The Effects of Seamount Subduction on Fore Arc Kinematics and Origin of the Nicoya Complex, Pacific Coast, Costa Rica

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INTRODUCTION

Along the Pacific coast of Costa Rica, nearly orthogonal convergence is occurring at the rapid rate of 10 cm/yr as the Cocos plate subducts beneath the Caribbean plate at the Middle America Trench (Figure 1). The Cocos plate is characterized by pronounced, linear ridges of seamounts that rise a thousand meters above the sea floor (Figure 2). Subduction of these rough elements has profound effects on seismicity (Protti et al., 1995) and deformation (Gardner et al., 1992) of the thinly sedimented accretionary prism along the Pacific coast. For example, subducting seamounts can produce rapid rates of fore arc deformation (Marshall and Anderson, 1995; Fisher et al., 1998). Collision of the seamounts weakens the upper plate and results in frontal erosion due to gravitational failure of the trench. Thus, at the toe of accretionary prisms, there are often trench embayments around incoming seamounts. The extent to which seamounts are subducted and possibly underplated well landward of the toe of the accretionary prism has important implications for the style and distribution of deformation and seismicity along the plate boundary and within the upper plate.

During June and July, 1998, twelve students (named later) and four faculty, representing a total of eight Keck Consortium colleges and universities, one Costa Rican institution and one minority school came together to examine fore arc deformation along the Pacific Coast of Costa Rica. We were joined by a doctoral student at Penn State, Jeff Marshall, who did his Masters thesis in the area and who is currently completing his dissertation on deformation along the Pacific coast of Costa Rica.

Together, we hypothesized that fore arc deformation along this thinly sedimented margin is characterized by differential uplift in the upper plate controlled by the roughness of incoming seamounts. To address this hypothesis we undertook an integrated study utilizing geomorphology, Quaternary geology, structural geology, geochemistry, paleomagnetism and geophysics. Our field area, the southern tip of the Nicoya Peninsula (Figures 2 and 3), is directly inboard of a line of subducting seamounts, has large historic earthquakes, a spectacular set of Holocene marine terraces, and beautiful bedrock exposures on marine abrasion platforms. It is a superb location to evaluate our hypothesis.

As a second goal we attempted to discover the origin of the crust on the upper plate (Kuijpers, 1980; Bourgois et al., 1984; Frisch et al., 1992; Donnelly, 1994; DiMarco et al., 1995; Stinton, 1997; Meschede and Frisch, 1998). Specifically, did the basaltic crust of the Caribbean plate originate in the Southern Hemisphere and move northward during the early Tertiary to “dock” at its present location on the Nicoya Peninsula? Conversely, did it form at its present location as an inherent part of the Caribbean plate?
As a third goal we investigated the response of fluvial systems to the known deformation that we were calculating in the marine terrace studies. Specifically, we were interested in the rates of fluvial incision into bedrock as knickpoints retreat headward.

STUDENT PROJECTS

To answer these intriguing questions, students and faculty systematically examined coastal, stream bed, and quarry exposures along two, forty kilometer sections of the coast that are nearly orthogonal to each other (Figure 3). Five students, Bhavani Bee (Franklin and Marshall), Reed Burgeret (Whitman), Emily Burton (Carleton), Jenny Cook (Trinity), and Natalie Kehrwald (Colorado College, Eric Leonard sponsor and project visitor), studied marine terraces. Over 30 shell samples were collected for radiocarbon dating. All samples yielded internally consistent ages ranging from about 500yBP to 7000yBP as we had hypothesized. Elevations of all samples were measured by either transit, hand level or altimeter surveys. Additionally, numerous topographic surveys were completed along the terraces to facilitate terrace correlation along the coast. These data, together with a paleo sea level curve, were used to determine uplift rates along the coast using the equation

\[ Z \text{ (m/ky)} = X_1 \text{ (m)} + X_2 \text{ (m)} + X_3 \text{ (m)} \]

\[ X_4 \text{ (ky)} \]

where \( X_1 \) is modern elevation above mean sea level, \( X_2 \) is depositional depth determined from modern facies reconstructions, \( X_3 \) is paleo sea level as determined from 3 different paleo sea level curves, and \( X_4 \) is sample age. We produced an exceptional spatial distribution of values, given the right angle bend of the peninsula. With these data we accurately characterized Holocene, upper plate deformation directly inboard of the Fisher and Christmas seamount chain (Figure 2). By combining all uplift data, we modeled deformation as block tilting by calculating the axis of
Figure 2: Generalized geologic map of Costa Rica, bathymetry of the Cocos Plate, and location of study area on Peninsula de Nicoya. Geologic units: Nicoya Complex—darkest gray; Active-arc volcanic rocks—dark gray; Extinct-arc volcanic rocks—light gray; fluvial to marine clastic and volcaniclastic rocks—lightest gray. Bathymetric data from von Huene and Fluh (1994) and von Huene et al. (1995). Bold contour interval is 1000 meters.

block rotation and its angular velocity. Emily Burton further expanded her marine terrace study to include Holocene pedogenesis and chronosequence development. Natalie Kehrwald and Bhavani Bee extended their Holocene marine terrace studies to include terraces from older, Pleistocene, marine highstands.

One student, Erin Krall (Washington and Lee), examined the response of fluvial systems to uplift. Specifically, she examined the rate of bedrock incision and the rate of knickpoint retreat for several streams on different rock types and with different uplift rates. In this study she wanted to compare incision rates as a function of rock type and uplift rate. The superb, datable marine terraces which make the knickpoints on these streams and
the known initial positions of knickpoints and stream beds gave this study the potential to fundamentally increase our understanding of rates and mechanisms of fluvial incision into bedrock in active tectonic areas.

Two students, Alix Krull (Pomona), and Alex Claypool (Franklin and Marshall), investigated mesoscale faults which are well exposed in Tertiary rocks on marine abrasion platforms. The Tertiary rocks have a complex history of deformation. Many hours of data collection on the HOT abrasion platforms at low tide helped unravel the sequence of tectonic events. These studies discovered the nature and style of deformation in the fore arc inboard of the subducting seamounts.

Another student, Anna Reeves (Mississippi State), drilled and collected rock core from those same Tertiary rocks for paleomagnetic studies. Core samples were processed at Bruce Panuska’s (Anna’s sponsor and project visitor) paleomag lab at Mississippi State.

Becky Starnski (Amherst) collected samples of basaltic seafloor for geochemical analyses. She traveled far and wide at all times of day and night to find unweathered Nicoya basalt. Becky worked closely with Tekla Harms, her sponsor and project visitor. Becky’s geochemical work was done at Amherst and Oregon. One intriguing and provocative question that she addressed concerned the nature of the basaltic “basement”.

Is it in-situ and thus part of the local Caribbean plate that is deforming in response

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to seamount subduction? Or is it allochthonous, having moved from the Southern Hemisphere into its present position during the early Tertiary. The paleomagnetism and geochemical studies helped resolve those questions.

Finally, two students, Todd Shearer (Whitman) and Enrique Hernandez (Universidad Nacional Autonomous) recorded earthquake activity (and Jeep Verde travels) during the project and reoccupied a 1950 topographic survey line across the peninsula using sophisticated, leveling and GPS equipment. From those studies they looked at historic deformation and compared it to the magnitudes and rates of deformation we determined from the Holocene, marine terrace record.

ACKNOWLEDGEMENTS
I would like to sincerely thank Barbara MacGregor owner and operator of Finca Los Caballos, our home during the project. I will be forever grateful to her for keeping us healthy and dry, no easy task. Thanks also to Frank's for those excellent hamburguesas con queso y papas fritas. Most of all I thank Queso Medio for his boundless enthusiasm every day.

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Rapid Quaternary uplift of marine terraces: Cabo Blanco to Montezuma area, Peninsula de Nicoya, Costa Rica

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INTRODUCTION
The Nicoya Peninsula of Costa Rica, located 65 km inland of the Middle America Trench, represents an area of uplifted forearc created by the northeastward subduction of the Cocos Plate beneath the Caribbean Plate. The southern coast of the Nicoya Peninsula is located near the rough-smooth boundary which separates rough ocean floor characterized by buoyant seamounts to the south from relatively dense and smooth crust to the north. Deformation along the southern Nicoya coast is amplified by the subduction of seamounts along this boundary (Gardner and others, 1992; Marshall and Anderson, 1995). Rough crust has been subducting along this margin for the last 1-5 million years (Gardner and others, 1992; Collins and others, 1995). The purpose of this study is to examine Quaternary tectonism as evidenced by Holocene and Pleistocene marine terraces to determine rates and mechanisms of net uplift of the Nicoya Peninsula. Ages and altitudes of Holocene and Pleistocene terraces are used to calculate the local uplift rates along the coast perpendicular to the trench. These uplift rates may be compared with other study areas on either side of Cabo Blanco to determine the block rotation of the southern tip of the peninsula.

STUDY AREA
This study focuses on the southern tip of the Nicoya Peninsula, extending from Cabo Blanco along the coast for 10 km, ending at Montezuma. A significant topographic feature of this coast is an extensive low elevation, wave cut surface, referred to as the Cabuya terrace, that lies between the abandoned Cobano sea cliffs and the modern shoreline (Marshall, 1991; Marshall and Anderson, 1995). In general, the width of the Cabuya platform decreases from approximately 1 km near the village of Cabuya to less than 100 m at Montezuma. Between Cabuya and the Río Cedro, the broad platform is cut in the Paleocene-Eocene Cabo Blanco Formation consisting of intensely folded interbedded marine mudstones and sandstones (Lundberg, 1982). From Río Cedro to Montezuma, the platform narrows considerably and is punctuated by small arcuate beaches at the larger stream mouths. Along this stretch, the platform is cut into the more resistant basalt of the Cretaceous Nicoya Complex (Lundberg, 1982).

Cabo Blanco itself has been uplifted relative to the Cabuya surface along the El Flor fault (Marshall and Anderson, 1995). In this area, a broad and continuous Cabuya surface is virtually absent. Instead, steep sea cliffs and narrow erosional platforms replace the Cabuya surface.

METHODS
Holocene Platforms
To establish an accurate uplift history along the coast, topographic surveys were conducted along Holocene wave-cut platforms (Figure 1), and shell samples were collected for radiometric dating. Beginning at Cabo Blanco, profiles of modern abrasion platforms were taken using altimeter, transit, and hand-level surveys to compare the morphology of the active wave platform with abandoned bedrock terraces. Inner edge, outer edge and terrace tread elevations were recorded for each terrace and later correlated with adjacent sites along the coast. When possible, precise elevations of shell fragments at several sites were also recorded (Figure 2), and these shells were sampled for C-14 radiometric dating (Beta Analytic Laboratory).

The rate of uplift for each of the dated sample sites can be calculated using the following expression:

\[ \text{Uplift (m/ka)} = \frac{(X_1 + X_2 + X_3)}{X_4} \]

where \(X_1\) is modern elevation, \(X_2\) is depositional elevation of the sample relative to mean sea level, \(X_3\) is paleo-sea level at the time of deposition, and \(X_4\) is calibrated 14-C age. Using a local
tidal chart, the modern elevations were corrected for sea level using a sine equation in Kaleidagraph. Field observations were used to determine the depositional facies. All the radiometric dates from the sites that are less than 1000 years old, were not affected by the Barbados sea level curve. As a consequence, we assume that sea level has remained the same for 1000 years. Using Excel, a spreadsheet of the profile sites was compiled, and the uplift rate calculated using the equation above. These rates were examined to observe the changing rate of uplift moving northeast parallel to the coast.

An example from Site 1 at Cabo Blanco illustrates how we calculated uplift rates from radiometrically dated shell fragments. The outer edge of the tread of a low, narrow terrace remnant is at an altitude of 2.61 m above sea level. The tread is formed on a thin veneer of intertidal sediments resting upon bedrock exposed in the riser between the terrace and the modern beach. The inner edge of the terrace is buried under hillslope colluvium. In order to estimate the altitude of the bedrock inner edge of the platform, which is the closest approximation to sea level at the time of formation, we use an error bar that is equal to the modern intertidal range of 1.2 m. Therefore, the inner edge could be as high as 3.81 m or as low as 2.61 m. The radiometric date on a shell fragment from the veneer of sediment on the terrace is 333 +30/-45 ybp. Assuming that paleo-sea level at that time was little different than today, the resultant uplift rate is 6.0 +3.8/-2.7 m/ka.

**Pleistocene Platforms**

An altimeter survey was conducted to measure elevations of discrete terraces within the Pleistocene Cobano surface above the town of Cabuya. Because of the greater ages of the higher terraces, a different technique was used to determine the longer-term uplift rate. Two altimeters were used, one to record elevations of sea level and the terraces, and the other which remained stationary to record changing barometric pressure during the 3-hour survey. After correcting for sea level and barometric pressure, the elevations of terraces were correlated with individual highstands of a Pleistocene sea level curve. After selecting the best fit sea level curve, an inferred uplift rate diagram was plotted to determine the average long-term uplift rate (Figure 3).

**RESULTS**

**Holocene Uplift-Rate Calculations**

Holocene terraces were surveyed at 12 sites along the coast of Peninsula de Nicoya between Cabo Blanco and Montezuma (Figure 1). Figure 2 is a coast-parallel projection of the sites, with altitudes of the outer and inner edges of each terrace and of points along the tread between the outer and inner edges (Figure 2). The eight southernmost sites are in the Cabo Blanco area. In the Cabuya area, we combine our survey at Site 9 with radiometric dates and survey data from Marshall (1991). At sites with radiometric dates, we calculated uplift rates from the altitudes of specific terraces and the radiometric ages of the samples. In general, uplift rates are highest at the southeastern end of the Peninsula, at Cabo Blanco, and decrease northeastward toward Montezuma.

Using this procedure to estimate altitudes of bedrock inner edges that are buried beneath terrace treads, we obtain the following results. In the Cabo Blanco area, uplift rates vary from 6.0 +3.8/-2.7 m/ka at Site 1, to 5.4 +1.6/-1.3 m/ka at Site 5, to 5.6 m/ka at Site 7. The error bars for each of these rates overlap; the three rates have in common a range in uplift rate from 4.1 to 7 m/ka. At Cabuya, Marshall (1991) dated 8 radiometric samples on two extensive, well-preserved terraces. For the lower terrace, radiometric ages ranged from 498 to 2378 ybp (increasing age with higher altitude along the terrace), yielding uplift rates that ranged from 3.3 to 4.0 m/ka. For the higher terrace, radiometric ages sampled in range from 4338 to 5273 ybp, yielding uplift rates that range from 3.4 to 3.9 m/ka. Both terraces yield similar uplift rates that are all less than the range of values from Cabo Blanco.

At Rio Lajas, two surveys identified at least 5, and perhaps 6, terraces. The greater number of terraces than at Cabuya might be the result of river erosion by Rio Lajas, so some of the terraces might be fluvial. Another possibility is that terrace preservation is better at Rio Lajas, and that individual surfaces cannot be discerned as easily at Cabuya. This possibility is more likely, considering the wide range in age estimates obtained by Marshall (1991) for the two easily discerned surfaces at Cabuya. Radiometric samples from the two lowest terraces at Rio Lajas are
378 and 808 ybp, yielding uplift rates of 4.8 and 4.9 m/ka. Although these rates are slightly higher than those at Cabuya, our correlation of terraces along the coast suggests that terraces are tilted down to the northeast, and that uplift rates should decrease in that direction.

**Holocene Terrace Correlation**

In addition to calculating uplift rates at sites with radiometric dates, we combined information on terrace elevations and radiometric dates in order to correlate terraces between Cabo Blanco and Montezuma (Figure 2). Although remnants of as many as 7 different terraces are preserved among the 12 sites and some terraces can be correlated over distances of several km, only two surfaces are extensive enough to be correlated along nearly the entire 10-km length of the Cabo Blanco to Montezuma coastline (see the lines correlating terrace inner edges for two terraces on Figure 2). Just as Holocene uplift rates decrease to the northeast, so too do the inner-edge elevations of these two terraces. The higher surface has the greatest relief, ranging in altitude from 17 m near Cabo Blanco to 13 m near Montezuma. The lower surface has an inner edge altitude of 8.5 m Cabo Blanco and of 7.5 m at Montezuma. The higher terrace is tilted a greater amount to the northeast because it is older (on the order of 5000 years, and has been tilted and raised over a greater period of time than the lower terrace, which is only about 800 to 1500 years old.

**CONCLUSIONS**

The varying uplift rates along the coast are most likely due to the northeastward subduction of the Cocos Plate seamounts and rough topography under the Caribbean Plate. As these seamounts move under Nicoya, they cause the peninsula to tilt in a northeastwardly direction, uplifting highest at the southeastern tip.

Although it is difficult to examine net uplift mechanisms of the Nicoya peninsula using only the data presented here, a correlation of other uplift rates along either side of this study area supports the these mechanisms for the tectonism occurring along the Nicoyan coast. It is evident from Cook’s data (this volume) that uplift rates decrease in a northwest direction.

