RESULTS OF PRIOR NSF SUPPORT

National Science Foundation, EAR- 9909375 [1/1/00-12/31/03], EAR- 0337467 [1/1/04-12/31/07] [TWG], EAR-9909699 [1/1/00-12/31/03], EAR-0337456 [1/1/04-12/31/07] [DMF]. These grants involved analysis of the effects of subducting seafloor roughness on forearc deformation along the central Pacific coast of the Costa Rican convergent margin and resulted in 4 publications, 3 submitted manuscripts and one manuscript in preparation. Sak et al. [2004a] develop a new model for weathering rind formation in basaltic andesite clasts and use this method to constrain ages of coastal fluvial terraces, which are then used to constrain deformation rates along the subducting seamount segment of the Costa Rican margin. Sak et al. [2004b] describe the history of vertical tectonism in the outer forearc as constrained by exposures of newly recognized late Pleistocene [50 to 27 ka], shallow water, marine deposits [i.e. Marenco formation] that record intervals of rapid subsidence and uplift across the Costa Rican forearc inboard of the subducting Cocos Ridge. The up-and-down response of the thin, outer forearc to underthrusting bathymetric highs is explained in terms of the pervasive deformation of the upper plate around rigid subducting features in the outer forearc. Vannucchi et al. [2006] characterized the structural history of the Osa Mélangé and argue for accretion of oceanic lithologies exotic to the margin. Fisher et al. [2004] constructed a balanced cross section along the Térraba gorge that depicts a minimum of 18 km of shortening related to an imbricate fan near the front of the Fila Costeña thrust belt [FCTB] in Costa Rica. The cross section indicates that this shortening involves detachment of the forearc basin sequence from the margin wedge, with regional scale underthrusting of the outer forearc along an out-of-sequence fault system. Deformed Quaternary terraces indicate that the shortening is more recent than 2 Ma and likely ongoing. Sitchler et al. [in review] mapped the FCTB over an ~2000 km² region and showed that shortening is greatest directly inboard of the axis of the Cocos Ridge. Morell et al. [in review] mapped the region near the eastern termination of FCTB and depicted a steep gradient in shortening that coincides with the arcward projection of the subducting Panama Fracture Zone [PFZ]. Marshall et al. [in prep.] reports on the first Optically Stimulated Luminescence [OSL] dating [over 20 OSL ages] for the Pacific coast of Costa Rica, identifying, for the first time, early Oxygen Isotope Stage 3 [45-60 ka] deposits and the last interglacial (~125 ka) marine and fluvial terraces. Identification of these deposits and terraces allows for calculation of longer-term uplift rates in the inner and outer forearc. In general, our previous work in Costa Rica has demonstrated that the inner forearc is thickened, uplifted, and experiences ongoing shortening inboard of the Cocos Ridge with the rates and magnitudes of deformation decreasing away from the ridge axis. Our proposed study builds on our years of experience and results, and is designed to evaluate the forearc response to migration of the Panama triple junction [PTJ], including continued indentation of the Cocos Ridge and PFZ, in southeastern Costa Rica and western Panama.
Publications and submitted manuscripts related to this research:


Introduction

The Cenozoic history of deformation along the active western margin of the American Cordillera records, among other things, the subduction and breakup of the Farallón plate, beginning with Paleogene breakoff of the Juan de Fuca plate, later division into the Cocos and Nazca plates and fragmentation of the Cocos and Juan de Fuca plates into numerous microplates [Lonsdale, 1991]. Each time a subducting plate breaks into two parts, a new triple junction develops, with a subduction boundary as two of the limbs [Stock and Lee, 1994] and a transform or ridge segment as the third. In some cases, there is significant deformation of the upper plate in the region of the subducting boundary as in the case of the active Colima Rift-Manzanillo Graben [Luhr, et al., 1985], whereas some upper plate regions show no effects of the triple junction, with all deformation restricted to the two oceanic plates, possibly because subduction ceases along the trench [Stock and Lee, 1994]. We propose an integrated study of forearc deformation inboard of the Panama triple junction [PTJ] at the Cocos-Nazca-Panama block plate boundary.

