectonic Geomorphology, Proceedings of the 15th Geomorphology Symposia Series, Binghamton, NY, pp. 76-104.

Hey, R. N., (1977), Tectonic evolution of the Cocos-Nazca spreading center, *Geol. Soc. Amer. Bull., 88*, 1404-1420.

Hinz, K., et al. (1996), Tectonic structure of the convergent Pacific margin offshore Costa Rica from multichannel seismic reflection data, *Tectonics*, *15*, *54.*

Hovius, N., et al. (1998), Landslide-driven drainage network evolution in a pre-steady-state mountain belt: Finisterre Mountains, Papua New Guinea, *Geology, 26*, 1071-1074.

Kay, S. M., et al. (2005), Episodic arc migration, crustal thickening, subduction erosion, and magmatism in the south-central Andes, *Geol. Soc. Amer. Bull.*, *117*, 67-88.

Kesel, R. H. (1983), Quaternary history of the Rio General Valley, Costa Rica, *Res. Rep. Natl. Geog. Soc., 15*, Oehser, P. and Lea, J., 339-358.

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., *Tex. A & M Univ., ODP*, College Station, Tex., USA.

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. Paper, Geol. Soc. Amer., 295*, Mann, P., 235-262.

LaFemina, P. C., et al. (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.

Lallemand, S. E., et al. (1992), Reconstruction Of Subduction Zone Paleogeometries And Quantification Of Upper Plate Material Losses Caused By Tectonic Erosion, *J. Geophys. Res.*, *97*, 217-239.

Lonsdale, P., and K.D. Klitgord (1978), Structure and tectonic history of the eastern Panama Basin, *Geol. Soc. Amer. 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. St. Univ., Baton Rouge, La., USA.

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., et al. (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., 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. (2003), The Costa Rica convergent margin: a textbook example for the process of subduction erosion, *Neues Jahrbuch Fur Geologie Und Palaontologie-Abhandlungen*, *230*, 409-428.

Mora, C. R. (1979), Estudio geologico de una parte de la region sureste del Valle del General, Provincia Puntarenas, Costa Rica, undergrad. thesis, 185 pp., Universidad de Costa Rica, San Pedro, Costa Rica.

Morell, K., et al., (2005), Forearc Deformation, Arc Volcanism, and Landscape Evolution near the Cocos-Nazca-Caribbean Triple Junction, *Eos Trans., AGU, 86*(52), Fall Meet. Suppl., Abstract T24A-05.

Murphy, K. (2002), Use of weathering rinds in fluvial terrace correlation along the coastal forearc, Pacific coast, Costa Rica, B.S., 70 pp., Trininty Univ., San Antonio, Tex., USA.

NASA (2003), 3 Arc Second SRTM Elevation Data, Shuttle Radar Topography Mission (SRTM), Jet Propulsion Laboratory (JPL), California Institute of Technology, Pasadena California, USA, v. 1.0.

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. St. Univ., Baton Rouge, La., USA.

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. Paper, Geol. Soc. Amer., 295*, Mann, P., 309-326.

Protti, M., et al. (2001), Evaluación del Potencial Sísmíco de la Península de Nicoya, *Fund. Univ. Nac.*, 1 ed., 144 pp.

Ranero, C. R., et al. (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 South Fla., Tampa, Fla., USA.

Shuanggen, J., and W. Zhu (2004), A revision of the parameters of the NNR-NUVEL-1A plate velocity model, *J. of Geodyn.*, *38*, 85-92.

Sak, P., et al. (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.

Silver, E. A., et al. (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*, v. 277, p. 1957-1962.

Tajima and Kikuchi (1995), Tectonic implications of the seismic ruptures associated with the 1983 and 1991 Costa Rica earthquakes, *Spec. Paper, Geol. Soc. Amer., 295*, Mann, P., 327-340.

Taylor, 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., et al. (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 S. E. Lallemand (1990), Tectonic erosion along the Japan and Peru convergent margins, *Geol. Soc. Amer. Bull.*, *102*, 704-720.

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. Paper, Geol. Soc. Amer., 295*, Mann, P., 291-307.

von Huene, R., et al. (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, et al., (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. St. Univ., Baton Rouge, La., USA.

Figure 1. Hillshaded DEM of Central America with superimposed with tectonic boundaries and major bathymetric features. CA – Caribbean plate; PM – Panama microplate; CO – Cocos Plate; NZ – Nazca plate; NA – North American plate; ND – North Andes plate; PFZ – Panama Fracture Zone. Black box indicates boundary of Figure 2. Topographic data from the SRTM30 dataset (source for this dataset is the Jet Propulsion Laboratory, http://www2.jpl.nasa.gov/srtm/) [*NASA*, 2003]. Bathymetric data from Smith and Sandwell, 1997.

Figure 2. Hillshaded 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 thrust belt (black circled 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, et al.,* 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. Box shows location of Figure 3. Maximum elevation is ~3800 m. Bathymetric data courtesy of GEOMAR.

Figure 3. Simplified geologic map of the southern Fila Costeña thrust belt showing fault traces, strike and dip, slickenline, and fold measurements. Stratigraphic column modified

from *Phillips*, [1983] and *Fisher, et al.*, [2004a]. Solid red line: Pan American highway, towns labeled, transecting the thrust belt through the Río Térraba gorge; Dashed black line: 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: onland projection of the Cocos Ridge axis; A-A': location of the cross section completed by *Fisher et al.*, [2004a]; B-B': position of the cross section completed during this study.

Figure 4. Balanced cross sections along two transects through the southern Fila Costeña thrust belt (See Figure 3 for location of sections A-A' and B-B'). Inset: Detachment depth 3500 – 4000 m. Minimum depth determined by placing axial surface at rearmost dip measurement (dotted line). Short dashed line shows probable axial surface location based on total dataset. Fault ramps dip 15º-30º to the northeast. The decollément at the basement/cover contact dips 4º 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. No vertical exaggeration.

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, et al.*, 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/yr southeast along MAT with respect to fixed PM. Intersection of MAT and CR migrates ~20 mm/yr northwest along MAT. Thick, dashed grey lines indicate PM-NZ and PM-CO convergence rates of ~20 mm/yr and ~80 mm/yr, respectively.

Figure 6. Elevation of the Fila Costeña topographic divide 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.