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Figure 3. (left and below)
Terrace altitudes corresponding to Pleistocene sea-level high stands. Insert shows inferred uplift vs inferred age of Pleistocene terraces. Figure modified from Merritts and Bull, 1989.

Figure 1. (below)
Profiles of Cabo Blanco Sites showing modern platforms and lower uplifted terraces. Zero on y-axis denotes sea level.

Figure 2. Holocene Terrace elevations along Nicoya coast
- Inner Edge
- Outer Edge
- Tread
- Dated Samples

Cabo Blanco
Cabuya
Río Lajas
Rate and style of Holocene uplift in response to subducting seamounts, Malpaís area, Península de Nicoya, Costa Rica

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INTRODUCTION

Crustal flexure due to Cocos Ridge subduction that controls much of Pacific Costa Rican tectonics is predicted to cause negligible uplift on the Península de Nicoya (Gardner et al., 1992; Gardner, this volume, fig. 1). However, high Holocene uplift rates have been reported from the southern Península de Nicoya, suggesting deformation from a different source. A terrace study by Marshall (1991) of the trench-perpendicular coast between Cabuya and Montezuma (Gardner, this volume, fig. 3) shows that uplift rates decrease arcward from 4.5 m/k.y. to 1.7 m/k.y. These data and evidence of subsidence in the Golfo de Nicoya to the east indicate an arcward rotation rate of 0.01-0.02°/k.y. Marshall (1991) suggests that this deformation of the southern Península de Nicoya may be caused by subduction of the Fisher Seamount chain. Bathymetric analysis of the continental slope offshore of Cabo Blanco, the southern tip of the Península de Nicoya, suggests that other seamounts in the Fisher Seamount chain are currently subducting below the forearc (von Huene et al., 1995; Gardner this volume, fig. 2). The uplift is likely produced by crustal thickening from seamount underplating.

This geomorphic study examines the style and rate of uplift along the trench-parallel coast of the Malpaís area. The high angle of intersection between the Malpaís coast and the trench-perpendicular coast data set of Marshall (1991) allows a more three dimensional analysis of the style of forearc deformation. Marine terraces developed around the southern tip of the Península de Nicoya represent an initially horizontal datum plane that has been exposed to the effects of differential uplift.

METHODS

Terrace Elevation and Age. Holocene marine terraces were identified in the Malpaís area on the southwestern coast of the Península de Nicoya between Cabo Blanco and the town of Carmen. This transect of coastline is 9 km as expressed on a coast-parallel projection line (Figure 1). Marine terraces were identified on the basis of geomorphology, i.e. relatively flat terraces separated by coast-parallel risers, and the presence of marine sediment. Elevation of the inner edge of marine abrasion platforms were used to calculate uplift. The inner edge between a gently sloping marine abrasion platform and its adjacent sea cliff is the singular geomorphic feature of a marine terrace with a well-constrained elevation. The shoreline inner edge defines an originally horizontal datum that is laterally continuous over the extent of the terrace. Additionally, elevation of bedrock abrasion platforms were used to correlate terraces along the coast. Terraces were dated using shell samples collected from marine sediments on abrasion platforms as discussed in (4) below.

Uplift Rate. Uplift rates were calculated for 6 dated samples along the 9 km transect from Cabo Blanco to Carmen (Figure 1). Data are reported in Table 1.

Figure 1. Map of the Malpaís area of the trench-parallel southwestern coast of the Península de Nicoya.
Uplift rate is determined using the following equation:

\[
\text{Uplift Rate (m/k.y.)} = \frac{\text{Elevation above MSL (m) + Depositional depth (m) + Paleo - sea level (m)}}{\text{Age in calibrated } ^{14}C \text{ years B.P. (k.y.)}}
\]

1. Elevation above MSL (mean sea level)— Elevations of dated samples were determined using transit and hand level surveys. Surveys were referenced to the current sea level using stable tidal pools. A sine function fit to the tidal data for Puntarenas, Costa Rica was used to calculate the sea level relative to the Puntarenas tidal gauge height at the time of each survey, and thus the initial elevation of each survey. A plot of the Puntarenas tidal data for the interval of the study yields a mean sea level (MSL) of 1.44 m on the Puntarenas tidal gauge. The tidal range is 2.4 m. All elevation data are expressed relative to this mean sea level.

2. Depositional depth— The depositional depth term relates the elevation at which a shell sample was deposited to MSL at the time of its deposition. A marine abrasion platform is a sloping surface; consequently, deposition may occur above, below, or at MSL. The depth below paleo-MSL at which each sample was deposited must be added to account for the non-tectonic source of elevation variation. The inner edge of modern abrasion platforms occurs at approximately the average high tide line, 1.2 m above MSL. Samples collected in close proximity to a terrace inner edge were assigned a depositional depth of -1.2 ± 0.6 m. Those samples collected on a terrace within view of an inner edge, but farther down the surface, are believed to have been deposited within the upper half of the paleo-terrace range, and receive a correction factor of -0.6 ± 0.6 m. Samples collected from terraces where the inner edge is obscured by colluvium shed off the late Pleistocene sea cliff are allowed the entire tidal range (0 ± 1.2 m).

3. Paleo-sea level— Global sea level has been rising since the last Pleistocene lowstand about 15-20 ka (Lajoie, 1986). Marine terraces that formed when sea level was lower than modern MSL have been uplifted from this negative elevation to their modern positions. No Holocene sea level curve has been determined for the Pacific coast of Central America, so a curve calculated by Marshall (1991) from uplifted coral reefs on Barbados was used (Figure 3a).

4. Age in calibrated \(^{14}C\) years B.P.— Six marine shell samples were collected from terrace deposits along the studied transect of coast (Figure 1) to provide a maximum age of uplift events. Collected shells were relatively unbroken and thin, to avoid dating older material deposited on older abrasion surfaces. The shells were radiocarbon dated, correcting for \(^{13}C\)/\(^{12}C\), and calibrated to calendar years B.P. Ages are reported with the asymmetrical one standard deviation ranges.

**HOLOCENE UPLIFT HISTORY**

Two prominent terrace surfaces are developed along the coast between Cabo Blanco and Playa Carmen. The inner edge on the abrasion platform of the lower terrace lies at an elevation of approximately 4 m above MSL and slopes gently to the northwest (Figure 2). This lower surface is present along much of the study area. The width of the tread from the modern sea cliff to the landward scarp varies from less than 10 m in the rocky southern section to over 200 m to the north. Covering sediments are thicker in the northern half of the section, and the terrace is often obscured by alluvial and deltaic sediments at stream mouths. The upper terrace slopes more steeply, from an elevation over 10 m near Playa Balsitas (Figure 1) to less than 5 m to the north. The upper surface is not as well preserved as the low surface, having been modified by fluvial processes, and covered by a colluvial wedge from the late Pleistocene sea cliff.

Radiocarbon dating of shells in lower terrace sediments yielded ages ranging from 943 to 1428 years B.P. (Table 1). This shows that this terrace was active as a marine abrasion platform for at least about 500 years. Rate of eustatic sea level rise has been quite low for the last 1.5 k.y. according to nearly all sea level curves. For a single abrasion platform to remain active over this period, the rate of uplift must have been similarly low for the period of 1.4-0.9 ka. Discrete uplifted Holocene marine strandlines appear to be the result of coseismic uplift events (Lajoie, 1986). The relatively long marine occupation of the lower terrace coupled with its well-defined morphology supports this coseismic uplift model for terrace formation, where uplift rates vary with seismic activity over time.

The two shell samples collected from the upper terrace yielded ages of 7210 and 2918 years B.P. The 4 k.y. inferred marine occupation of this abrasion surface may be explained by examining the pattern of Holocene eustatic sea level change. At 7.2 ka, sea level curves show a high rate of marine transgression (Figure 3a). Using the Barbados sea level data and average rate of uplift for this surface, 2.2 m/k.y., this older abrasion surface would remain at or below the paleo-sea level until approximately 2.8 ka. It is hence reasonable to conclude that deposition of the Sample 6 shells occurred on the same abrasion surface as Sample 4 more than 4 k.y. previous.
Table 1: Radiocarbon ages, elevations, and uplift rates for shell samples collected from the Malpaís area on the Peninsula de Nicoya.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Calibrated $^{14}$C age (years B.P.)</th>
<th>Elevation above MSL (m)</th>
<th>Depositional depth (m)</th>
<th>Paleo-sea level (m below MSL)</th>
<th>Uplift rate (m/k.y.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (CR-RB-5)</td>
<td>943 (978-853)</td>
<td>3.54 ± 0.2</td>
<td>-1.2 ± 0.6</td>
<td>0</td>
<td>2.5 (3.8-1.6)</td>
</tr>
<tr>
<td>2 (CR-RB-6)</td>
<td>588 (638-563)</td>
<td>3.14 ± 0.2</td>
<td>-0.6 ± 0.6</td>
<td>0</td>
<td>4.3 (5.9-2.7)</td>
</tr>
<tr>
<td>3 (CR-96-5)</td>
<td>1218 (1288-1083)</td>
<td>4.08 ± 0.2</td>
<td>0 ± 1.2</td>
<td>0.2 ± 1.0</td>
<td>3.5 (6.2-1.5)</td>
</tr>
<tr>
<td>4 (CR-RB-7)</td>
<td>2918 (3008-2833)</td>
<td>5.905 ± 0.05</td>
<td>0 ± 1.2</td>
<td>0.75 ± 1.0</td>
<td>2.3 (3.1-1.5)</td>
</tr>
<tr>
<td>5 (CR-RB-1)</td>
<td>1428 (1523-1358)</td>
<td>2.800 ± 0.05</td>
<td>-1.2 ± 0.6</td>
<td>0.2 ± 1.0</td>
<td>1.3 (2.5-0.6)</td>
</tr>
<tr>
<td>6 (CR-RB-2)</td>
<td>7210 (7278-7078)</td>
<td>5.51 ± 0.2</td>
<td>0 ± 1.2</td>
<td>10.4 ± 1.0</td>
<td>2.2 (2.6-1.9)</td>
</tr>
</tbody>
</table>

Figure 2. Regression trends for bedrock terrace elevations along the Malpaís area coast of the Peninsula de Nicoya. Lower surface elevations are measured at the inner edge, and represent the highest points on the surface (black diamonds). The upper terrace inner edge is obscured by colluvium, and these bedrock elevations are lower points on the surface (gray squares). Dated samples are plotted as open triangles. Cabo Blanco lies at 0 km.

Figure 3. Uplift rates calculated from six dated shell samples along the trench-parallel coast from Cabo Blanco (0 km) northwest to Carmen (8.6 km). Inset Figure 3a is the Barbados Holocene sea level curve determined by Marshall (1991) used to calculate uplift rates.

Uplift rates along the trench-parallel coast decrease to the northwest from Cabo Blanco toward Carmen (Figure 3). Samples with poor depositional depth constraint and the large percent one sigma error of the young samples prohibit the calculation of a definitive trend of uplift rate over this segment of the coast. The error bars for Sample 2 and Sample 5 do not overlap, suggesting that the positive slope of Figure 3 is real. Approximately 20 km northwest of Cabo Blanco, near Rio Ario, uplifted Holocene terraces are absent, further supporting the northwest-
decreasing trend of uplift rates for the southwest coast. The bedrock elevation data of Figure 2 correspond to the distribution of calculated uplift rates as well. As the upper terrace has experienced the effects of differential uplift for a longer period than the lower terrace, the trends diverge toward the southeast.

The scatter of points in Figure 3 is largely due to the variation between the younger ages having a large effect upon the calculated uplift rate. The samples from the lower terrace (1, 2, 3, and 5) vary in elevation by only about 1.3 m (approximately half the tidal range) as they were deposited on the same marine abrasion platform. Given that deposition of these samples occurred over a period of about 500 years, each sample records a different average rate of uplift. The two older samples show a more consistent rate of uplift, as the effect of one recent uplift event is moderated by the time over which the uplift rate is averaged, thus smoothing out the coseismic deformation signal.

TECTONIC IMPLICATIONS

The observed pattern of uplifted marine terraces in the Malpaís area of the Península de Nicoya is consistent with that found on the southeastern coast by Marshall (1991). On the trench-perpendicular southeastern coast a set of lower elevation samples yield ages of 490-2330 years B.P., and a group of samples on a higher surface date at 4190-5130 years B.P. A fairly major vertical tectonic event likely occurred in the interval of 2-3 ka, which resulted in uplift of marine platforms around the southern tip of the Península de Nicoya. Formation of two discrete terraces was assisted by a concurrent decrease in rate of eustatic sea level rise over this interval.

The decreasing rate of uplift to the northwest observed in this study implies down-to-the-northwest rotation of the southern Península de Nicoya in addition to the arcward (northeast) rotation calculated by Marshall (1991). Scatter of the uplift rate data in this study precludes a meaningful quantitative calculation of the rate of northwestward angular rotation. However, the near-orthogonal angle between the two coastlines of the Península de Nicoya allows a qualitative three-dimensional analysis to be made of the style of forearc deformation. Combining the trend of down-to-the-northwest rotation along the trench-parallel coast with the down-to-the-northeast trend of the trench-perpendicular coast shows that the southern Península de Nicoya block is experiencing a more northerly tilt than the pure arcward trend previously reported.

The bathymetry of the Península de Nicoya continental slope mapped by von Huene and others (1995) strongly suggests other seamounts in the Fisher Seamount chain are being subducted offshore of Cabo Blanco. The decrease in uplift rate to the northwest along the trench-parallel coast is consistent with the presence of a subducting seamount, now under Cabo Blanco, deforming the forearc. The southern Península de Nicoya appears to be responding in a similar manner to the Península de Osa, which sits astride the larger-scale Cocos Ridge. Gardner and others (1992) indicate a similar northeast rotation is affecting the Osa block. Just as uplift rates decrease to the northwest away from the axis of the Cocos Ridge, a similar crustal flexure is likely deforming the southern Península de Nicoya. The smaller diameter of the seamount under Cabo Blanco results in the rate of uplift diminishing to negligible levels over the approximate 20 km distance observed in this study, rather than the greater than 200 km influence proposed for the Cocos Ridge. This uplift may be due to pure upwarping of crust over a single lower plate seamount high, or may represent the cumulative effects of seamount underplating, or some combination of the two processes.

ACKNOWLEDGMENTS

Thanks to the whole CR crew. A grande gracias to Tom Gardner for his energy and patience in the field and in analysis. Special thanks to Jeff Marshall for sharing a carbon date and his wisdom in the field and over email. I am grateful to Kevin Pogue and Bob Carson for their suggestions on analyzing data and writing.

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The marine terrace record of Holocene uplift,
Peninsula de Nicoya, Costa Rica

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INTRODUCTION

Offshore of the southern edge of Costa Rica's Nicoya Peninsula (Gardner, this volume, Fig. 1), an intermittent seamount chain is subducting nearly orthogonally to the coast. This chain follows the boundary between rough and smooth seafloor provinces to the south and north. Southward, rough seafloor subduction has eroded the outer forearc and scalloped the trench slope (Gardner, this volume, Fig. 2) (von Huene et al., 1995). Northward, the outer forearc forms the Nicoya Peninsula, where emergent marine terraces record Holocene uplift along both the trench-parallel and trench-perpendicular coastlines of the peninsula's southern tip. Marshall and Anderson's (1995) study of terraces along the trench-perpendicular coast showed increasing uplift toward the trench, with maximum uplift of greater than 4 m/ka.

This study examines terraces along a section of the trench-parallel coast between 8 and 12 km from Cabo Blanco (Gardner, this volume, Fig. 3). Correlation of terrace data with that of other Keck researchers elsewhere along the coast will allow the modeling of the magnitude and distribution of Holocene uplift for the entire peninsula. The terraces I studied record a sequence of relative sea level rise and fall that has juxtaposed two flights of terraces. Understanding the terrace record of this transgression and regression will be critical to correlating terraces along both coasts of the peninsula.

METHODS

To determine the modern elevation of the terraces I made five surveys inland from the shore, using a transit (error ± 0.05 m) or hand level and stadia rod (± 0.2 m). These surveys were adjusted to modern mean sea level (MSL) by adding or subtracting the tidal position within its 2.4 m range, calculated for the time of the survey. I collected shell samples to be radiocarbon dated from sediment along each of these surveys and categorized each sample into either inner edge facies (depositional depth at high tide, or 1.2 m ± 0.6 m above the paleo-MSL at the time of formation,) or mid-platform facies (deposited at paleo-MSL, ± 1.2 m). Shell samples were submitted to Beta Analytic, Inc., where they were radiometrically dated with funds from the Keck foundation.

Uplift rates can be calculated for terraces where four parameters are known: modern elevation (X1), facies depth of the dated sample (X2), paleo-sea level from a published sea level curve (X3), and sample age (X4) (Gardner et al., 1992), according to the equation:

\[ Z = X1 + X2 + X3 \times X4 \]

Three different paleo-sea level curves were selected for evaluation by the Keck research group: a curve fit to Lighty et al.’s (1982) Barbados data by Marshall (1991), a New Zealand curve (Gibb, 1986), and a polynomial equation fit to multiple Pleistocene sea level maxima and minima by Pinter and Gardner (1989). I found that the Pinter and Gardner (1989) model produced the most consistent uplift rates. However, this model shows a late Holocene increase in uplift rates that is an artifact of the equation and is not supported by strandline records. Therefore, I rejected the Pinter and Gardner (1989) model and used the curve based on Lighty’s (1982) data, which was the next best fit and which has been used in previous studies in the area. Paleo-sea levels were assigned error values according to date: levels from 7 ka and older had an error of ± 2 m, 7 ka to 1 ka had error of ± 1 m, and less than 1 ka had error of 0 m.