The breakup of the Farallón plate into the Cocos and Nazca plates and formation of the Galápagos rift system led to the development of the triple junction between the Cocos, Nazca and Caribbean plates and eventually the Panama microplate. This triple junction, the Panama triple junction [PTJ] lies offshore of the Burica Peninsula [Figure 1A], where the right-lateral Panama Fracture Zone [PFZ], a seismically active, north-south-oriented segment of this ridge-transform system, intersects the Middle America Trench [MAT]. From northwest to southeast, the upper plate
above this transform is subjected to dramatic changes in convergence parameters such as rate, azimuth, bathymetry and crustal thickness. To the northwest of the PFZ, the abnormally thick oceanic crust [Figure 1B] of the Cocos plate [i.e., CNS-2 to Cocos Ridge] collides orthogonally with the MAT at a velocity of ~91 mm/yr [Bird, 2003; DeMets, et al. 1990]. To the southeast of the PFZ, Nazca plate convergence is highly oblique [>70°], with a rate of 30 mm/yr, and a significant portion of this may be accommodated along the North Panama Deformed Belt [LaFemina et al., submitted; DeMets, et al. 1990]. A velocity diagram based on NUVEL-1 estimates for relative Nazca, Cocos and Caribbean plate motions suggests migration of the triple junction to the southeast at a rate of 55 mm/yr [Figure 1A, inset, DeMets, et al., 1990].

In other words, the upper plate experiences a 3-fold increase in convergence rate, an increase in slab thickness, and a decrease in bathymetry in the wake of the migrating triple junction. Such a system allows for time-for-space substitution in the analysis of the structure, Quaternary stratigraphy, volcanic history, and tectonic and landscape evolution of the upper plate. Furthermore, it allows for analysis of both the long-term evolution of topography and structure [e.g., Furlong and Schwartz, 2004] and short-term indicators of active deformation rates and lateral variations in plate coupling relative to the present three-dimensional geometry of the system.

Here, we propose to complete a multidisciplinary study of forearc evolution in the vicinity of the PTJ in a region that straddles the subducting PFZ. This study will include detailed structural and geologic mapping, development of a Quaternary stratigraphic framework that can be used to constrain the deformation history, and geodetic GPS and modeling studies to investigate the driving mechanisms for strain in the upper plate. We will test several critical hypotheses, including: 1) upper plate deformation is primarily a consequence of indentation tectonics related to Cocos Ridge collision; 2) the Fila Costeña thrust belt [FCTB] is propagating laterally into Panama with the migration of the PTJ [i.e., Cocos Ridge and PFZ]; 3) the velocity field in the upper plate reflects Cocos Ridge collision, including shortening across the FCTB and shear and uplift across the onshore projection of the PFZ [i.e., the Medial fault zone, Burica Peninsula], and elastic strain associated with the earthquake cycle.

We hope to answer several fundamental questions related to forearc dynamics:

1) How does the forearc respond to the fundamental changes in slab thickness, velocity and dip that accompany collision of an aseismic ridge and fracture zone, and passage of a triple junction?
Figure 1. Plate tectonic setting: 

A) Map of identified magnetic anomalies on Cocos and Nazca plates from Lonsdale [2005], MacMillian et al. [2004], Barckhausen et al. [2001], Meschede et al. [1998], Hardy [1991], Lowrie et al. [1979] and Lonsdale and Klitgord [1978]. Numbers show age in millions of years based on the chron time scale of Cande and Kent [1995]. EPR=East Pacific Rise, CNS =Cocos Nazca spreading, CR=Coiba Ridge, MR=Malpelo Ridge, RR=Regina Ridge, SR=Sandra Rift, PFZ=Panama Fracture Zone, BFZ=Balboa Fracture Zone, CFZ=Coiba Fracture Zone. Plate vector diagram from Sitchler et al. [in review], relating Cocos [CO], Nazca [NZ], Caribbean [CA] and Panama microplate [PM]. Solid colored lines denote relative plate velocity vectors based on velocity model NNR-NUVEL-1B derived from Bird [2003], DeMets [2001], Shuanggen and Zhu [2004], and Silver et al. [1990]. Bold dashed lines represent the Middle America Trench [MAT] in red and Panama Fracture Zone [PFZ] in black. The intersection of these represents the Panama triple junction [PTJ], which migrates to the SE along the MAT with respect to a fixed PM at a rate of ~55 mm/yr [see inset]. 

B) Upper mantle and crustal structure and seismic velocities of the Cocos plate (B) from Walther [2003] and von Huene et al. [2000] and Nazca plate (B’) Sallarès et al. [2003]. Yellow lines in A locate crustal sections. The two sections show the prominent change in crustal thickness across the PFZ, illustrating the magnitude of the "step-up" as upper plate material crosses from the Nazca to Cocos plate with southeastward migration of the PTJ. 