RESULTS

Terrace correlation. Four shell samples taken along the survey profiles were submitted for dating (Table 1). An additional sample from my area that had been dated by Gardner (pers. comm, 1998)
Table 1. Terrace ages, elevations, and uplift rates

<table>
<thead>
<tr>
<th>Site Description</th>
<th>km along coast</th>
<th>calibrated radiocarbon ages yrs B.C. *</th>
<th>modern elev. (m)</th>
<th>paleo-sea level (m below MSL)†</th>
<th>calculated uplift (m/ka) (high, low ranges)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quebrada Carmen: QC1</td>
<td>8.8</td>
<td>1510, (1605, 1430)</td>
<td>5.2 ± 0.2</td>
<td>1.4 ± 1</td>
<td>1.5 (2.1, 1.0)</td>
</tr>
<tr>
<td>Dude Ranch: DR1</td>
<td>9.2</td>
<td>3295, (3344, 3105)</td>
<td>4.4 ± 0.2</td>
<td>3 ± 1</td>
<td>1.17 (0.8, 1.57)</td>
</tr>
<tr>
<td>Itauna: IU</td>
<td>9.4</td>
<td>5440 (5490, 5404)</td>
<td>3.8 ± 0.2</td>
<td>11 ± 2</td>
<td>1.8 (1.4, 2.2)</td>
</tr>
<tr>
<td>Cabinas: CB1</td>
<td>10.5</td>
<td>1750, (1865, 1670)</td>
<td>5.4 ± 0.2</td>
<td>1.4 ± 1</td>
<td>2.0 (1.0, 2.7)</td>
</tr>
<tr>
<td>Quebrada Danta: QD</td>
<td>8.4</td>
<td>1385, (1385, 1300)</td>
<td>2.6 ± 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quebrada Carmen: QC2</td>
<td>8.8</td>
<td></td>
<td>2.2 ± 0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dude Ranch: DR2</td>
<td>9.2</td>
<td></td>
<td>6.2 ± 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cabinas: CB2</td>
<td>10.5</td>
<td></td>
<td>2.0 ± 0.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* The Quebrada Danta sample was judged to be reworked, so it was not used for uplift rate calculations. All dates calculated and calibrated by Beta Analytic, Inc. High and low dates given are the 1 sigma (68%) values. The Itauna sample is courtesy of Gardner (1998).
† Paleo-sea level curve used is Marshall, 1991, from Lighty et al., 1982.

was also included. I did not use the date for the lowest uplifted terrace, QD, in my uplift calculations. This sample yielded a date of 3.4 ka, similar to the 3.5 ka terrace nearly 2 m above it. I judged that the sampled deposit had been reworked and contaminated by older materials from the terrace above.

The IU (7.4 ka) and DR1 (5.3 ka) samples occur at similar elevations despite the difference in their ages. This could result from actual irregularities in uplift, such as coseismic deformation (Marshall and Anderson, 1995), from sediment reworking, or from other natural variability in the terrace record.

There are at least four terraces in my field area. Survey profiles show that they often pinch out between one profile and the next, are not laterally continuous, and that they alternate in age, with the youngest dated terrace above the oldest ones (Fig. 1). This pattern is attributed to relative paleo-sea level rise and fall in the mid- to late Holocene and to the spatial variability of terrace formation.

**DISCUSSION**

**Sea level transgression and regression.** During the early to mid Holocene sea level rose at rates of 4 m/ka or more. The net crustal uplift in my section was too slow to keep pace with the rising water, so sea level rose with respect to the coast, submerging terraces as they formed. Once sea level increase fell below the crustal uplift rate, sea level began to recede with respect to the land. The same vertical section that had been submerged was uplifted above sea level, forming new terraces at 3.5 ka and younger.

Because the oldest terraces have been at sea level twice, there is the possibility of contamination of the sediments on these terraces with younger beach deposits. For the determination of uplift rates, these reworked deposits can be just as effective as the original ones, since they still record a time when sea level was at that terrace elevation. That some of these original sediments have been preserved does suggest some details about the environment in which the terraces formed, however. For instance, the modern platform in my section is forming discontinuously on rocky promontories separated by sandy stretches of beach. Sediments on older terraces may have been preserved in these depositional embayments, while younger terraces were overprinted onto the headlands. Lateral breaks in terraces may also occur after terrace uplift when lower terraces are beveled back into the sea cliff, eroding the terrace above (Bull, 1984).

The transgression/regression sequence will leave a different terrace record in areas of different uplift rates. During a transgression, when sea level is rising rapidly, coastal areas with little or no uplift will have widely spaced terraces (Fig. 2). These terraces will have less difference in elevation in the areas with more rapid uplift, and merge where crustal uplift matches the rising water. When sea level is rising more slowly, terraces will have the most vertical separation in areas where crustal uplift is highest, and ramp together in lower uplift areas.

The record of sea level fluctuation with respect to the coast that is preserved in my section may help explain the terrace morphologies that will emerge when the terraces are correlated among the three field sections on this coast. I therefore expect that the terraces, when they are correlated, will create different patterns along the
Effects of relative sea level rise and fall on a tilting coastline

Figure 2. Sea level transgressions and regressions leave different terrace patterns on a tilting coast. During a period of rising sea level with respect to the land, areas of high coastal uplift can keep up with water level, and terraces merge in the direction of highest uplift (gray line). When the water is rising more slowly, as it has in the late Holocene, high uplift areas are imprinted with more widely spaced terraces (black line). Terraces in my field area alternate between young and old, a pattern similar to that seen near the middle of this diagram. Sea level curve by Marshall, 1991, from Lighty et al., 1982.

Coast parallel projection of terraces

Figure 1. Terrace elevations in my field area. View is looking at the coast from offshore. Note lateral discontinuity between sampled survey lines. Distance along coast is measured along the coast parallel line from Figure 3, and site labels are from Table 1.

Calculated uplift rates

Figure 3. Uplift rates plotted along the coast-parallel line of Figure 3. Terraces in my area did not show an increase in uplift in either direction. Sample numbers are from Table 1.
coastline depending on whether the terraces record relative sea level rise or fall. The number of terraces may actually decrease in either direction as transgressive or regressive terraces ramp together.

**Uplift magnitude and distribution.** The uplift rates that I calculated from my dated samples range from 1.4 to 2.1 m/ka, with maximum and minimum ranges between about 0.5 and 5 m/ka (Fig. 3). On their own, they do not show an increase in the rate of uplift in either direction along the coast. However, increasing uplift rates southward toward the tip of the peninsula can be expected based on the high uplift values found near Cabo Blanco (Marshall and Anderson, 1995).

**CONCLUSIONS**

During the Holocene, the southern tip of the Nicoya Peninsula has been experiencing fairly rapid, unequally distributed uplift. Along the section of the peninsula’s southwestern coast between 8 km and 12 km from Cabo Blanco, uplift rates recorded by marine terraces reach 1.4 to 2.1 m/ka. Although there is no observable tilt within this section, it is expected that uplift rates increase southward towards Cabo Blanco, where they should match rates from Marshall and Anderson’s (1995) study. When combined with terrace data from elsewhere along the coast my uplift rates will help generate a three-dimensional view of uplift on the southern Nicoya Peninsula. The record of sea level transgression and regression that is recorded in my section may also be useful in correlating individual terraces along both coastlines.

**ACKNOWLEDGEMENTS**

Generous financial support from the Keck Foundation and Carleton’s Duncan Stewart Research Fellowship made this work possible. Thanks also to project advisors Tom Gardner, Jeff Marshall, Dorothy Merritts, Ed Beutner, and Marino Pratti, and to the other students of the Costa Rica Keck. At Carleton, thanks to my thesis advisor Dave Bice and to the rest of the geology department.

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Fore arc deformation in response to subducting seamounts, Peninsula de Nicoya, Costa Rica

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INTRODUCTION

Landward of the Middle America Trench along the Pacific coast of Costa Rica, subducting rough oceanic lithosphere of the Cocos plate is deforming the fore arc of the Caribbean plate (Gardner, this volume, Figs. 1 and 2). At the southeast tip of the Peninsula de Nicoya, the Christmas, Fisher, and unnamed seamounts are subducting parallel to the trench-perpendicular coastline (Gardner, this volume, Fig. 2). Marine abrasion platforms serve as excellent horizontal reference planes that record Holocene uplift in response to these subducting seamounts. Uplift rates can be determined from the following equation (Gardner et al., 1992): uplift rate (m/ka) = (X1+X2+X3) / X4, where X1 is the modern elevation (m), X2 is the depositional elevation (m), X3 is paleo-sea level (m) determined from several Holocene sea level curves, and X4 is the calibrated radiocarbon age (ka) for shell and beachrock samples from Holocene marine abrasion platforms. Angular rotation of the southeast coast of the Peninsula de Nicoya can be quantified using linear regression through a distribution of calculated uplift rates. Constraining uplift and angular rotation rates is important for understanding fore arc deformation in this active margin setting. This information is useful in determining how long the peninsula has been effected by incoming seamounts, and locating where underplating occurs with respect to the Middle America Trench and the overriding Caribbean plate.

![Figure 1](image1.png)  
**Figure 1.** Study area: southeast coast of the Peninsula de Nicoya, Costa Rica. Radiocarbon samples are indicated by stars.

![Figure 2](image2.png)  
**Figure 2.** Generalized profile of a marine abrasion platform and facies relationships to mean sea level (MSL). This figure shows the modern abrasion platform as well as abandoned abrasion platforms I and II.

METHODS

Uplift rates of individual sites along the trench-perpendicular coast of the Peninsula de Nicoya were calculated according to the equation (Gardner et al., 1992): uplift rate = (X1+X2+X3) / X4.

**X1, modern elevation (m).** Modern elevation of spot-elevation points and dated samples were determined using altimeter, hand level, tape measure, and transit survey techniques. In this study, elevation data were collected from Playa Cedro to Tambor, a coastal distance of approximately 15km (Fig. 1). A transit survey conducted near Quebrada Palmiche, provided detailed elevations along the marine abrasion platform profile. Tide fluctuation and wave run-up make it difficult to pinpoint MSL in the field. Therefore, elevations were recorded with respect to the
visible high tide debris line (HTDL) and the modern inner edge (MIE), rather than MSL (Fig. 2). The tide chart for Puntarenas, Costa Rica was used to translate elevation points referenced to HTDL, MIE, or water level, into X1 elevations above MSL.

**Figure 3.** X1 is the elevation above MSL of radiocarbon samples and inner edge survey points. Samples 1-9 are from Marshall and Anderson (1995); samples 10-15 are from this study.

**Figure 4.** Paleo-sea level, X3, for three Holocene sea level curves.

X2, depositional elevation (m). Marine abrasion platforms were divided into facies based upon the modern platform environments relative to MSL (Fig. 2). The front of the modern abrasion platform was assigned a depositional elevation of -1.2m +/- 0.6m relative to MSL. This environment is characterized by biological activity of bedrock-boring clams and intertidal organisms such as barnacles that can withstand alternating cycles of subaerial exposure. Beachrock formation is restricted to the inner edge facies along the modern platform, corresponding to a depositional elevation of 1.2m +/- 0.6m. At this high-energy environment, the release of CO₂ promotes calcite precipitation and the cementation of beach deposits (Marshall, 1991). The mid-platform facies, 0m +/- 1.2m, consists of sandy, shelly deposits and is constantly affected by rising and falling tides. Samples collected from locations along the platform where neither the front, nor the inner edge were visible, were designated a mid-platform depositional environment and assigned an error factor corresponding to the full tidal range. In all cases, the depositional elevation, X2, was subtracted to reflect the amount of uplift of a deposit located at MSL.

X3, paleo-sea level (m). There is no Holocene sea level curve specifically for Costa Rica. Therefore, paleo-sea level was determined from several Holocene sea level curves including: a Barbados sea level curve (Marshall, 1991), a New Zealand sea level curve (Gibb, 1986), and a polynomial model for Holocene sea level (Pinter and Gardner, 1989). Uplift rates were calculated using all three sea level curves (Fig. 4).

X4, calibrated radiocarbon age (ka). For this study, six shell and beachrock samples were dated by Beta Analytic, a radiocarbon dating service (Fig. 6). A spatial and temporal distribution of samples were collected so that the radiocarbon dates would yield ages of platforms I and II at various distances along the coast. Samples dating platform I include: a shell deposit collected from the strath of Quebrada Cocal, a shell deposit from the banks of Quebrada Cocal, a beachrock deposit from Tongo Mar, and a shell deposit from Tambor. Platform II was dated with a shell deposit along the transit profile near Quebrada Palmiche and a beachrock sample collected inland from Playa Cocal (Fig. 1). These six samples, as well as ten additional samples from Marshall and Anderson (1995), were used to constrain the ages and elevations of the marine abrasion platforms along the southeast coast.

**RESULTS**

**Platform correlations.** There are clearly two platforms distinct in both elevation and age (Fig. 3).

Inner edge elevations along the coast sample elevations, and radiocarbon ages can be used to resolve two abandoned abrasion platforms. Platform I is the lower elevation platform and ranges in age from 0.5ka to 2ka. Platform II is represented by higher elevations and 4ka to 6ka samples. The two platforms become more difficult to discern as uplift rates decrease.

**Uplift Rates.** In order to better understand the deformation occurring along the southeast coast of the Peninsula de Nicoya, the data from this study, collected along a stretch of coast from Montezuma to Tambor, was
integrated with the data from a previous study by Marshall and Anderson (1995) which focused research from Cabo Blanco to Montezuma (Fig. 5). Compilation of these two data sets (15 dated samples) yields uplift rates that vary from 4.4m/ka to 0.2m/ka. Uplift rates decrease landward from the Middle America Trench and do not vary significantly with choice of paleo-sea level curve (Fig. 6).

**Angular Rotation.** Rotation of the Nicoya block of the Caribbean plate can be modeled using the uplift rates calculated in this study and Marshall and Anderson (1995). Using a least squares regression line through uplift rates of individual samples, the angular rotation of the southeast coast of the Peninsula de Nicoya is 0.01°/ka. The x-intercept of the linear model predicts a change from uplift to subsidence to occur between a coastal distance of 21km to 23km, near Bahia Ballena (Fig. 7).

<table>
<thead>
<tr>
<th>Sample</th>
<th>X1(m)</th>
<th>X1(m): F&amp;B</th>
<th>X1(m): B &amp; S</th>
<th>X1(m): NZ</th>
<th>X4 (ka)</th>
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<tr>
<td>1</td>
<td>3.4±0.2</td>
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<td>2</td>
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</table>

**Figure 5.** Error for X1 includes measurement technique; X2 error values assume tidal range variations; samples younger than 1 ka have +/-0m for paleo-sea level; samples older than 1 ka are assigned +/-1m error.

**Figure 6.** Error bars were constructed according to the following: maximum uplift rate = (X1+X2+X3) max / X4 min; minimum uplift rate = (X1+X2+X3) min / X4 max.

**DISCUSSION**

Deformation of the fore arc of the Caribbean plate along the southeast coast of the Peninsula de Nicoya can be attributed to subducting rough oceanic crust of the Cocos plate. The effects of this are two-fold. First, seismic activity as a result of the coupling of the Cocos and Caribbean plate is producing earthquakes which serve to uplift the Nicoya Peninsula. Second, after a certain distance, the subducting seamount underplates onto the overriding Caribbean Plate (Fig 7). Isostatic uplift or lithospheric flexure, in response to this addition of mass, also contribute to deformation (Fisher et al., 1998). Subduction of the seamount chain parallel to the southeast coast of the Peninsula de Nicoya is producing uplift which decreases landward from the Middle America Trench. The coastal expression of this uplift, as evidenced by abandoned marine abrasion platforms, is constrained to 60km-90km landward from the trench. A change from uplift to subsidence occurs 90km landward from the trench, corresponding to a coastal distance of 21-23km. The cessation of uplift may indicate that the seamount has been underplated onto the Caribbean Plate. This would suggest that underplating occurs when the overriding plate has enough mass to shear off and assimilate the seamount. Other implications are that the change from uplift to subsidence represents the completion of underplating.

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Broader inspection of the structure and stratigraphy of the Nicoya Peninsula allows for interpretation of how long the subduction of the rough oceanic lithosphere of the Cocos Plate has been controlling the deformation of the same region. Decreasing uplift rates yield an angular rotation rate of 0.01°/ka, or 1°/100,000 years, for the southeast coast of the Peninsula de Nicoya. This rotation rate is consistent with the less than 1° dip of the Cobano Surface, oxygen isotope stage 5e sea level highstand at 125 ka (Fisher et al., 1998). A 0.01°/ka angular rotation rate is also consistent with the 2°-5° dip of the Pliocene to Pleistocene Montezuma Formation (Lundberg, 1982) and (Gardner et al., 1992). This suggests that uplift in response to subducting seamounts has only been operating for the past 100,000 to 200,000 years; otherwise the dip of the Montezuma Formation would be much greater.

Figure 7. Uplift and rotation of the southeast coast of the Peninsula de Nicoya. Convergence rate from Gardner (this volume, Fig. 2.) Subduction angle from Protti et al. (1995).

ACKNOWLEDGEMENTS

I would like to acknowledge the South Central section of GSA and the Department of Geosciences at Trinity University for their financial support of this project. Additionally, I would like to thank Dorothy Merritts and Jeffrey Marshall at Franklin and Marshall University for their assistance in the field.

REFERENCES CITED


A tale of eight terraces: Landscape response to active tectonics of the southern Peninsula de Nicoya, Costa Rica.

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INTRODUCTION

Marine terraces of the Peninsula de Nicoya, Costa Rica, record a history of repeated uplift events caused by seamount subduction along the Middle America Trench (Gardner, this volume, Figs. 1 and 2). The peninsula lies in a rare geologic setting, containing both trench-parallel and trench-perpendicular coasts with strandlines. Pacific Coast platforms parallel the trench, while the Gulf of Nicoya terraces lie orthogonal to subduction (Gardner, this volume, Fig. 3). The goal of the project is to provide a series of marine terrace uplift rates along both coasts in order to quantify deformation of the peninsula.

Shorelines form at the interface between water, air, and land, and record slight shifts in sea level or land movement. Once uplifted, these variations remain and provide clues to specific paleo-elevations on the terrace. Shell samples gathered on top of marine bioabrasion platforms were radiocarbon dated to provide absolute ages of abandoned terraces. Terrace elevations must be corrected for facies depositional depth and paleo-sea level in order to accurately portray the change in elevation through time. I examined both Holocene and Pleistocene uplift rates along seven kilometers of Pacific shoreline. Uplift rates were determined by relating 14C dated shells with terrace elevation, and by connecting Pleistocene platform height with past sea level highstands.

STUDY SITE

The Pacific Coast marine terraces have previously received little attention due to prior difficulties with accessibility. My study area is located between Pacific Coast kilometers 12.0 to 19.0 (Gardner, this volume, Fig. 3). Initial inspection identified a single ramping abandoned terrace lower than 2.0m above msl, bounded by a series of emergent strandlines ranging from 10m to 107m. Regional correlation with previously radiocarbon-dated terraces suggested that the low terrace was of Holocene age, and the terraces at 10m or higher are of Pleistocene age.

Figure 1: Trench-parallel coastline of the Peninsula de Nicoya, Costa Rica. Distances based on kilometer line drawn from the highest point of Cabo Blanco to the farthest seaward platform of Penon de Arlo. My study site encompasses 12.0 - 19.0 km. See Gardner, this volume, Fig. 3 for general location.
**HOLOCENE UPLIFT RATES**

Holocene Uplift Methods

Elevation uses modern mean sea level as a horizontal datum. It is essential to maintain an understanding of daily tidal cycles when determining heights of 0-2m inland of the swashface. Raw terrace measurements were modified in relation to mean sea level by accounting for the 2.4m (0+/-1.2m) tidal range and time of measurement.

Shell samples for 14C dating were collected on the uplifted Holocene platform. Facies depositional depth was determined in relation to the sample location on the abraded bedrock. Inner edge samples were deposited at the highest tidal reaches (1.2 +/-0.6m) while borings lay on the lower half of the swashface (-0.6 +/- 0.6m). Samples were radiocarbon dated by Beta Analytic, Inc. and ages range from 500 to 5000 14C yr BP. Mean, minimum, and maximum uplift rates were determined using the equation:

\[
X_1 + X_2 + X_3 \text{ or } \text{Current Elevation (m) + Depositional Elevation (m) + Paleo-Sea Level (m)} \frac{X_4}{\text{Calibrated 14C Age (ky BP)}}
\]

Uplift rate calculations use original elevation with respect to modern mean sea level (X1) and are adjusted for depositional elevation (X2). Shells from the upper swashface are given negative values because they originally were deposited above mean sea level. Three Holocene sea level curves (Pinter and Gardner, 1989; Fairbanks, 1989; Gibb, 1986) give slightly different paleo-sea level elevations (X3).

**TABLE 1: HOLOCENE UPLIFT RATE DETERMINATION FROM SAMPLE ELEVATIONS AND 14C DATES.**

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Lambert Grid Coordinates</th>
<th>Distance Along Coast (km)</th>
<th>Elevation (m) Raw Survey</th>
<th>14C Elevation (m) to MLS</th>
<th>X₂  Depressional Elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1NK (CR-NK-5)</td>
<td>191,700m/400,200m</td>
<td>12.1</td>
<td>0.70</td>
<td>1.90, 1.85-1.95</td>
<td>( ) 0.50, 0.00-1.20</td>
</tr>
<tr>
<td>5NK (CR-NK-10)</td>
<td>193,600m/400,500m</td>
<td>12.8</td>
<td>-0.32</td>
<td>1.50, 1.30-1.70</td>
<td>( ) 1.20, 0.60-1.00</td>
</tr>
<tr>
<td>6NK (CR-NK-11)</td>
<td>193,200m/400,800m</td>
<td>14.4</td>
<td>-0.82</td>
<td>0.36, 0.18-0.58</td>
<td>0.00, -0.20-1.00</td>
</tr>
<tr>
<td>8NK (CR-NK-12)</td>
<td>184,450m/404,700m</td>
<td>15.9</td>
<td>0.74</td>
<td>1.24, 1.18-1.99</td>
<td>( ) 1.20, 0.60-1.00</td>
</tr>
<tr>
<td>9NK (CR-NK-1)</td>
<td>183,300m/404,700m</td>
<td>16.8</td>
<td>52.00</td>
<td>52.20, 52.70-53.70</td>
<td>( ) 1.20, 0.60-1.00</td>
</tr>
<tr>
<td>11NK (CR-NK-2)</td>
<td>183,300m/404,700m</td>
<td>16.7</td>
<td>52.00</td>
<td>52.20, 52.70-53.70</td>
<td>( ) 1.20, 0.60-1.00</td>
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<tr>
<td>12NK (CR-NK-3)</td>
<td>183,300m/404,700m</td>
<td>16.7</td>
<td>52.00</td>
<td>52.20, 52.70-53.70</td>
<td>( ) 1.20, 0.60-1.00</td>
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<tr>
<td>2NK (CR-NK-6)</td>
<td>181,700m/400,200m</td>
<td>12.1</td>
<td>-0.07</td>
<td>1.13, 1.08-1.18</td>
<td>( ) 1.20, 0.60-1.00</td>
</tr>
<tr>
<td>3NK (CR-NK-7)</td>
<td>181,700m/400,200m</td>
<td>12.1</td>
<td>0.02</td>
<td>1.22, 1.17-1.27</td>
<td>( ) 0.80, 0.00-1.20</td>
</tr>
<tr>
<td>4NK (CR-NK-9)</td>
<td>182,300m/404,950m</td>
<td>13.0</td>
<td>1.30</td>
<td>2.50, 2.45-2.55</td>
<td>( ) 1.20, 0.60-1.00</td>
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<tr>
<td>7NK (CR-NK-13)</td>
<td>183,300m/405,950m</td>
<td>14.4</td>
<td>0.58</td>
<td>1.78, 1.66-1.96</td>
<td>( ) 0.80, 0.00-1.20</td>
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<tr>
<td>13NK (CR-NK-8)</td>
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<td>16.9</td>
<td>0.75</td>
<td>1.95, 1.84-2.15</td>
<td>( ) 1.20, 0.60-1.00</td>
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**Holocene Uplift Results**

Mean Holocene uplift rates average approximately 0.80m/ky. Differences in paleo-sea levels provided by the three curves proved to be the most important factor in producing differences between calculated uplift rates. Sample CR-NK-9 (Table 1) represents rates ten time greater than others due to possible contamination by modern shells.

Of the three sea level curves, the Barbados curve (Fairbanks, 1989) provides results most easily correlated with other sections of the Pacific and Gulf of Nicoya coastlines (see E. Burton, R.Burgette, B.Bee, and J.Cooke, this volume). The Barbados curve yields uplift rates that rise with proximity to Cabo
Blanco (Figure 2). Sea level for the past 6000 yrs is depicted as zero on the New Zealand curve (Gibb, 1986) which causes a greater spread of possible uplift. The Pinter and Gardner (1989) curve reveals negligible changes in uplift rates. However, because error was calculated by regarding variables as independent of one another, differences between best-fit lines may not be indicative of trends caused by the three curves. Calculated Holocene rates for Pacific Coast kilometers 12.0 to 19.0 are constrained within a range of low uplift values (Table 1 and Figure 2).

![Graph showing Holocene uplift rates from various sea level curves](image1)

**Figure 2**: Holocene uplift rates determined from measured terrace elevation, depositional depth, paleo-mean sea level, and calibrated radiocarbon dates.

**PLEISTOCENE UPLIFT RATES**

**Pleistocene Uplift Methods**

Seven Pleistocene terraces were distinguished with altitudes of 10m or higher. A break in slope was defined as a terrace if it contained bored bedrock, rounded marine cobbles, or could be correlated with a band level along kilometers of coastline. Terrace treads are often overlain with thick colluvium as a result of high erosion rates, but step-like features are still easily apparent. Stream incision has dissected the terraces but the surfaces correspond across the channel valleys. Platform elevations and their locations were plotted on 1:50,000-scale topographic maps (Figure 3). Indistinct platforms are present at 10m and 17m, but the lack of bedrock or marine cobbles prevent their certain identification as marine terraces. The 52m terrace contains bored bedrock covered by oyster shells, and may be the oldest direct evidence of an uplifted terrace in Costa Rica. Unfortunately, oyster shells provide ambiguous dates through amino acid racimization, so an absolute age cannot be determined. Relative ages can be determined through graphical analysis of terrace elevations (Figure 4).

![Map showing marine terrace elevations on the Pacific Coast, Península de Nicoya, Costa Rica](image2)

**Figure 3**: Marine terrace elevations for the Pacific Coast, Península de Nicoya, Costa Rica.
Pleistocene Uplift Results

Measured terrace heights correspond to global highstands of the three sea level curves (Figure 4). The slope between the two elevations represents the long-term uplift rates assuming that terraces represent highstands and uplift has remained constant (Merritts and Bull, 1989). Another necessary assumption is that the only terraces present are those that have never been overlapped from sea level fluctuations. Graphical representations include rates based on the correlation of the highest terrace with the 125,000ka highstand, or the connection between the lowest terrace with the 60ka peak (Table 2). No absolute age controls exist for the Pleistocene terraces. Although graphically calculated uplift presents two plausible models consistent with Holocene rates, other possibilities may exist. Rates approach 1.10m/ky, which places Pleistocene rates only slightly higher than Holocene uplift rates.

![Figure 4: Uplift Rates Based on Pinter and Gardner (1989) Sea Level Curve](image)

**TABLE 2:** High and low estimates of Pleistocene uplift rates determined through strandline and paleo-sea level correlation.

<table>
<thead>
<tr>
<th>Pinter and Gardner (1989) uplift rates</th>
<th>New Zealand (Gibb, 1986) uplift rates</th>
<th>Barbados (Fairbanks, 1989) uplift rates</th>
</tr>
</thead>
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<tr>
<td>Model 1: 1.30 m/ky</td>
<td>1.10 m/ky</td>
<td>1.32 m/ky</td>
</tr>
<tr>
<td>Model 2: 0.97 m/ky</td>
<td>0.98 m/ky</td>
<td>1.10 m/ky</td>
</tr>
</tbody>
</table>

DISCUSSION

Marine terraces can be used as a tool to interpret tectonics. Terraces are formed at sea level and contain precise paleo-elevation indicators. When elevations are combined with 14C dating methods, pliform uplift rates can be determined. The terraces from 12.0 to 19.0km are the northern extremes of the group study site and record low uplift rates because of their distance from the subducting seamounts. Holocene rates average near 0.80m/ky for my entire study area. This rate is consistent with other students' higher uplift values nearer to the active tectonism. Both models for initial Pleistocene terrace age record similar rates of 0.97m/ky to 1.3m/ky. Pleistocene values are therefore only slightly greater than Holocene uplift rates, suggesting that this style of uplift may have occurred for at least 100,000 to 200,000 years.

REFERENCES

See T. Gardner, this volume, for full listing.


Merritts, D. and Bull, W., 1989. Interpretation of Quaternary uplift rates at the Menocino
Bedrock incision and knickpoint processes in streams along an uplifting coast, southern Península de Nicoya, Costa Rica

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INTRODUCTION

Marine terraces and river profiles of the Península de Nicoya, Costa Rica record a pattern of non-uniform uplift and provide the opportunity to study interactions between tectonic and geomorphic processes. Tilted marine terraces along the southwest coast indicate that the uplift rate decreases from Cabuya (4.5 m/k.y.) to Montezuma (<1.7 m/k.y.) over approximately 6 km (Marshall & Anderson, 1995). This study uses the well constrained rates to closely examine fluvial response to different uplift rates. I studied three bedrock streams along the southwestern edge of the peninsula (Gardner, this volume, Fig. 3) where bedrock incision processes accompany the most recent uplift events. When uplift lowers relative sea level, the stream experiences a drop in base level and the surrounding platforms become a marine terrace. This geologically sudden event produces rapid incision and often creates a knickpoint (KP) in the stream profile which migrates upstream and changes in morphology over time. The KP migration rate and the change of KP morphology provide information about the incision processes of the stream.

KNICKPOINT & PLATFORM RELATIONSHIP

Following Hill (1972), the wave platform is the area from the fringing cliffs to the low tide line (LTL) and includes all the identifiable elements of an active erosional surface. The marine terrace is a nearly horizontal, planar surface extending from low tide up the platform to a position between mean sea level (MSL) and the high tide line (HTL). The wave ramp described in other literature as the platform ramp, swash face, or bench reaches up from the terrace to the base of the cliff with a steeper, possibly concave upward profile. The HTL defines the inner edge and the LTL defines the outer edge of the modern platform (Fig. 1). The Puntarenes tidal chart shows 2.4 m range in the Cabo Blanco area.

Streams grade to the HTL during normal flow because beach berms and piles of debris clog the mouths of the streams and form an intertidal pool (Fig. 1). This pool is a scour hole in bedrock at HTL which erodes by a combination of fluvial and oceanic influences. During floods and ocean storms, both stream and wave erosion can scour out the stream base level. The intertidal pool at Rio Lejas (estimated to 3 m) forms behind a large beach berm, at Cocal (1 m) is covered by an unknown thickness of sand, and at Palmiche is only about 0.33 m deep. Below HTL, the stream slope follows the expression of the beach or platform, where wave erosion dominates fluvial erosion.

Knickpoint formation. Field observations reveal a relationship between stream profiles and the actively forming marine platform; on some uplifting coasts, the slope of the wave cut platform is steeper than adjacent streams such that uplift permits the formation of KP's. During a period of uplift, HTL moves down the platform to a lower elevation. The former HTL becomes the inner edge of the most recently created marine terrace and the new HTL marks the starting position of the new inner edge of the actively forming marine platform. The elevation change across the uplifted marine terrace is a function of the magnitude of uplift; only when uplift is greater than 2.4 m is the entire platform abandoned. The migration of HTL associated with uplift activates the KP already present as a scour hole at the former HTL. The initial energy of the KP is associated with the slope of the beach face or the size of the scour hole and the magnitude of uplift exposing the platform.

RIVER PROFILES

Stream profiles were surveyed with a pocket transit and hip chain. Each stream crosses the abandoned Holocene marine platforms and rises onto the uplifted Cobano surface, lithology from Gardner, this volume, Fig. 3. Associated stream terraces and marine terraces were connected to the profile using a pocket inclinometer and tape. Cumulative error over 100 m approaches ± 50 cm.

Rio Lejas. The largest river in the southern Nicoya Peninsula is a 3rd order stream that enters the ocean halfway between Cabuya and Montezuma (Gardner, this volume, Fig. 3). The surveyed section erodes a folded and faulted shaley limestone turbidite sequence with resistant beds of chert (Table 1; Fig. 2). The lower 700 m has few alluvial bars though bars of sand, gravel, and a few cobbles are common upstream. The stream profile of the Rio
Lejas rises nearly 8 m in the first 900 m in two steep reaches (L1 & L2). From 900 m to nearly 1200 m the river has a more regular, steep profile as it erodes up into the upper plateau (L3). The coastal plain surrounding Rio Lejas extends 700 m back from the beach, climbing 18 m in a series of up to 5 risers (Bee, this volume).