C) Upper crustal section across the Burica Peninsula and Gulf of Chiriqui showing the prominent structural feature, the Medial fault zone, and nature of the upper plate deformation [step-up] near the on-land projection of the PFZ; Gulf of Chiriqui section from Kolarski and Mann [1995a] and Kolarski, et al. [1995b]. Burica section from Corrigan et al. [1990].
2) Is the Medial fault zone on the Burica Peninsula [Figure 1C], immediately inboard of the PFZ, a strike-slip fault driven by indentation of the Cocos Ridge or is it dip-slip accommodating the large step across the transform boundary? Or both?

3) How does upper plate deformation vary at time scales of 1) millions of years [based on constraints from cross sections and thermochronology of unroofed structures], 2) 100’s of thousands to thousands of years [based on deformation of fluvial and marine terraces], and 3) 100's of years to years [based on geodetic measurements and analysis of historical seismicity]?

The field area in southeastern Costa Rica and western Panama is an excellent place to study the effects of triple junction migration because there is already a wealth of onshore and offshore data, including crustal thickness, age constraints and bathymetry. Moreover, there is a rich record of fluvial terraces related to incision of the fluvial systems into the FCTB. This is the one place along the FCTB where the active thrust belt intersects an active portion of the volcanic arc, with all the potential associated timing constraints. Additionally, there is a superb flight of marine terraces on the Burica Peninsula. These terraces should be amenable to radiocarbon and Optically Stimulated Luminescence [OSL] dating and will provide an unsurpassed record of late Quaternary deformation of the Burica Peninsula. The current geodetic network and velocity field in southeastern Costa Rica and western Panama suggests intriguing variations across the proposed study area [Figure 2A, LaFemina et al., submitted; LaFemina, et al., 2006], including strong interplate coupling on the Osa Peninsula segment of the MAT, strain partitioning across the isthmus [i.e., across the FCTB and North Panama Deformed Belt] and divergence away from the Cocos Ridge axis. Densification of our network across the FCTB and Medial Fault Zone will improve our understanding of the kinematics of current forearc strain. We propose to continue our successful international collaborative studies of the forearc here, by integrating geologic and geodetic studies to investigate the effects of triple junction migration including the effects of the Cocos Ridge and PFZ.

**Evolution of the Cocos and Nazca plates**

The Galapagos rift system split the Farallon plate into the Nazca and Cocos plates in the early Neogene [Lonsdale, 2005]. The ridge-transform system lies astride the Galapagos hot spot, with two aseismic ridges [the Cocos and Carnegie ridges] that represent opposing hot spot tracks for the Cocos and Nazca plates, respectively. The relatively buoyant Cocos Ridge and adjacent Cocos crust [CNS-2, Barckhausen, et al., 2001] play a major role in the deformation of the forearc; the greatest deformation in the forearc is inboard of the ridge axis [Gardner, et al., 1992; Sitchler, et al., in review]. Because the ridge axis is oriented more than 10˚ counterclockwise from the convergence vector [DeMets, et al.,...
it migrates slowly to the northwest along the MAT as the PTJ migrates to the southeast. We propose to study the area where the forearc is exposed to the greatest lateral variations in forearc strain, the area inboard the migrating triple junction.

Offshore of central Nicoya Peninsula, there is a subducting margin-perpendicular ridge that represents the fossil trace of the Pacific-Cocos-Nazca triple junction. All of the Cocos plate to the southeast of this ridge was created at the slow-spreading Galapagos rift system, and as a consequence, there are numerous seamounts, ridges, and plateaus with >1 km relief. Long wavelength bathymetry on the Cocos plate is marked by decreasing water depths to the southeast up to the axis of the Cocos Ridge, which collides with the margin offshore of the Osa Peninsula, 75 km northwest of the PFZ. The age of the Cocos plate varies from 24 Ma offshore Nicaragua to ~13.5 Ma offshore southeast Costa Rica, [Barckhausen, et al., 2001] with crustal thickness increasing from under 10 km to approximately 20 km [Figure 1A and B, Walther, 2003].

The main structures on the edge of the Nazca plate offshore western Panama are the Panama, Balboa and Coiba Fracture Zones [BFZ, CFZ Figure 2A]. Earthquake focal mechanisms indicate right-lateral motion on the Panama and Balboa Fracture Zones [Figure 2B], with $M_w > 6$ earthquakes over the last 30 years [www.globalcmt.org].

![Figure 2. A) Tectonic setting near the Panama triple junction. Topography is GTOPO30 and bathymetry ETOPO2 [www.ngdc.gov]. Focal mechanisms are for earthquakes with $M > 6$ [www.globalcmt.org] indicate right-lateral strike slip earthquakes on the Panama Fracture Zone [PFZ] and Balboa Fracture Zone [BFZ] and thrust earthquakes across the MAT and North Panama Deformed Belt [NPDB]. CFZ= Coiba Fracture Zones, PB=Panama Block, BP=Burica Peninsula B) Observed [black] versus calculated [red] horizontal velocities. GPS velocities are relative to a stable Caribbean plate. Finite element model domain is shown as a blue line and open triangles with feet indicate fixed northern boundary. Open blue vectors indicate zone of forcing along the MAT. Faults near the volcanic arc [black dotted lines] accommodate forearc sliver transport. Dashed blue line in back arc represents rheological boundary between strong Caribbean crust and weak Central American crust.](image)
There is a good agreement between the indenter model shown here and the measured nine-year velocity field.

Right-lateral slip between the Cocos and Nazca plates has shifted in the late Neogene from the CFZ to BFZ and finally to the PFZ at approximately 2 Ma when a ridge segment that connected the CFZ and BFZ ceased spreading [Figure 1A, Cande and Kent, 1995; Lonsdale, 2005; Lowrie, et al., 1979; Moore and Sender, 1995; Silver, et al., 1990]. From that point on, the triple junction has migrated to the southeast through time, so at 2 Ma, the PTJ was 100 km northwest of the present position along the MAT. The Nazca plate between these fracture zones has a thinner crust and deeper bathymetry than the Cocos plate to the northwest and the Nazca plate to the southeast. The Nazca plate east of the PFZ also contains several bathymetric features, including the Coiba, Malpelo and Carnegie Ridges. The Coiba Ridge abuts the CFZ on its east flank and the Panama margin to its north. It has Galapagos hot spot geochemical affinities and is ~22 Ma [Lonsdale, 2005; Werner, et al., 2003]. The Malpelo Ridge, located south of the Coiba Ridge, is a NE-trending aseismic ridge that most likely originated at the Galapagos Hot Spot and may have been continuous at one time with the Cocos Ridge [Lonsdale, 2005; Lonsdale and Klitgord, 1978; Macmillian, et al., 2004]. Thus, the PFZ juxtaposes the Nazca plate with a hot-spot thickened portion of the Cocos plate in the vicinity of the PTJ [Figure 1B].

**Evolution of the upper plate**

The proposed study area is the southern edge of the Panama block, a microplate that is thought to be detached from the Caribbean plate by diffuse deformation zones, the North Panama [NPDB] and Central Costa Rica Deformed Belts [CCRDB], along its northern and western borders, respectively [Kellogg and Vega, 1995; Marshall, et al., 2000; Silver, et al., 1990]. The volcanic arc within the Panama block has separated from the Caribbean plate, perhaps due to collision with South America beginning in the Miocene [Silver et al. 1990] or the Cocos Ridge in Plio-Pleistocene time. Relative to a stable Caribbean plate, the Panama microplate is moving northward at a rate of ~11 mm/a [Bird, 2003; Kellogg and Vega, 1995; Trenkamp, et al., 2002], with convergence accommodated across the NPDB. We consider the mechanical effects of Cocos Ridge and PFZ collision on two different parts of the upper plate: the outer and inner forearc in southeastern Costa Rica and western Panama.

**The outer forearc**

Inboard of the seamount domain on the Cocos plate there are scallops in the thrust front and linear or cuspatate depressions gauged out of the margin, largely the result of basal erosion during seamount subduction. Basal erosion is also indicated by records of subsidence on the upper plate based on benthic foraminifera [Vannucchi, et al., 2001]. Thus, the outer forearc of the upper plate of
The MAT is experiencing tectonic erosion to the northwest of the triple junction. To the southeast of the triple junction, there is an accretionary wedge [Moore and Sender, 1995; Silver, et al., 1990], and thrust focal mechanisms from recent earthquakes [Figure 2B] that attest to seaward growth of the margin due to oblique convergence between the Nazca plate and the upper plate along the MAT in this region. The accretionary wedge is deformed by collision of the Panama, Balboa and Coiba Fracture Zones [Moore and Sender, 1995; Silver, et al., 1990].