**Quebrada Cocal.** This small 2nd order stream crosses the Holocene platform cut on Nicoya basalt and Montezuma conglomerate approximately 1 km northeast of Montezuma (Fig. 3 & Gardner, this volume, Fig. 3). Queb. Cocal has three KP’s; the lowest is a steep bedrock stretch whereas the following two are waterfalls. The first KP (C1) terminates in a long pool (85 to 120 m) that is 0.75 m at its deepest and filled with sand and gravel. The lower waterfall (C2) carves a narrow chute into the bedrock and terminates in a plunge pool approximately 1 m deep. Upstream of the first waterfall the stream leaves the uplifted marine terraces and cuts into the uplifted plateau. At 200 m, the upper waterfall ends in a plunge pool at least 2 m deep (C3). Further upstream the channel becomes an alluvial bed with pool and riffle sequences.

**Quebrada Palmiche.** Southeast of Tango Mar (Gardner, this volume, Fig. 3), the profile of 1st order Quebrada Palmiche starts on the basalt beach face near the low tide line (Tab. 1 & Fig. 4). The first part of the profile records the relief of the active marine platform. A lag jam at high tide debris line, from 56 m to 64 m, creates a pool that extends upstream to the first small KP (P1). A shallow pool extends from the lower to the upper KP. Here the stream has a much steeper grade gaining 1.2 m in several steps from 86 m to 100 m (P2). Above the second KP, the stream enters the steep upland topography where it flattens and has alluvial bed.

**INCISION & MIGRATION RATES**

By dating the timing of marine platform abandonment, we can measure stream incision rates and migration rates of KP’s associated with each terrace. Marshall (1991) distinguished two marine terraces near the town of Cabuya, that finally merge into one terrace northeast of Tango Mar as the uplift rate significantly decreases (Cooke, this volume). The lower Cabuya (2400 yr B.P.) surface is 10 m above MSL and the upper Cabuya (4400 to 5200 yr B.P.) surface is 13.7 to 17.1 m above MSL (Marshall and Anderson, 1995). Each terrace includes the accumulated uplift of several events that form smaller terraces. In Lejas, S1 and S2 are samples from these inset terraces within the lower Cabuya surface. The terraces surrounding Cocal and Palmiche do not have smaller events recorded in their topographic expression, so I used the dates established for the upper and lower Cabuya.

The starting point of a KP is assumed to be the elevation of the inner edge of an abandoned platform. However, the potential presence of a scour hole means that using the inner edge yields the maximum vertical incision and horizontal retreat. Vertical incision is the change in elevation between the inner edge and modern stream level. Horizontal migration is assumed to be the distance in the stream profile between the inner edge and the top of the KP. Both of these assume that the inner edge exposed in the stream bank is perpendicular to the location of the start of the scour hole in the stream.

**RESULTS**

The lower Rio Lejas is experiencing extremely high incision (4.5 & 3.0 mm/yr) and rapid migration (0.53 & 0.33 m/yr), as a result of the uplift of the lower Cabuya surface (Tab. 2). Incision and migration at the other streams is at least one order of magnitude lower. To compare incision and migration rates, it is necessary to account for the differences of drainage basin size, rock type, and uplift rates. Rio Lejas is at least ten times larger in length and drainage area than Cocal or Palmiche, therefore it has greater erosional power. The incision rate is normalized to discharge calculated by dividing by the drainage area and reveals that normalized streams incision and retreat rates are within the same order of magnitude. Rio Lejas is eroding into a much weaker bedrock than Cocal and Palmiche. The rates also seem to lessen with distance upstream, hence with the age of the KP.

**Knobpoint Shape.** KP morphology is generalized by height (change in elevation from the top to bottom) and length (the horizontal extent in the stream bed). Rio Lejas KP’s are less steep overall and become less steep upstream. In contrast, at Cocal and Palmiche, the KP’s become steeper upstream. The height decreases with distance from Cabo Blanco, L1 and L2 are 3.00 m and 3.22 m respectively, C1 and C2 are 1.29 m and 1.54 m, while Palmiche is 0.215 m, consistent with drainage area, uplift rates, and bedrock.

**DISCUSSION**

Incision and migration rates, when normalized for discharge, indicate that rates are strongly controlled by drainage basin size. The larger discharge together with weak bedrock and greater uplift combine to produce greater changes at the Rio Lejas. Also S1 and S2 represent maximum rates because young KP’s probably incise and migrate quickly after formation, but slow down with falling height to
length ratios.

In Cocal there are two different types of knickpoints formed in the same bedrock. C1 has a gentler slope and has migrated upstream and C2 is a distinct step and in spite of an older age, has migrated less. These morphological differences may represent a different style of formation. While the upper and lower Cabuya are separated by a distinct riser, there are several small terraces within the lower Cabuya (S1 and S2 reflect some of these smaller uplifts). C1 may have been exposed in a series of smaller uplifts; more frequent uplift would have inhibited the formation of a deep scour hole. Rather than a large uplift event, abandoning a single, distinct step, the KP would be an accumulation of smaller events. Conversely, C2 would be associated with a deep scour hole exposed by a singular event. Compared to the other KP's, C2 has a very low migration rate, which could be a reflection of either the basalt bedrock or a low length:height ratio, or both. In a steep KP with hard, homogenous bedrock, the stream has a difficult time eroding the top of the KP, and steepens by scouring the plunge pool. The upper portion of the KP could have migrated upstream and is no longer distinctly expressed in the bedrock profile, therefore producing the appearance of lower migrations rates. Eroding back into the uplifted plateau, C3 may have been formed when relative sea level was higher. In addition, C3 may represent the accumulation of KP's where the stream enters a different topographic setting.

In Palmiche, P1 is associated with the lower Cabuya and represents a smaller magnitude of uplift. Like C3, P2 probably represents the accumulation of multiple uplift events. Unfortunately, the inner edge of the upper Cabuya in this area is indistinguishable from the talus of the eroding uplands.

The Rio Lejas incision rates (S1 & S2) compare well to the uplift rate of 3 m/ka (Marshall & Anderson, 1995), indicating that for weak bedrock and higher discharge streams are keeping pace with the drop in base level. Moreover, the small stream, Cocal and Palmiche also keep pace given a low uplift rate. Likewise, Burbank, et. al. (1996) recorded some of the highest bedrock incision rates (2-12 mm/yr) along the Indus River as the rivers keep pace with the rapid rise of the northwestern Himalayas.

REFERENCES

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Lejas</th>
<th>Cocal</th>
<th>Palmiche</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from Cabo Blanco (km)</td>
<td>4.5</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>Total length (km)</td>
<td>30</td>
<td>3.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Drainage area (km2)</td>
<td>21</td>
<td>1.6</td>
<td>0.5</td>
</tr>
<tr>
<td>Discharge (m3/s)</td>
<td>2.7</td>
<td>0.2</td>
<td>8.0E-03</td>
</tr>
<tr>
<td>Slope of surveyed section</td>
<td>9.0E-03</td>
<td>0.07</td>
<td>0.04</td>
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</table>

Table 1 – Stream characteristics for fluvial systems. Distance from Cabo Blanco along line from Cabo Blanco to the NE tip. Total length, drainage area, and discharge were digitized from topographic maps.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>S1</th>
<th>S2</th>
<th>C1</th>
<th>C2</th>
<th>P1</th>
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<tr>
<td>Distance intertidal pool to base of RP (m)</td>
<td>136</td>
<td>452</td>
<td>147</td>
<td>187</td>
<td>18</td>
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<tr>
<td>Horizontal distance from inner edge (m)</td>
<td>196.8</td>
<td>254.0</td>
<td>43.3</td>
<td>21.3</td>
<td>30.2</td>
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<tr>
<td>Vertical distance from inner edge (m)</td>
<td>1.700</td>
<td>2.395</td>
<td>1.620</td>
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<td>Age of abandonment of inner edge (YFB)</td>
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<td>808</td>
<td>2400</td>
<td>4400-5200</td>
<td>2400</td>
</tr>
<tr>
<td>Height (m)</td>
<td>3.00</td>
<td>–</td>
<td>1.29</td>
<td>1.54</td>
<td>0.215</td>
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<tr>
<td>Length (m)</td>
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<td>–</td>
<td>17.6</td>
<td>4.9</td>
<td>1.9</td>
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<tr>
<td>Length:Height ratio</td>
<td>72.8</td>
<td>–</td>
<td>13.6</td>
<td>3.2</td>
<td>8.8</td>
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<tr>
<td>Vertical incision rate (mm/yr)</td>
<td>4.5</td>
<td>3</td>
<td>0.7</td>
<td>0.5-0.4</td>
<td>0.3</td>
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<tr>
<td>Horizontal retreat rate (m/yr)</td>
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<td>0.327</td>
<td>0.18</td>
<td>0.005-0.004</td>
<td>0.016</td>
</tr>
<tr>
<td>Vertical rate/drainage area (mm/yr/km2)</td>
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<td>0.4</td>
<td>0.3</td>
<td>0.6</td>
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<tr>
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<td>0.02</td>
<td>0.01</td>
<td>0.003</td>
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</table>

Table 2 – Knickpoint information associated with Figs. 2-4. Dates for C1, C2, P1 after Marshall(1991). S1 is correlated to a section within L2, therefore length and height are not determined.
Figure 1 illustrates the relationship between the stream profile, actively forming platform, stream knickpoints, and abandoned terraces.

Figure 2 — Rio Lejas stream and terrace profile. Notation as follows KP’s (L1, L2, & L3) and radiocarbon dated shell samples (S1 & S2). Field and river bank profiles were surveyed adjacent to the river (Bea, this volume).

Figure 3 — Quebrada Cocal stream and marine terrace risers. KP’s are labelled C1, C2, and C3. Inner (IE) and outer (OE) edges are identified with a 1 (lower Cabuya) or 2 (upper Cabuya).

Figure 4 — Quebrada Palmiche stream and terrace profile. KP’s are P1 and P2 with risers labelled as in Fig 3.
Fault kinematics in the MalPais sandstones of the Península de Nicoya, Costa Rica

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INTRODUCTION

The Pacific coast of the Peninsula de Nicoya in Costa Rica is an area of active seafloor subduction (Gardner, this volume, Fig. 1 and 2). The coastline is parallel to the orientation of the Middle American Trench, where the Cocos plate subducts beneath the Caribbean plate at a rate of about 71 to 87 mm/year [DeMets et al., 1990; Hey, 1977]. Accretion occurs along this margin, along with extension from the subduction of large bathymetric features such as ridges and seamounts [Fisher et al., 1998; Gardner et al., 1992]. Significant changes have occurred in the triple junction of the Cocos, Nazca and Caribbean plates in the Tertiary. Around 11 to 8 Ma, a piece of the Cocos became a part of the Nazca plate, moving the triple junction to somewhere off of the Nicoya margin. Since 8 Ma, the triple junction has moved southeast to its present location [Hey, 1977, Gardner, 1987, McIntosh, 1992]. Each of these factors plays a role in the deformation of the rocks along the margin.

My research looks at the Miocene MalPais sandstone. It records a deformational history from just over 20 Ma. This is exposed along the Pacific coast from approximately 2 km north of Cabo Blanco to 2 km north of Santa Teresa (Gardner, this volume, Figure 3). Three subunits of the MalPais sandstones have been noted by Mora [1985]. The Mar y Luz subunit is located at the southern end of my field area and is generally the oldest, the Barrigona is located in the central portion, and the Sta. Teresa comprises the northern end and is the youngest subunit, although there is overlap in age. In my analysis, I am investigating both the kinematics of the faults that appear along the Pacific coast of the Peninsula de Nicoya as well as observing the characteristics of the faults and rock subunits through microscopy. I am looking at stress history of the region in order to: 1) determine the mechanism for the formation of the faults, i.e. if they are a result of slumping or tectonic deformation, 2) investigate the role of seafloor roughness on the deformation of the region and determine if there is evidence that the rough boundary has moved south since the Miocene. The micro-scale observations provide a clearer understanding of why the area shows different styles of deformation and what controls the deformation, and 3) determine if the migration of the triple junction has been recorded in the deformation of the rock to better understand how and where it has moved.

METHODS

Field methods included collecting data from faults along the Pacific coast at thirteen different sites within my field area and collecting samples of each of the subunits and of typical rocks within each of the three subunits of the MalPais sandstones. All data were collected on faults in the Miocene silt and sandstones of the MalPais Supergroup. The data I attempted to collect for each fault were: strike, dip, rake (trend and plunge of lineations on the fault surface), separation, sense of slip, and cross-cutting relationships. Every fault did not display all of the above characteristics, but as many as possible were recorded for each fault. Bedding measurements were also taken at each site and major synclines and anticlines were noted. The rock samples for thin sectioning were chosen based on location for subunit rocks and other samples were taken if they could be removed and still maintain fault and rock material intact.

In the laboratory, all of the samples were thin sectioned and characterized under plain and cross-polarized light. I looked for changes across fault margins and differences in texture and composition between the three subunits. All of the fault data were entered into Stereonet and, if rake measurements were available, they were entered into FaultKin, both programs developed by R.W. Allmendinger and explained in Marrett and Allmendinger [1990]. This allowed me to view the data in different forms, using great circles, poles and Bingham plots in order view any trends within the data.

FIELD AND SAMPLE OBSERVATIONS

Within my field area, the three subunits of the MalPais sandstone appear different compositionally as well as displaying differences in deformation. The Mar y Luz appears gray and shows a lateral stratification of shale and
sandstone, with a large number of benthic foraminiferas, possibly indicating that this was an ancient turbidite flow. Faults within this region are well defined and bedding is coherent throughout with fairly gentle synclines and anticlines. The Barrigona subunit shows laminar cross-bedding and is a slightly more bluish-gray. Mora [1985] described evidence of bioturbation, with an abundance of mollusks and large foraminifera in this subunit, though I saw no fossil material within this subunit at all. The region appeared to have a great deal of soft-sediment flow, which may have been what Mora [1985] described as bioturbation. Nearly all faults were soft-sediment faults and there were no apparent bedding planes. The Sta. Teresa shows primarily trough cross-bedding of sandstone beds including lithoclasts and bioclasts and appears slightly purple in hand sample. One exposure within this subunit is incoherent, showing no clear bedding planes and no obvious fault planes. The contact between the coherent and incoherent bedding is roughly N80E, 80SE, with the downdrop block towards the coast. At the far north end of the field site, fault planes could once again be seen and measured on seastacks, which provided three dimensions by which to measure the faults.

**FAULT DATA**

Two main types of faults were noted within the field area. The first is a soft-sediment fault that formed before the rock had fully lithified. These faults often contain a darker gouge-like layer that is not always visible in thin section. In some of the soft-sediment faults this layer does display cataclasis, and in others there is very little difference between this layer and the host rock. The soft-sediment faults also commonly appear in zones of parallel faults. All other faults have formed since lithification. These include normal and strike-slip faults. A few reverse and calcite filled extensional fractures were seen, but reverse faults only comprised 2% of the total faults measured and the extensional fractures comprise only 5%. By far the most predominant were the extensional faults, and there was a relatively equal proportion of right- and left-lateral faulting. Figures 1 and 2 are examples of normal and soft-sediment faults.

The orientation of the faulting shows a few trends. Most faults strike N60E, N20E or due north, with very steep to vertical dips. In the northern sites, the faults trend more westward, still maintaining steep dips. Below is a chart of average fault orientations:

<table>
<thead>
<tr>
<th>Site</th>
<th>Strike-slip</th>
<th>Normal</th>
<th>Soft-sediment</th>
<th>N=</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N60E; N30W; N30W; N20E</td>
<td>N30E 50SE; N72E 60NW; N18E 60SE; N80W 70SW; N20E 70SE</td>
<td>N50W</td>
<td>42</td>
</tr>
<tr>
<td>2</td>
<td>N60E</td>
<td></td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>N65E; N3W</td>
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<td>4</td>
<td>N60E</td>
<td>N10E; N15E</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>5</td>
<td>N30W; N30W; N30E; N8E</td>
<td>N45W 50NE; N8W 70 SW</td>
<td>N70W; N39W 80SW</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>N10E</td>
<td>N35W 50SW; N15W 70SW; N50E 80SE</td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>7</td>
<td>N10E</td>
<td></td>
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<td></td>
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<td>10</td>
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</tr>
<tr>
<td>11</td>
<td>No common</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Table 1: Average orientations of faults at each of the field sites. Sites 1-5 are located at the southern end of the field area between MalPais and Punta Barrigona and sites 6-11 are north of Santa Teresa. Site 9 contained no measurable faults. Sites 12 and 13 are located between sites 5 and 6 and contain very little data. All strikes in the strike-slip column have no dip values because all have vertical (90°) dips. N is the total number of faults measured within the area.

Stereonets for the faults at the southernmost site within the field area and a site at the northern end are shown in figures 3 and 4. In each of these stereonets, the poles to the fault planes are plotted to show the clustering of faults. In the southern site, fault poles are clustered in the northwestern and southeastern regions, and most are near vertical. In the northern site, there are more clusters of faults, with a greater range of strikes as well as dips.