One focus of this proposed study is the Burica Peninsula, an outer forearc peninsula that lies immediately inboard of the PTJ within 20 km of the MAT. The peninsula is approximately 30 km long and 3 km wide at its narrowest point. The geology has been extensively mapped [Corrigan, et al., 1990] and consists of late Cretaceous sea floor basalts [Nicoya Complex] with intercalated chert and pelagic limestones unconformably overlain by generally eastward dipping Neogene to Quaternary lower slope turbidites to shallow shelf fossiliferous clastics [Charcoal Azul Fm]. The most prominent structural feature, the north-striking Medial fault zone [Figure 1C] with up to 2500 m of up-to-the-west displacement, is described as a right-lateral strike slip fault with a significant dip slip component [Corrigan, et al., 1990]. Paleobathymetric studies [Corrigan, et al., 1990] indicate that the peninsula has experienced rapid shoaling from lower-middle bathyal depths during the late early Pleistocene to shelfal depths about 1 m.y ago. Corrigan et al. [1990] calculated a long-term, average Quaternary uplift rate of ~1 mm/yr.

The inner forearc

The inner forearc basin of Costa Rica has been shortened into a fold and thrust belt that culminates in the FCTB directly inboard of the axis of the indenting Cocos Ridge, with numerous thrust sheets that carry the deepest Eocene strata of the basin to the surface. In the area of seamount subduction, the inner forearc thrust belt is segmented by steep faults that cut the underlying basement and allow lateral variations in uplift rate [Fisher, et al., 1998]. The intervening blocks with the greatest uplift rate lie directly inboard of the greatest erosion offshore, an observation that suggests either underplating of seamounts or inner forearc thickening because of seamount collision with the inner forearc.

Within the FCTB, the greatest number of thrust faults and greatest shortening occurs directly inboard of the Cocos Ridge axis [Sitchler, et al., in review]. This pattern of deformation is consistent with episodic GPS [EGPS] studies that indicate high coupling and strain partitioning inboard of the Cocos Ridge and across the isthmus [LaFemina et al., submitted; LaFemina, et al., 2006]. The measured shortening decreases to the NW and to the SE into the proposed study area, where the thrust belt ultimately plunges beneath the volcanic debris fan of Volcán Barú [Figure 3, Morell, et al., in
From there southeastward, the slope of the volcanic debris fan is intermittently broken by what appears to be the lateral subdued continuation of the FCTB across western Panama. The region of intersection of the FCTB and the volcanic debris fan from Volcán Barú is critical to evaluate whether the thrust belt is actively propagating or not, and it is the area with the most potential timing constraints. Finally, it is an area with a long-term geologic history that bears directly on the triple junction evolution since the initial breakup of the Cocos and Nazca plates.

Figure 3. A) Structure of the FCTB thrust belt [see Figure 2 for location]. Dashed lines are thrust faults with ticks on hanging wall. Green lines are tear faults. Yellow lines show location of balanced cross section with associated numbers giving total amount of shortening with values in parentheses giving per cent decrease in length. Active thrust belt is propagating to southeast with migration of the PTJ into the volcanic debris fan [red] from Volcán Barú. Modified from Morell et al. [in review], Sitchler et al. [in review], and Fisher et al. [2004]. Stratigraphic column modified from Phillips [1983] and Fisher et al. [2004]. Inset shows asymmetric trunk stream segments deflected to east around eastward propagating FCTB. Geology is draped on 90-m SRTM data. B) Schematic cross section of the Río Blanco thrust. Brito Fm [buff], Térraba Fm [gray], lahars [pink]. The lahar involved in the thrust is probably not significantly older that ~500 ka based on stratigraphic relationships in Figure 4A.
**The Volcanic Arc**

The active volcanic arc of Central America continues unbroken from Guatemala to central Costa Rica. The last active volcano in Costa Rica is Volcán Turrialba, which lies within the CCRDB, the proposed western boundary of the Panama microplate. Southeast of Volcán Turrialba and inboard of the Cocos Ridge, the arc is extinct and ~8-10 Ma granitic plutons [Grafe, et al., 2002] are exposed in the highest range on the Central American isthmus, the Cordillera de Talamanca. Southeast of the PFZ, volcanism continues with Volcán Barú, in western Panama. Variations in arc volcanism may correspond with changes in the geometry of the Beniof zone, with steep subduction in Nicaragua and northwest Costa Rica, decreasing slab dip in central Costa Rica, shallow subduction/collision in southern Costa Rica [Protti et al., 1995] and finally a potentially steeper slab in western Panama [de Boer, et al., 1995; Vergara Muñoz, 1988] or slab tear along the subducted portion of the PFZ [Abratis and Woerner, 2001; Defant, et al., 1992].

The arrival of the Cocos Ridge is likely responsible for the shallowing of subduction, squeezing out of the mantle wedge, extinction of the volcanic arc and uplift of the Talamanca Range in southern Costa Rica. The onset of this event is directly related to the time since migration of the triple junction from NW of the Osa Peninsula to the present position offshore of the Burica Peninsula. Since initial arrival of the Cocos Ridge axis, the position of this collision has remained fixed or drifted slowly northwest whereas the triple junction has migrated to the southeast.

**Proposed Research**

Here we propose an integrated, multidisciplinary investigation of the response of the upper plate to the collision of the Cocos Ridge and the variations in incoming plate thickness, convergence rate and azimuth, and bathymetry across the PFZ. This research will involve structural analyses, Quaternary geologic mapping and dating, and geodetic GPS and modeling studies in an effort to integrate a long-term record of deformation with short-term indicators of kinematics to allow for assessment of rates and styles of deformation of the upper plate. We will investigate two areas, the leading edge of the FCTB in western Panama and the Burica Peninsula immediately inboard of the PFZ.

There are three important reasons why we can evaluate upper plate deformation in the proposed areas. First, the leading edge of the FCTB intersects the volcanic debris fan from Volcán Barú containing Neogene through Quaternary volcanic flows and tuffs, lahars and fluvial terraces [de Boer, et al., 1988; de Boer, et al., 1995; Defant, et al., 1992; Drummond, et al., 1995; our preliminary dating as in Figure 4A]. This debris fan will provide exceptional timelines to constrain deformation. The thrust sheets are well exposed within gorges of the major rivers crossing the FCTB [Figure 3B].
and are amenable to detailed structural analyses. Second, there is a superb flight of marine terraces on
the Burica Peninsula, in fact the best developed and most extensive along the Pacific coast from
Nicaragua through Panama. These terraces should be amenable to radiocarbon and OSL dating and
will provide an unsurpassed record of late Quaternary deformation of the Burica Peninsula. Third, our
continuing geodetic research of strain partitioning in Costa Rica, existing data for Panama and the
installation of new EGPC sites in January and June 2007 [Figure 5], allow for the spatial and temporal
patterns of short-term elastic strain to be measured during the time of the proposed research.

**Inner forearc [FCTB]**

The combination of bedrock geology and Quaternary mapping of fluvial and volcanic deposits
and Ar-dating will enable us to constrain deformation rates in western Panama and to determine if the
FCTB is actively propagating to the east with the migration of the PTJ. Balanced cross sections from
the FCTB show a lateral gradient in the amount of shortening near the on-land projection of the PFZ,
yet short segments of the thrust system outcrop across the lower part of the lahar fan on the slope of
Barú [Figure 3]. By extending our mapping of the FCTB into Panama, we will answer questions such
as: How does the thrust belt terminate? Are the ridges in Panama that align with the FCTB the results
of an older deformation history, with a subdued topography buried by the lahar fan or is the Cocos
Ridge collision in southeast Costa Rica producing active deformation in western Panama? Are the
Panama structures part of a separate thrust system propagating toward the FCTB? We plan to evaluate
these questions through the combination of geologic mapping and dating of a suite of volcanic rocks in
the critical region that straddles the PFZ, including two flows that have the potential to bracket the age
of the lahar package [Figure 4A]. We will also survey fluvial terraces along margin-perpendicular
streams such as the Río Chiriquí Viejo [Figure 4A] to evaluate active deformation and incision rates.

Several lines of evidence support our hypothesis for active deformation in the FCTB. First,
from northwest to southeast along the inner forearc over the subducting PFZ, there are dramatic
variations in the morphometry of drainage basins crossing the FCTB. Consequent streams from
Volcán Barú have typical radial patterns as they descend the debris fan to the coast. However, in
proximity to the FCTB, they become noticeably deformed with pronounced hook-like-shapes where
they cross the FCTB or its eastward projection [Morell, *et al.*, in review]. The asymmetry indicates
eastward deflection of trunk streams around the eastward propagating FCTB [Figure 3A, inset].
Second, one of the major thrusts within the FCTB, the Río Blanco thrust [Figure 3B], displaces lahars
that we have tentatively constrained to not significantly older than ~507 ka [plateau age on 14
hornblende microphenocrysts]. Third, we have identified a flight of fluvial terraces along the Río
Chiriquí Viejo that appear to be deformed across the leading edge of one of the principle thrusts of the
Detailed, differential GPS surveying and dating of these terraces will yield active permanent deformation rates for comparison with geodetic measurements. Collectively, these observations suggest propagation of inner forearc uplift into Panama with the migration of the triple junction.