**DISCUSSION**

The development of the deformation of the MalPais sandstones along the Pacific coast of the Peninsula de Nicoya can be broken down into at least two events, though it is likely there was a significant amount of activity in between. During deposition but before lithification, soft-sediment faulting occurred. This suggests an unstable depositional environment. These faults do not show any common orientations within the field area, but all lay parallel to the general trend of the shoreline at the individual site. This may indicate that the sediments where these
soft-sediment faults are common may have undergone post-depositional slumping or been deposited in a turbidity current. The benthic foraminifera found in thin section also implies that these may be turbidite deposits.

Following lithification of the sediments, tectonics played a larger role in the deformation of the rock. The southern end appears to have undergone at least two more faulting events. The most recent event is seen in the conjugate set oriented N60E and approximately due north, indicating that the primary compressive stress is roughly trench perpendicular. Three conjugate sets in this orientation were observed, and none were cut by any other faults. The other faults seen in these orientations were also strike-slip, with a majority of them striking N60E. Roughly half of them left lateral and the other half right lateral. This may be explained by left-lateral faulting occurring in the compressional environment, and later during a period of extension, some of the faults were reactivated as right lateral. Cross-cut by these faults are a set of normal faults, mostly striking N20E and dipping steeply to the southeast. This illustrates an earlier extensional environment.

The north end has significantly more fault sets, and they are also not as clearly defined into clusters. There is a larger distribution of fault orientations, so may have undergone more changes in the tectonic history. As in the south, they show periods of extension and compression, though in different orientations. The strike-slip faults are closer to N10E, and there are several sets of normal faults.

Finally, the contact between the coherent and incoherent bedding appears to be fairly recent, as there is little to no faulting within the incoherent beds and no through-going features across the contact. This may have been caused by later slumping, and the contact is the headwall of the slump.

CONCLUSIONS
The deformation of the MalPais sandstone since the Miocene that can be seen today was probably caused by a depositional environment of slumping and/or turbidity currents, bioturbation and tectonics from the subduction of the Cocos Plate beneath the Caribbean Plate. Before lithification, slumping caused soft sediment faulting throughout the region. After lithification, the predominance of normal faults strongly suggests that extension from seafloor topography has led to a flexure of the land, and it is expressed differently in the north and in the south. Finally, compression from the subduction of the plate followed, with some extension possibly following reactivating existing fault planes.

Because the subunits of the MalPais were deposited at different times, it is difficult to make any correlation through time throughout the field area. Therefore, I cannot relate deformation to the movement of the triple junction.

ACKNOWLEDGEMENTS
I'd like to thank Tom Gardner, Ed Beutner, Linda Reinen, and Don Zenger for all of their help throughout the project. I'd also like to thank Carrie Elliot for her help teaching me how to use all the machines for thin sections.

REFERENCES CITED
McIntosh, K., 1992, Geologic structure and processes of the eastern pacific margin: California and Costa Rica [Dissertation for the Doctor of Philosophy]: University of California, Santa Cruz, 1707 p.
Figure 1: Image of a normal fault. Field book for scale.

Figure 2: Image of soft-sedimentary faults. Faults are the gray bands running horizontally across the image. Hammer for scale.

Figure 3: Stereonet plot of the poles to the fault planes at site 1, which is located at the southernmost tip of the field area. Note the clustering of points around the northwestern and southeastern regions.

Figure 4: Stereonet plot of the poles to the fault planes at site 7, near the northern end of the field area, just south of the coherent/incoherent boundary. Note there are several clusters of points illustrating the more diverse range of fault orientations in the north.
Faults and folds in the Cabo Blanco Formation, Peninsula de Nicoya, Costa Rica

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Faculty Sponsor: Edward Beuiner, Franklin and Marshall College

PURPOSE
The Cabo Blanco Formation is a sedimentary unit of interbedded deep water marine, hemipelagic mudstones and fine grained terrigenous turbidites deposited from Paleocene to lower Eocene times. Crustal uplift has exposed the Cabo Blanco on marine terraces along the southeastern shore of the Peninsula de Nicoya, Costa Rica (Figure 1). Faults and folds exposed on the terraces and in adjacent sea cliffs record the deformational history of this unit. The purpose of this project was to unravel the deformational history and to develop an explanation for deformation of the Cabo Blanco Formation. Understanding the strains involved in producing these faults and folds will provide insight as to the interactions between the Cocos and Caribbean plates that have affected the Cabo Blanco since Paleocene times.

TECTONIC SETTING
The Middle American Trench (MAT) strikes about N50W and lies nearly 70 km southwest of the Peninsula de Nicoya. At the MAT the Cocos plate is subducting below the Caribbean plate at a rate of approximately ~9 cm/yr. Convergence between these plates along an azimuth of N29E (Lundberg, 1982) indicates subduction is slightly oblique. The time at which subduction initiated along the MAT remains uncertain, and is part of a larger dispute over the tectonic history of the entire Caribbean region. The presence of volcanic rocks and volcaniclastic sediments of late Cretaceous age landward of the trench suggests that subduction began between 60 to 70 Ma (Lundberg, 1982; McIntosh, 1993). However, it has also been postulated that present MAT subduction initiated as late as the Oligocene, forming the Talamanca volcanic belt (de Boer, 1979). Trench-related compression has caused the Caribbean crust to warp as a broad anticline, uplifting the forearc. Regional uplift began during the Paleogene and has remained active during Quaternary times (Lundberg, 1982; Gardner et al., 1992). The initial age of MAT subduction is important for distinguishing the origin of the sediments that comprised the Cabo Blanco turbidites. Assuming that subduction began prior to the deposition of the Cabo Blanco sediments, this unit can be restricted to the parautochthonous landward slope along the Caribbean margin. However, if subduction initiated following the deposition of sediments, the source and site of initial deposition is less constrained relative to the trench.

METHODS
Field observations included measuring and classifying faults, folds, and bedding at 11 separate localities. All measurements were made using a Brunton compass. Fault orientations, striations and sense-of-slip, cross-cutting relationships, and character of fill were determined. Axial surfaces were determined from combining hinge line and axial trace measurements on folds. Sense of rotation was also determined. Stereonet and Faultkin were used to plot fault and fold sets and to make location comparisons. Hand samples were collected and prepared for thin-section analysis. Samples were appropriately cut and observed for evidence of microstructural deformation and composition.
OBSERVATIONS & DISCUSSION

The Cabo Blanco Formation consists of two distinct sections, varying somewhat in lithology and dramatically in structure. These two sections also differ slightly in age. Strata in the northeastern section are believed to be of Paleocene age while the southwestern strata are believed to be of younger late Paleocene and Eocene age (Chaves, 1983, unpublished). In thin section the compositions of the southwestern strata are foraminifera-rich calcareous mudstones. Many samples showed multiple episodes of veining. Twinning of sparry calcite indicated additional strain post-veining. Fault breccia samples included angular clasts and stylolitic pressure solution seams. The northeastern strata are predominantly composed of fine-grained graywackes, mudstones, and shales. In thin section foraminifera were rarely seen in any of the northern rock. Grain sizes were slightly larger than those in the southern section, while calcite veining was less common. Both sections possess volcanic rock fragments and feldspar laths indicating a regional volcanic source. A significant hemipelagic component indicates that both sections of the Cabo Blanco were likely deep water slope deposits. The fine grain size of these sediments indicates a distal facies, so it has been postulated by Lundberg (1982) that a bathymetric high prevented much of the coarser detritus from reaching this area. Some graywackes are subtly laminated and weakly graded and are interpreted to be turbidites. The severely folded strata in the northeast and the intensely faulted strata in the southwest distinguish these sections structurally. The transition of these two sections in the Cabo Blanco is somewhere south of Cabuya Playa and north of Cabo Blanco where the shoreline presently has no exposed terrace outcrops. There does appear to be some exposure of a terrace near the southwest segment of the isthmus connecting Isla Cabuya to the peninsula near station 12 in Figure 1. An abrupt change from the folding to faulting is separated by a 20 to 30 meter covered interval of incoherent rubble.

Structure in the Southwestern Section: Strata in the southwestern section are intensely faulted, with abundant calcite vein-filled and gouge-filled faults. When fault offsets were observed, in all cases the vein-filled faults were cross cut by younger gouge-filled faults (Figure 2). Most locations revealed several fault orientations, and observed cross-cutting relationships indicated several generations of faulting had occurred. South of Punta El Flor, at station 1, as many as five fault sets may be present. Cross-cutting relationships indicate two gouge-filled faults sets that post-date an array of calcite-filled faults. The calcite-filled faults strike approximately: north, dipping steeply to the east and west; N60E, dipping steeply to the SE; and N55W, dipping shallowly to the NE and SW, suggesting that there could have been as many as three generations.

The absence of cross-cutting relationships makes it impossible to determine the precise number and sequence of fault sets. Some locations exhibit mainly faults with similar attitudes indicating a single generation of faulting. The most widespread fault set was a calcite-filled right-lateral strike-slip set striking approximately N40W and dipping to the NE. Another major set seen in many localities is a left-lateral strike-slip fault set striking approximately N45E and dipping steeply to the SE (Figure 3). Younger normal faults striking NW and filled with up to 1 meter of gouge were observed in the sea cliffs at stations 3 and 5.

Structure in the Northeastern Section: Well exposed terrace outcrops at Cabuya Playa exhibit intense folding and contain a set of layer-shortening wedge faults that strike approximately N80W and N70E and dip steeply to the south. Here, the buckle folds are disharmonic with an overall counterclockwise sense of rotation viewed looking NW (Figure 4). Axial surfaces strike approximately N75W, with hinge lines trending roughly trench parallel and plunging shallowly to the NW and SE (Figure 5). The mechanism of folding is uncertain. Some sedimentary slump features were observed, but most structural features indicate tectonic deformation. Extensive bending of some axial surfaces indicates that more than one generation of folding deformed this location, but
shearing along fold hinges made it impossible to measure earlier folds. Using Stereonet, faults at Cabuya Playa were rotated back to paleohorizontal by removing the dip of adjacent folded bedding. This provided a stereonet with gently NE and SW dipping contemporaneous fault pair striking nearly N50W with near parallel striations, indicating these faults were likely produced prior to folding by a roughly MAT-perpendicular compression (Figure 6). South of Cabuya Playa, at station 11, axial surfaces change strike to nearly N40E with hingelines plunging shallowly to the SW. It is unclear whether these folds are related to the set at station 8 or whether they were rotated by secondary deformation associated with the contact.

South of Playa Cedro, the northern edge of the Cabo Blanco is in contact with mid Cretaceous basalt of the Nicoya Complex. This is a structural shear zone and does not indicate an angular unconformity as proposed by Lundberg (1982). An intense vertical anastomosing shear fabric striking approximately N45W was observed within the 12 to 15 meters of Cabo Blanco adjacent to the contact. Under thin section Cabo Blanco graywacke samples do not contain any basaltic grains from the Nicoya Complex, further indicating this contact is a structural shear zone.

**Figure 4:** This photo, facing NW at station 8, shows an asymmetrical anticline exposed in the marine terraces at Cabuya Playa.

**Figure 5:** Stereonet plot of axial surfaces and hingelines at station 8, Cabuya Playa.

**INTERPRETATIONS**

The Cabo Blanco Formation as a whole can be differentiated by the structural and lithologic differences between the strata of the northeastern and southwestern sections. The folding and wedge faulting of the slightly older northeastern section did not affect the southwestern section. This means that neither all of the deformation in the northeastern section occurred prior to the deposition of the southern section or that the strains recorded in the Cabo Blanco to the northeast did not affect strata to the southwest. This must mean that either strains were localized or these sections of strata were at a greater distance from each other than they are presently. It is equally apparent that faulting in the younger southern strata did not affect the strata of the northeastern section. For example, fault sets do not correlate across the transition between these sections. This supports the idea that the strains on the Cabo Blanco affected these sections locally and that they have since been brought closer together. As most of the transition which separates these sections remains unexposed, an explanation for why the sections differ must in large part be inferred.

One possibility is that the abrupt transition between these two sections near Isla Cabuya may represent a past subduction-related thrust that placed some of the older northeastern strata on top of the younger southwestern.
Cabo Blanco. The orientation and vergence of folds at Cabuya Playa in the northern section supports this hypothesis. This places the shortening direction at approximately N15E, within 15 degrees of the present direction of subduction. The layer-shortening wedge faults, believed to have predated folding indicate shortening was earlier oriented close to N80E. This requires a 65 degree counterclockwise rotation of shortening between the times of formation of the faults and the folds. A counterclockwise change in the direction of shortening is supported by evidence indicating that the convergence of the Cocos Plate has rotated counterclockwise from a more easterly direction since deposition of the Cabo Blanco (Pindell and Barrett, 1990).

Figure 6. This set of Stereonet plots shows how the layer shortening wedge faults were rotated back to paleohorizontal. Stereonet A) shows a fault pair with rakes and local average bedding. Stereonet B) shows this fault pair after the dip was removed from bedding.

ACKNOWLEDGMENTS
I would like to recognize a few individuals whom helped make this project possible. I would like to thank Edward Beutner for his continued support and guidance throughout this year as my project sponsor. I would like to commend Tom Gardner for his organization and leadership as the director of the 1998-99 Costa Rica KECK project, his efforts made this project a joy to be a part of. I would also like to thank Alix Krull and Becky Stamski for their dedicated assistance in the field.

REFERENCES


A Study of Paleomagnetism of the Nicoya Terrane, Costa Rica

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Abstract

The Chorotega Terrane constitutes the backbone of the southern Middle America volcanic arc, formed on the western edge of the Caribbean plate. The adjacent Nicoya Terrane, lying trenchward of the Chorotega Terrane, was previously determined to be located at 7° S during the Cretaceous, with conflicting data constraining accretion timing. New paleomagnetic data from Paleocene rocks reveal that the Nicoya Terrane was at its present latitude relative to the autochthonous Chorotega Terrane. These data suggest that the Nicoya Terrane accreted to the Chorotega Terrane by Paleocene time.

Introduction

The Nicoya Terrane and the adjacent Chorotega Terrane are located between the converging Caribbean and Cocos Plates along the Middle America Trench (Gardner, this volume, Fig. 1). The accretion timing of the two terranes is at present poorly understood. DiMarco et al. (1995) suggest that Paleocene coarse channel-fill and overbank deposits, including boulders of andesites and limestones, indicate the initial amalgamation of the two terranes. Previous paleomagnetic studies indicate that the Nicoya Terrane was located about 7° S latitude, compared to the 10° N latitude of the Chorotega Terrane in Late Cretaceous time (DiMarco et al., 1995). The present latitude of the Nicoya Terrane is 10° N, indicating a 17° northward latitudinal displacement (~1900 km). These data largely support the reconnaissance paleomagnetic work of Gose (1983). However, Gose's (1983) Tertiary paleolatitudes give equivocal results for age of accretion, possibly due to uncertain age control and/or questionable assignment of outcrops to various terranes. The purpose of this study is to provide additional paleomagnetic evidence to help constrain the accretion timing of the Nicoya Terrane.

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Figure 1. Diagram showing Nicoya Peninsula with Nicoya and Chorotega Terranes. Sample localities: (1) Punta Barrigona (2) Punta Cuevas (3) Playa Cabuya and adjacent Río Lajas area. Diagram from DiMarco et al. (1995)(Figure 8).

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Paleomagnetic Sample Localities and Technique

The Nicoya Terrane was sampled at three localities: Playa Cabuya and the adjacent Rio Lajas area (75 cores from 12 beds, Cabo Blanco Formation), Punta Barrigona (37 cores from 9 beds, Santa Teresa Formation), and Punta Cuevas (22 cores from 8 beds, Punta Cuevas Formation) (Figure 1). These three localities were chosen due to their location on the allochthonous ocean-ward side of the Nicoya Peninsula and representing a variety of Tertiary ages. Well indurated, fine grain sedimentary rocks, most likely to contain single-domain magnetite, were drilled to obtain best results. Playa Cabuya rocks were of particular importance because small scale folds could be sampled in order to apply the fold test for paleomagnetic stability.

Standard 2.5 cm x 2 cm samples were prepared and measured using a Schonstedt SSM-1A spinner magnetometer. Samples were magnetically cleaned in a stepwise manner, using a Molspin tumbling alternating field (AF) demagnetizer, to isolate secondary magnetic overprints. Vector plots of declination and inclination were used to identify secondary and characteristic components. The characteristic vectors were identified based on little or no shift in direction with decreasing intensity, indicating a stable demagnetization endpoint.

Data Analysis

Samples collected from the Eocene Punta Cuevas locality failed to yield stable demagnetization endpoints and therefore were not considered further. Well-defined characteristic directions were obtained from about 52% of the cores measured from Playa Cabuya (Paleocene) and about 47% from the cores at Punta Barrigona (Miocene). Punta Barrigona yielded 8 acceptable samples from 6 beds out of 17 measured specimens (Table 1). At all three localities, samples providing no usable data displayed overlapping coercivity spectra for both primary and secondary vectors, failing to yield stable endpoints and therefore were not included in the calculations.

Stereographic plots of both geographic and stratigraphic directions, from the Punta Barrigona locality, gave modest clustering. The geographic mean direction is 347°, 21° (declination, inclination) (k=165, alpha-95=5°, n=6) and the mean stratigraphic direction is 316°, 33° (k=74, alpha-95=8°, n=6). A fold test was not possible, at this locality, due to the homoclinal attitude of the strata.