Figure 4. A) Cross section of Río Chiriquí Viejo valley and fluvial terraces on the hanging wall and foot wall of the Río Blanco Thrust. Color-coding of terraces shows preliminary correlation across thrust fault. Note the increased separation of terraces on the hanging wall relative to the footwall which we suspect is related to uplift on the hanging wall. Terraces post-date 507 ka [plateau age on 14 hornblende microphenocrysts] brecciated tuff at top of lahar, consistent with late Pleistocene soil profiles on these terraces and absence of an unconformity between the brecciated tuff and the underlying lahar. B) Cross section on the Burica Peninsula showing 4 prominent and extensive marine terraces. Lowest terrace is late Holocene [Gardner, et al., 1992], can be traced around the entire peninsula and may represent co-seismic deformation. We infer, based upon uplift rates and weathering profiles, that the higher terraces are late Pleistocene with the highest [~60-70 m] being the last interglacial sea level highstand terrace at ~125 ka. See Figure 3 for location of A and Figure 2 for location of B.

Geodetic GPS measurements in southeastern Costa Rica and Western Panama indicate a radial pattern of elastic strain accumulation centered on the axis of the Cocos Ridge that is suggestive of Cocos Ridge indentation as the driver for upper plate deformation [Figure 2B]. To the northwest from the Nicoya Peninsula and into Nicaragua, the velocity field has been explained as due to sliver transport due to oblique subduction, despite an obliquity of only <10-15° [DeMets, 2001; DeMets, et al., 1990; Norabuena, et al., 2004]. However, geodynamic models indicate that forearc sliver transport is more likely caused by CNS-2 - Cocos Ridge collision [Figure 2B]. The test of this indentation model lies in the symmetry of the velocity field and the pattern of deformation in Western Panama. How does interseismic elastic strain accumulation vary laterally on the upper plate inboard
of the PFZ where the convergence rate, azimuth and bathymetry changes? This question can be
answered by constraining the velocity field in the forearc of southeastern Costa Rica and western
Panama, particularly to the east of the subducting PFZ and across the FCTB.

We propose to expand our episodic GPS network into Panama and across the Cordillera de
Talamanca [Figure 5] with these goals: 1) investigate strain partitioning across the Central American
isthmus; 2) quantify elastic strain accumulation across the FCTB and Medial Fault Zone; and 3)
investigate the broader pattern of upper plate strain related to Cocos Ridge collision and PFZ
subduction within the forearc. EGPS and CGPS data from existing sites will be integrated with data
obtained from the geologic studies proposed here and analytical and numerical modeling studies [e.g.,
Figure 2b] to investigate the short to long term effects of Cocos Ridge – PFZ collision and PTJ
migration on the forearc.

We simulate the mechanical response of Central American crust to indentation of the Cocos
Ridge on geological [long term] time scales [Figure 2b]. This model assumes that normal subduction
is not strongly felt in the overriding plate for much of the region [see above]; deformation is driven
primarily by collision of buoyant CNS-2 - Cocos Ridge crust. We use the finite element code G-
TECTON [Govers and Meijer, 2001]. GTTECTON was developed from TECTON version 1.3 [Govers,
1993; Melosh and Raefsky, 1981] by Rob Govers at Utrecht University, Netherlands. GTTECTON uses
the finite element method [FEM] to solve the mechanical equilibrium equation for 3D displacements.
We will integrate the long term geological constraints with the velocity field from the GPS network to
test the model for Cocos collision and then, if the velocity field is not consistent with this model (i.e.
symmetry about the axis of the ridge), we will consider the impact of other variables related to the
subducting PFZ.

Outer forearc [Burica Peninsula]

The Burica Peninsula, lying immediately inboard of the PTJ within 20 km of the MAT, is
seismically active and well located to investigate upper plate deformation [Figure 2a]. We propose to
use flights of marine terraces to evaluate the uplift and tilt rates on the Burica Peninsula near the
Medial fault zone and geodetic GPS studies to investigate potential interseismic locking on the fault.
Mesoscale faults will also be analyzed in terms of kinematics [Marrett and Allmendinger, 1990] in
exposures near the Medial Fault Zone. This combination of datasets will allow us to answer questions
such as: Does the Medial Fault Zone primarily allow vertical motions related to the forearc climbing
the thickened Cocos plate during eastward migration of the triple junction, or does the fault primarily
produce right-lateral slip related to Cocos Ridge and PFZ indentation?

Our preliminary reconnaissance of the peninsula indicates not less than 4 well-develop marine
terraces extending from ~2-4 m amsl to well over 60 m amsl [Figure 4B]. The lowest terrace is late Holocene, 830 yr ± 50 BP [Gardner, et al., 1992] yielding an uplift rate of ~4.7 mm/yr. That terrace occurs along the entire coast of the peninsula, varying in elevation from <2 m amsl to ~4 m amsl. It is possible that this latest Holocene terrace represents a coseismic event and as such could yield information on the seismic moment and recurrence interval for great earthquakes on the peninsula.

We hypothesize that the three higher terraces range in age from Oxygen isotope stage 3 [~30-60 ka] to Oxygen isotope stage 5e [~125 ka]. The highest, most extensive terrace forms the flat upland of the southern end of the peninsula and appears to be tilted, down to the east [Figure 4B]. We propose an extensive radiocarbon and OSL dating and GPS campaign to evaluate: 1) if the latest Holocene terrace is synchronous around the entire peninsula, indicating one seismic event; 2) age of the higher terraces; 3) deformation rates during the late Pleistocene; and 4) geodetic surveys to investigate active elastic strain accumulation. Because of the narrowness of Burica Peninsula, geodetic studies will be conducted at the northern extent of the peninsula, where it becomes wide enough for a profile of GPS sites to be installed that cross the Medial Fault zone [Figure 5]. These studies will allow us to provide quantitative constraints on deformation on the 10’s to 100,000 year time-scale of the upper plate as it responds to migration of the PTJ.

Figure 5. Existing [red squares] and proposed [orange triangles] GPS site locations in the region surrounding the southeastern termination of the Fila Costeña thrust belt [FCTB]. DEM supplied by NASA’s 90-m SRTM dataset. MFZ=Medial Fault Zone.

Summary

In western Panama and southernmost Costa Rica, we plan to combine geologic mapping of the bedrock structure of the FCTB, surveying and dating of fluvial terraces and lahar surfaces, Ar-dating of Quaternary volcanic flows, and geodetic GPS and modeling studies designed to elucidate the nature of the termination of the FCTB and characterize the surface velocity field related to long and short-term interaction of the Cocos Ridge and migrating PTJ. On Burica Peninsula we propose to use flights
of marine terraces to evaluate the uplift and tilt rates near the Medial fault zone and geodetic GPS studies to investigate potential interseismic locking on the fault[s]. This combination of studies will allow us to distinguish whether upper plate deformation is driven by migration of the PTJ; Cocos Ridge collision with a symmetric velocity field and shortening distribution about the axis of the incoming Cocos Ridge; or differences in basal tractions related to the changes in plate motions associated with the subducting transform, with a distinctly asymmetric velocity field and variations in kinematics that are centered on the subducting PFZ.

**Work Plan and Personnel**

This study will require three field seasons:

During January-March, 2008, we will focus on mapping the termination of the FCTB in western Panama. This will include: 1) completion of a structural cross section across the thrust belt along the Río Chiriquí Viejo and Río Jacú; 2) mapping, dating and correlation of fluvial terraces along the gorge of the Río Chiriquí Viejo and Río Jacú; 3) reoccupation and establishment of new EGPS sites across the northern Burica and FCTB.

During January-March, 2009, we will focus on the Burica Peninsula. Our work will include: 1) detailed structural mapping of the Medial fault zone and other significant faults and 2) characterization of the Quaternary marine terraces with detailed GPS and altimeter topographic surveys, measurement of stratigraphic sections and radiocarbon and OSL dating. We will complete mapping of the margin wedge on Osa and also collect samples from marine terraces for C\textsuperscript{14}, OSL and paleomagnetic dating. We will also begin Finite Element Modeling of the Cocos Ridge – PFZ collision, incorporating geologic and geophysical data as boundary conditions.

During January-March, 2010, we will 1) map, date and correlate the Quaternary lahar sequences from Volcán Barú, 2) continue sampling marine terraces for C\textsuperscript{14} and OSL dating and 3) reoccupy the EGPS network and produce an expanded velocity field for the area, which will be used to further develop geodynamic models of this margin.

Gardner is responsible for the Quaternary studies and will supervise undergraduate senior theses by students at Trinity University. Fisher and LaFemina are responsible for studies of structural geology, geodetic GPS and modeling, and will supervise the fieldwork of a graduate student at Penn State [Morell, biographical sketch attached]. We have also included support for two Panamanian scientists to contribute to our field studies in western Panama [see appendix].