<table>
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<tr>
<th>Sample</th>
<th>Bed</th>
<th>Demag</th>
<th>NRM</th>
<th>NRM</th>
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Table 1
The Playa Cabuya locality yielded 17 acceptable samples from 10 beds out of 33 measured cores (Table 1). Replicate samples from the same bed displayed similar characteristic directions generally within ~10° from each other, demonstrating reproducible results. Identifiable characteristic directions were plotted on an equal-angle stereonet in both the geographic (in situ) and stratigraphic (tilt corrected) frame of reference. Stereographic plots show a dispersed pattern trending from the NW shallow quadrant to nearly vertical vectors with both positive and negative polarity. The mean geographic direction is 282°, 18° (k=1.7, alpha-95=55°, n=10) (Figure 2A); the kappa of 1.7 is random according to the test of Watson (1956). Stratigraphic vectors show an improvement in clustering in the NW quadrant, with moderate to shallow vectors. There is also a secondary clustering in the SSW with negative inclinations (beds 8, 9, and 10) (Figure 2B). Even interpreted as reversals and inverted through the origin, the resulting NNE cluster is separated from the main NW cluster. Stratigraphic direction yielded a mean direction of 329°, 16° (k=4.7, alpha-95=25°, n=10). Beds 4C and 4D, different limbs of the same bed, show a slightly greater divergence on the stereoplot.

![Figure 2. Equal angle projections of remanence directions for Playa Cabuya locality. A) Geographic directions (in situ), B) Stratigraphic directions (tilt corrected about present day strike-line), C) Two-stage corrections (deplunged and unfolded) remanence directions for 10 beds. Solid and open symbols represent positive and negative inclinations, respectively. Triangles represent directions inverted through 180° (reversals).](image)

The occurrence of distinct clusters of the stratigraphic directions suggests multiple tectonic deformations. The standard tilt correction of rotating about the present-day strike line is too simplistic. A plunging fold, at Playa Cabuya, permits a two-stage structural correction to be attempted. The fold axis attitude was obtained by plotting beta diagrams, for the limbs of a plunging anticline, on an equal-area stereonet and determining the average intersection (fold axis). This fold axis was used to deplunge the poles to bedding and to deplunge geographic vectors. The deplunged geographic vectors were then restored to ancient horizontal, using the deplunged bedding attitudes to give deplunged stratigraphic vectors (D-P Strat, Table 1).

After two-stage corrections were completed, deplunged stratigraphic vectors showed improved clustering in the WNW quadrant with shallow vectors (Figure 2C). In the deplunged stratigraphic frame of reference, there is a much improved clustering of beds 4C and 4D. The two limbs are 4° apart, as opposed to 44° apart in the standard stratigraphic reference frame. This may be taken as a positive fold test, indicating a pre-folding magnetization and good evidence for a stable magnetic remanence (see Butler, 1992 for a discussion of the fold test). Because beds 8, 9, and 10 yielded negative inclinations and differed by about 110° in declination from the main cluster, the vectors were interpreted as reversals and inverted through the origin. Although the data grouping improves, the declination is off by a considerable amount. This may result from deformational rotation not accounted for in the two-stage correction. Perhaps a detailed structural analysis of the outcrop area would yield better results. The deplunged stratigraphic
mean direction was calculated to be 320°, 15°(k=8.1, alpha-95=18°, n=10). The kappa of 8.1 for the deplunged vectors shows a considerable reduction of dispersion over the standard stratigraphic frame. The stratigraphic inclination from Playa Cabuya was used to calculate a paleolatitude from the equation:

$$\tan I = 2 \tan \lambda$$

where $I$ equals the inclination and $\lambda$ equals the paleolatitude. Playa Cabuya (Paleocene) samples yielded a 7.6° (± 8°) N paleolatitude and Miocene cores at Punta Barrigona yield 18° (± 4°) N paleolatitude (Figure 3). The Playa Cabuya paleolatitude indicates that the Nicoya Terrane was at its present latitude relative to the Chorotega Terrane by the Paleocene and probably in place. With no stability tests and only 6 beds measured, the Miocene samples may not be a reliable tectonic indicator. The somewhat high paleolatitude of the Miocene samples may be due to incomplete averaging of secular variation over time; however, the paleolatitude is in rough agreement with the Paleocene value.

![Figure 3. Compilation of paleolatitudes for Chorotega and Nicoya Terranes. Solid triangle is paleolatitude for Cabuya data. Solid hexagon is paleolatitude for Punta Barrigona data. There are no stability tests for the Punta Barrigona data and secular variation may not have been averaged out; thus, Miocene paleolatitude is not well constrained. Diagram from DiMarco et al. (1995) (Figure 22).](image)

**Conclusions**

The purpose of this project is to provide data on the accretion age/timing of the Nicoya Terrane. The samples from Punta Barrigona (Miocene) yielded equivocal data possibly due to the lack of stability tests and sufficient averaging of secular variation. Data from Playa Cabuya, after a two-stage tectonic correction, pass both fold and reversal tests, insuring the presence of a primary remanence. The paleolatitude calculated for Paleocene cores give a value of 7.6° (± 8°). This value is essentially the same as today's latitude indicating that the Nicoya Terrane was in place relative to the Chorotega Terrane during the Paleocene.

**Acknowledgments**

Thanks to the Costa Rica Keck Group and Dr. Bruce Panuska for their help and support.

**References Cited**


Tectonic and geochemical investigation of basalts and associated deep sea sediments in the southern Península de Nicoya, Costa Rica

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INTRODUCTION
Basalts of the Península de Nicoya represent the ocean crust platform upon which the Central American magmatic arc is being constructed due to subduction at the Middle America Trench. (Gardner, this volume; Fig. 1) The southern peninsula basement outcrops are dominated by massive and pillow basalts with lesser amounts of associated deep sea sediments, conglomeratic broken formations, and monolithic basalt breccias. There is much debate concerning these basement rocks, in relation to both the isolated peninsula in question and to the greater Caribbean region. One area of contention comes out of the discrepancy between the models of Di Marco and others (1995) and Sinton (1996). Sinton (1996) uses geochemistry and geochronology to argue that the entire Península de Nicoya is underlain by thick, basaltic ocean crust of the Caribbean-Columbian Cretaceous Igneous Province (CCCIP) (Kerr et al., 1997). The theory of a large igneous province (LIP) as a model for the anomalously thick (8km to >20km) oceanic crust of the Caribbean is widely supported in Costa Rican geology (see Donnelly, 1994 for a review). The LIP model implies that a more geochemically enriched source, possibly influenced by a hot spot plume head, thickens large areas of ocean floor (CCCIP = 6 x 10^5 km^2) in a matter of a few million years (CCCIP = 88-90 Ma) (Kerr et al., 1997). In opposition to Sinton (1996), Di Marco and others (1995) used paleomagnetism and post-basalt stratigraphy to distinguish two terranes in the Nicoya region: the autochthonous Chorotega Terrane (CT), representing the Caribbean plate on the east half of the peninsula, and the allochthonous Nicoya Terrane (NT), which was accreted to create the western peninsula (Fig. 1). A third, slightly older model developed by Kuypers (1980) suggests that the entire peninsula was involved in accretionary burial and nappe structure formation during its accretion onto the Caribbean plate.

OBJECTIVES, SAMPLING, AND METHODS
The goal of this investigation is to utilize geochemistry, geochronology, and micropaleontology to constrain the formation and evolution of the southern section of the peninsula, a multi-faceted project which is outlined below:

1. One of the main discrepancies in the debate is the fact that Sinton (1996) sampled only the northern section of the Península de Nicoya, well within Di Marco and other’s (1995) NT. This study attempts to characterize the southern CT geochemically and compare these data to both Sinton’s (1996) NT data set and to four NT samples collected during this investigation. Fourteen massive and pillow basalt samples (10 CT, 4 NT) were gathered along coastal and road outcrops (Fig. 1). X-ray fluorescence (XRF) was conducted at the University of Massachusetts to obtain major and trace element geochemistry for all fourteen samples. In addition, six samples underwent instrumental neutron activation analysis (INAA) at Oregon State University for supplemental trace element data.

2. X-ray diffraction (XRD) was employed for eight samples, including two monolithic basalt breccias, in order to examine cryptocrystalline mineral phases for signals of alteration and/or subduction-related metamorphism.

3. One of the strongest arguments in support of the CCCIP is the contemporaneous igneous activity found across the Caribbean at 88-90 Ma (Sinton 1996). In order to investigate the possible link of the CT to the CCCIP, three of the freshest samples from the CT will be dated via whole rock 40Ar - 39Ar at the Massachusetts Institute of Technology. In addition, three inter-pillow radiolaria chert samples were collected for microfossil dating to help constrain the timing of volcanism.

PETROGRAPHY AND MINERAL CHEMISTRY
Southern Península de Nicoya basalts are aphyric with the following mineral assemblage and modal percentages: plagioclase (dominantly An_{50-70}), 40-55%; augite, 30%; Ti-magnetite and illmenite, 10-15%; altered mesostasis, cryptocrystalline alteration minerals, and calcite veining: 5-15%. Augite crystals display varying degrees of Fe rimming. One sample from the NT has highly altered plagioclase in which An_{70-73} has been converted to An_{23-}
Ab_{31.35}-Or_{42.46}, indicating some element mobility.

XRD analyses searched for eight specific subduction-related minerals: lawsonite, aragonite, glaucophane, jadeite, pumpellylite, prehnite, actinolite, and epidote. No such metamorphic phases were detected; the majority of XRD peaks were explained by feldspar and pyroxene. On the other hand, veins of the zeolite clinoptilolite were encountered with both SEM and XRD analysis; clinoptilolite is interpreted to be an alteration phase. Incompatible trace element plots show scatter for Sr, Rb, and Ba. Together, this evidence suggests typical hydrothermal alteration.

GEOCHEMICAL CHARACTERIZATION AND COMPARISON

Coherent trends of major and trace elements imply that the rocks from this study were derived from a similar parental source and variation between samples can be explained through fundamental magmatic processes. In addition, similarity to Sinton's (1996) data from the northern peninsula demonstrate a high probability that a common parental magma is responsible for producing the basement rocks of the entire Península de Nicoya.

Basalts of this study are tholeiitic with 4 to 9 wt % MgO, represented by a total alkalis-silica (TAS) chart (Fig. 2) and an AFM diagram (Fig. 3). Bi-variate diagrams versus MgO indicate that this basalt sequence has simultaneously undergone fractionation of clinopyroxene and plagioclase, with late-stage opaque phases. Figure 4a displays a decrease in the ratio CaO/Al_{2}O_{3} with magma evolution (decreasing MgO) because clinopyroxene fractionation forces the removal of CaO relative to Al_{2}O_{3}. Figure 4b shows the synchronous crystallization of clinopyroxene and plagioclase as the incompatible phase TiO_{2} increases sharply with decreasing MgO. Yet, at 4 wt % MgO, an inflection in the data indicates late-stage fractionation of Ti-oxides. Steep negative slopes on plots of other incompatible elements (Y, Nb, Ce, and P) versus increasing MgO indicate concurrent clinopyroxene and plagioclase fractionation; steep positive slopes for compatible elements, especially Ni, give evidence for the fractionation of olivine, despite its absence in the rocks of this study.

Bi-variate plots using the highly incompatible elements Ce, Zr, and Y versus Nb display reliable linear trends that pass through the origin, showing that these elements retain a constant ratio through magma evolution (Ce versus Nb is shown as an example in Fig. 5). Because of this coherency and because these elements are readily released to the liquid upon initial melting, the patterns suggest a common source for the basement rocks of Sinton (1996) and those of this investigation. Similarly, when ratios of incompatible elements are plotted against Nb (eg. Zr/Y, Ce/Y, Zr/Nb, and Nb/Y), nearly horizontal trends indicate that common source ratios are retained through fractionation for all samples, thus substantiating the relationship of the CT and NT basalts.

TECTONIC DISCRIMINATION

Standard basalt tectonic discrimination diagrams pose several problems, including utilization of mobile elements and ambiguity in defining tectonic setting due to overlapping fields. Using these triangular plots, rocks from this study could have formed in mid-ocean ridge (MORB), island arc (IARC), or ocean island (OIB) settings. This investigation chooses to rely upon trace element spider diagrams in order to assess the tectonic setting of the southern peninsula. Figure 6 is a multi-variable spider diagram showing relatively flat patterns for rocks of this study, normalized to primordial mantle; Sinton's (1996) data show comparable trends. Península de Nicoya basalts show enrichment relative to normal MORB (N-MORB) for the most incompatible elements, but neither does the pattern resemble that for OIB.

Chondrite normalized rare earth elements (REE) for this study are plotted in Figure 7. Because N-MORB REE patterns are characteristically light REE (LREE) depleted, the flat pattern of these six samples suggests that volcanism in the study area was affected by some enrichment process, possibly hot spot activity (Sinton 1996).

From this study, ratios of chondrite-normalized La to Ce for fresh basalts in both the CT and the NT are 0.833 to 1.500. This enrichment of La relative to Ce, both highly incompatible, indicates a less depleted mantle source (E-MORB) than N-MORB, which has (La/ Ce)_{N} significantly less than 1.0 (Kaula, 1981). In sum, interpretation of the Península de Nicoya as an LIP, with likely plume influence, is reasonable.

CONCLUSIONS

Geochemical comparison of NT and CT basalts does not support the separation of the Península de Nicoya basement rocks into two terranes of differing origins, as proposed by Di Marco and others (1995). Instead, this study finds a set of basalts that can be related, through fractional crystallization, to a similar parental magma source. Sinton (1996) has already tied the NT to the CCCIP with geochronology, supporting the idea that the entire
peninsula was created during the same event. Therefore, this debate is restricted to the following two models: 1) both the CT and the NT formed from the same event at the same location; or 2) the CT and the NT formed from the same source, spatially separated, and then were tectonically juxtaposed via movement of the allochthonous NT. The latter model would account for the fossil and sediment differences documented by Di Marco and others (1995), which suggest a more open ocean environment for the NT than the CT following basalt formation. To further constrain the evolution of this region, \(^{40}\)Ar-\(^{39}\)Ar whole rock geochronology and inter-pillow radiolaria chert dating will test the hypothesis that the CT is indeed contemporaneous with the CCCIP. Finally, the theory of Kuipers (1980) is not supported by the SEM and XRD analyses of this investigation. Thus, a lower plate origin for the NT is not substantiated.

Regardless of which of the above theories is more probable, the geochemical studies of this and previous investigations point to an E-MORB style of volcanism for the entire Península de Nicoya basement. The influence of an enriched plume head during the CCCIP formation appears to be a probable mechanism to explain the volcanic history of this region.

ACKNOWLEDGEMENTS

I would like to thank the KECK Undergraduate Research Consortium and the Costa Rica 1998 project leaders, Thomas Gardner, Edward Buettner, Dorothy Meritts, and Marino Protti for giving me this amazing opportunity to explore and learn. Many thanks to my fellow Costa Rica KECK participants.

REFERENCES


Figure 1: Sketch map of the Peninsula de Nicoya (see Gardner, this volume, figures 1 and 2, for general tectonic setting).

Figure 2: Total alkalis-silica (TAS) diagram for this study.

Figure 3: AFM diagram for this study showing tholeiitic compositions.
Figure 4: Bi-variante plots of CaO/Al2O3 and TiO2 versus increasing MgO. 4a shows fractionation of clinopyroxene. 4b exhibits concurrent plagioclase and clinopyroxene crystallization with magma evolution. Inflection at 4 wt% MgO indicates fractionation of late-stage Ti-oxides. Coherent trends for data from this study and from Sinton (1996) suggest a similar magmatic source.

Figure 5: Bi-variante plot of highly incompatible elements shows retention of source ratio through fractionation. No distinctions between the CT and NT can be inferred.

Figure 6: Multi-element diagram normalized to primordial mantle of McDonough et al. (1991). Flat overlapping patterns generated from rocks of this study combined with data from Sinton (1996) show E-MORB affinities for both data sets.

Figure 7: Chondrite normalized REE diagram using chondrite values of McDonough et al. (1995). Relatively flat patterns suggest E-MORB source for this study (see legend on preceding page).
Geodetic measurements of Holocene deformation in response to subducting seamounts, southern Península de Nicoya, Costa Rica.

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INTRODUCTION

Costa Rica is located on the southern end of the Central American arc system, which marks the beginning of the subduction of the Cocos plate and associated rough crust beneath the Caribbean plate (Gardner, this volume, Fig. 1). The Pacific margin of Costa Rica is affected by orthogonal convergence as the Cocos plate subducts beneath the Caribbean plate along the Middle American Trench (MAT) at the rate of 9.1 cm/yr (DeMets et al., 1990). Linear chains of seamounts oriented perpendicular to the margins, rising thousands of meters above the sea floor of the Cocos plate, are actively deforming the accretionary prism and forearc as they encounter the central Pacific segment of the subduction zone in Costa Rica (Gardner, this volume, Fig. 2). Furthermore, these seamount chains might be affecting the southern portion of the Peninsula de Nicoya, which provides a unique opportunity to study this deformation because shorelines run both parallel and perpendicular to the direction of convergence. Uplift rates determined from 14C dating of shells from Holocene terraces indicate the forearc is uplifting 1.5 mm/yr and tilting towards the arc at a rate of 0.01-0.02°/k.y. (Marshall and Anderson, 1995). Additionally, more than 1 m of uplift occurred along the Pacific coastline during the last major rupture of the Nicoya subduction zone in 1950, which resulted in a M7.7 earthquake located beneath the Peninsula de Nicoya (Marshall and Anderson, 1995). Five years later the Instituto Geográfico Nacional de Costa Rica installed numerous surveying monuments across the peninsula and completed a geometric leveling line tied to mean sea level. Because only two monuments were located during this 1998 project, one of which was vandalized, there is no accurate means to geodetically tie into the 1955 survey. Therefore, attempts to quantify the interseismic deformation during current or future earthquake cycles are difficult and relative at best.

The main focus of this project is to create a base-line survey that can be reoccupied at a later date. Through comparisons between this 1998 base-line survey and a future survey, the relative magnitude and direction of forearc deformation can be determined. A second focus of the project is to compare the accuracy of three survey techniques to see which is best suited for geodetic studies on the Península de Nicoya. The last objective is to create a forward model of the uplifted forearc and subsided forearc basin using a simple dislocation program to determine the geometry of the Nicoya subduction zone.

METHODS

Geometric Leveling. Geometric leveling is a first-order leveling method with the precision of ± 1 mm. The technique uses two stadia rods, each with a strip of graduated invar steel designed to resist expansion and contraction from heat. In addition, a Wild Nak 2 precision optical level with a micrometer plate is attached to a surveyor's tripod. Two stadia rods are placed on either side of the level and a reading is taken from both rods. The readings are used to calculate changes in elevation from the first to the second stadia rod.

Trigonometric Leveling. Trigonometric leveling is a second-order leveling method with the precision of ± 1 cm. The technique uses an electronic theodolite, which measures an angle from a vertical axis between the center of the geoid and the instrument. Additional equipment includes an electronic distance meter (EDM), which uses a single frequency infrared light to detect the distance to a point, and a target/prism used for sighting and reflecting infrared beams. The theodolite and EDM are set up at one point while the prism is moved to another location, and measurements are taken. Later, the difference in elevation is calculated using the angle from the vertical (measured using the theodolite), the distance to the prism (measured using the EDM), and simple trigonometric functions.

Global Positioning System Campaign. Four permanent monuments were installed along the proposed survey lines and then occupied for three to five days by a Trimble 4000 SSI dual-frequency geodetic receiver in a static style campaign. Daily data sets were stored with the receiver and processed using GPS Inferred Positioning System (GIPSY) by Paul Lungren at the Jet Propulsion Laboratory in Pasadena, CA. All geographical coordinates and elevations are based on the global reference WGS-84.
Dislocation Modeling. A dislocation model created by Ward and Barrientos (1986), models elastic deformation due to a buried point source, and is designed to mimic deformation produced from the rupture of a fault. The program allows the user to input grid dimensions, number of planes, strike, dip, rake, length, and width of faults. The subsequent output file produces a three dimensional \((X,Y,Z)\) data set showing the vertical displacement due to a buried point source. The data set is then translated into a three-dimensional graph showing areas of uplift or subsidence using DeltaGraph to interpolate and contour.

RESULTS AND DISCUSSION
Detecting current rates of forearc deformation using geodetic survey techniques requires a combination of high precision and sufficient time. This insures measured uplift is greater than experimental errors. Because the last survey was completed in 1955, enough time has passed so actual uplift overprints any errors. A series of six permanent survey benchmarks and GPS monuments were surveyed along lines roughly parallel and perpendicular to subduction on a Pliocene marine terrace (Fig. 1). Elevations for each site and errors from each of the three survey techniques show the differences in precision (Table 1). Elevations determined by geometric leveling and GPS have millimeters of error, while trigonometric leveling has centimeters of error. A benefit of geometric leveling is the high level of precision, less instrument error, and the ability to field check data. But since terrain is steep and vegetation thick, geometric surveying is very slow; a meager 600m was completed in four days. In addition, to maintain high levels of precision, shots were kept under 30m. For distances greater than 30m the refraction from temperature and heat make readings difficult and inaccurate.

**Figure 1.** Map of study area. PN=Peninsula de Nicoya.

**Table 1.** Monument elevations \((m)\) for 1998. Elevations with no error represent an arbitrary elevation where the survey began. Spaces marked -- represent no data collected.

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</tbody>
</table>

Considering time constraints, completing the proposed survey line using geometric leveling appeared impossible, so a switch was made to the quicker trigonometric survey style. Completing 2km in a day was common, topography was no longer a hindrance, and the equipment was more portable, making trigonometric surveying a better choice. A total of 8.5 km was completed for the base-line survey. Longer shots, up to 400m, made the
technique faster, but the ability to cover more ground came at a cost as trigonometric surveying is less precise than geometric surveying (Table 1).

Initial plans designated LOCA as the starting point for all surveys, but the large error associated with the GPS solution for the LOCA monument forced us to designate KECK as the starting point instead (Table 1). The large error is believed to be associated with a movement of the antenna and failure to record proper antenna height rather than instrument error. Subsequent solutions for KECK, COBA, and RINE show expected errors of approximately ±5.0mm and are considered accurate.

Direct elevation comparisons are poor indicators of precision. By looking at the difference in elevation between monuments, the effects of assigned elevations are removed (Table 2). It is important to remember that 1998 surveys are “floating” with respect to the 1955 survey. We were unable to directly tie into the 1955 survey, so absolute uplift rates are unobtainable. Portions of the 1998 survey connected monuments G-66 and G-64 from the 1955 survey. Monument G-66 was in excellent shape, while G-64, in the town of Cobano, was vandalized. An estimated 10cm of concrete was removed as vandals successfully extracted a metal pin used for centering. Fortunately, trigonometric leveling data shows less relative uplift at G-64 than G-66, indicating uplift decreases away from Cabo Blanco at the tip of the Peninsula de Nicoya (Table 3 and Fig. 2). The relative elevation difference between the surveys of 1955 and 1998 indicates an arcward tilting of the Peninsula de Nicoya at and angular rotation rate of 0.09%/k.y. This value is significantly higher than the angular rotation rate 0.02%/k.y. from Marshall and Anderson (1995). The discrepancy could either be recording aseismic accumulation of strain or be an artifact of the method’s precision.

**Table 2.** Elevation differences (m) between monuments for the 1998 surveys. Spaces marked -- represent no data collected.

<table>
<thead>
<tr>
<th>Method</th>
<th>LOCA-KECK</th>
<th>KECK-COBA</th>
<th>COBA-RINE</th>
<th>RINE-G-66</th>
<th>COBA-ROCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometric</td>
<td>23.2170</td>
<td>--</td>
<td>--</td>
<td>-1.2897</td>
<td>--</td>
</tr>
<tr>
<td>Trigonometric</td>
<td>23.2458</td>
<td>6.0011</td>
<td>1.8245</td>
<td>-1.2861</td>
<td>-31.0073</td>
</tr>
<tr>
<td>GPS</td>
<td>23.4752</td>
<td>5.8960</td>
<td>1.1333</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

**Table 3.** Elevations and differences (m) between monuments for the 1955 and 1998 survey.

<table>
<thead>
<tr>
<th>Location</th>
<th>1955</th>
<th>1998</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-64</td>
<td>158.1007</td>
<td>160.9935</td>
</tr>
<tr>
<td></td>
<td>±9.6cm</td>
<td>±11.0935</td>
</tr>
<tr>
<td>G-66</td>
<td>172.9787</td>
<td>176.1363</td>
</tr>
<tr>
<td></td>
<td>±12.7cm</td>
<td>±15.2cm</td>
</tr>
<tr>
<td>ΔH</td>
<td>14.8780</td>
<td>15.1428</td>
</tr>
</tbody>
</table>

**Figure 2.** Graphical representation of Table 3, showing decreasing amounts of uplift towards the arc.

Forward modeling of deformation resulting from a buried point source reveals a constant increase in uplift from the trench to 60 km, at which point uplift of the forearc dramatically increases (Fig. 3). Maximum uplift is located at 80 km, and coincides with the coastline of the Peninsula de Nicoya. Continuing arcward, uplift steadily decreases, forming the Golfo de Nicoya. All modeled elastic coseismic deformation is the result of a single rupture along the fault and follows a 40 year earthquake cycle.

The large magnitude of uplift arcward from the trench forms the forearc, while subsidence represents the forearc basin of the Nicoya subduction zone. Theoretical uplift and subsidence is a response to the accumulation and release of strain in the forearc, but doesn’t allow for the effects of underplating buoyant seamounts, which is thought to play a significant role in forearc deformation along this section of the coast. Modeled forearc deformation simulated the rupture of a two planes, one dipping 8°, and extending from 10 km northeast of the trench to the southwestern side of the Peninsula de Nicoya, and a second plane dipping 25°, and extending from the southwestern of the peninsula to the Golfo de Nicoya. The dimensions of the modeling plane are believed to be accurate as they correlate with plate geometry described by Protti (in press).
CONCLUSIONS
The main objective of completing a baseline survey is a success since a total of 8.5 km of trigonometric leveling is completed and ready to be reoccupied following a large seismic event. Future surveys can easily tie into this survey given the addition of six permanent monuments, three of which have absolute elevation as determined by GPS.

A comparison of survey techniques shows geometric leveling provides the greatest accuracy, but is too slow given the topography and vegetation. Trigonometric surveys are the fastest, but don’t provide enough precision. On the other hand, GPS is both time effective and provides enough precision for geodetic point surveying to determine small amounts of deformation. When time and accuracy are important, a static style GPS campaign can cover a significant amount of terrain and provide enough resolution to determine small amounts of uplift.

Both the 1955 and 1998 surveys are snapshots in time, and when compared show the interseismic strain accumulation, manifested as uplift, within a single earthquake cycle. Because the surveys are contained within a single earthquake cycle, uplift rates spanning thousands of years cannot be determined. Relative elevation differences between the two surveys suggest arcward tilting of the peninsula at an angular rotation rate of 0.09°/k.y. The observed angular rotation of the peninsula towards the arc supports conclusions made by Marshall and Anderson (1995). This style of deformation is correlative with forward modeling predictions of an uplifted forearc high, subsided forearc basin, and resumed uplift at the foot of the arc. The plate geometry for the theoretical deformation indicates the Cocos plate is dipping 8° between the trench and the coast of the peninsula, where it steepens to 25°. Mechanisms for forearc deformation include interseismic accumulation of strain, coseismic release of strain, and/or underthrusting of buoyant oceanic seamounts from the Cocos Ridge.

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Leveling Techniques Applied to the Southern Part of the Nicoya Peninsula in Northern Costa Rica

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INTRODUCTION

Seismic activity along the Pacific coast of Costa Rica results from the subduction of the Cocos plate under the Caribbean plate. The zone of instability produced by this collision represents a region of constant crustal deformation and therefore requires extensive geodetic studies. The construction of a geodetic network with permanent benchmarks will allow the recording and quantification of vertical and horizontal movement in the region due to future large earthquakes associated with this process.

The region between the coastal town of Montezuma and Cóbano, in the southern part of the Nicoya peninsula in Costa Rica constitutes the area where we started, during our Keck project, the first stage of monumentation and leveling. Our work focused on a set of sites along two lines parallel and perpendicular to the subduction direction. This work was part of a larger project that pretends to build and level a baseline across the peninsula with the goal of documenting crustal deformation in the region associated to the earthquake cycle.

We built 6 new monuments, conducted 600 m of geometrical leveling, almost 8.5 km of trigonometric leveling, and occupied 4 monuments with global positioning systems (GPS). This way we initiated a component of a project that will collect geodetic and geophysical information all over the Nicoya peninsula.

As part of this project we compare the resolution and precision obtained by three different geodetic techniques in order to define which one will be the most appropriated to be apply to the rest of the peninsula.

METHODS

Before we started the fieldwork, we collected all available geodetic information from the region. This information included topographic sheets, an inventory of previously occupied monuments and their descriptions, and gathered the precise elevation of measured benchmarks. We obtained all this information from the Costa Rica National Geographic Institute (IGN).

After all data was collected we conducted a field check of reported benchmarks but, out of nearly 20 sites, we were able to find only two. These two monuments were labeled by IGN as G-64, located near the school in Cóbano, and G-66 located 2.4 km SW from G-64. Since we only found the concrete pier but not its brass plate, we had to rebuild G-64 installing a stainless steel pin. The monuments of the G series were built and geometrically leveled in 1955.

When you are interested in measuring elevation of benchmarks you have to first decide what kind of exactness you require, then you choose what technique to apply (De Obaldia et al., 1991). This led us to apply three different techniques and conduct and analysis and comparison of them:

- **Geometric leveling.** Depending on the application, this technique receives three different names: leveling by heights, geodesic leveling and precision leveling (Jordan, 1996). Sights on a horizontal plane characterize this technique. The instrument is selected based on the application and required exactness. In our fieldwork we used a Nak2 Wild level, with a GpM3 micrometric parallel plate, which transforms the level into a first order level. This is an automatic level, which does not require centering the bubble each time you take a reading. We also used stuffs with invar tapes that are not susceptible to thermal contraction or expansion. Geodesic leveling is used at two different scales. Large-scale regional networks are occupied, in the case of Costa Rica, by IGN or the National Cadastre and are called official networks. Small or local scale networks are constructed and occupied for specific projects by institutions like OVSICORI-UNA with the goal of documenting crustal deformation.

- **Trigonometric leveling.** In this leveling technique, sights are taken along inclined lines and therefore requires the use of instruments capable of measuring vertical angles and distances, values needed to compute the elevation difference between two points. Although this technique is not as precise as geometric leveling, it can reach the exactness of 5 to 10 mm per leveled kilometer (De Obaldia et al., 1991). We used a Wild 2000 electronic theodolite, which gives vertical angles to half a second, and a WILD 3000 electronic distancemeter which can reach up to 14 km and have an mean error +-(5mm+1ppm).

- **Global positioning system (GPS).** GPS gives tridimensional position of points in a geometrical and very precise way (Hollmann and Welsch, 1995). Conventionally all positions are given in global geocentric coordinates under the WGS84 reference frame. For our GPS occupations we utilized dual-frequency (L1 and L2) 4000 SI Trimble receivers and ground plate antennas. We monumented four sites (LOCA, KECK, COBA and
RINE) which also constituted anchor points in our geometric and trigonometric leveling lines. The first three sites were occupied with the GPS receiver for 4 to 5 consecutive days and the last one for only a day. The GPS campaign was carried out while conducting the leveling and the data was later processed at the Jet Propulsion Laboratory in Pasadena using the GIPSY software.

**DISCUSSION**

We call geodesic leveling to every line leveled twice by different surveyors each time, which has a final error equal or less than 1.5 mm times the square root of the total length (in km) of the line surveyed, and to which has been applied the required gravimetric corrections (we ignored this last condition given the short length of our line) (Valbuena and Dolores, 1996). We conducted geodesic leveling between LOCA and KECK with an error of 0.07 mm in a 600 m line. Applying the above condition (1.5 mm * sqrt(0.6 km) = 1.16 mm) we have that 0.07 mm is less than 1.16 mm and therefore our leveling line is considered a first order geodesic line.

For trigonometric leveling the tolerance is 2.5 mm times the square root of the total length (in km) of the line surveyed. We also conducted trigonometric leveling between LOCA and KECK and obtained a final error of 36 mm in a 402.13 m of surveyed line, which is way too large for the accepted tolerance (2.5 mm * sqrt(0.4 km) = 1.58 mm).

From the 1955 leveling the elevation difference between G-64 and G-66 was 14.878 m. Our trigonometric leveling between these same two sites gives an elevation difference of 14.9627 m, and therefore results in an elevation rate of 1.9 mm/year for G-66 with respect to G-64.

For the KECK-COBA baseline the computed elevation differences using GPS give a difference of 1.6 cm with respect to that obtained with trigonometric leveling (Table 1).

**Table 1. Comparison between elevation differences obtained with the different techniques**

<table>
<thead>
<tr>
<th>Method</th>
<th>Operator</th>
<th>LOCA-KECK</th>
<th>Difference</th>
<th>KECK-COBA</th>
<th>Difference</th>
<th>RINE-G66</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Todd</td>
<td>Enrique</td>
<td></td>
<td>Todd</td>
<td>Enrique</td>
<td></td>
<td></td>
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<tr>
<td>Geometric</td>
<td>23,217</td>
<td>23,2177</td>
<td>-0.0369</td>
<td>6,011</td>
<td>5,883,552</td>
<td>0.117548</td>
<td>0</td>
</tr>
<tr>
<td>Trigonometric</td>
<td>23,2458</td>
<td>23,2539</td>
<td>-0.0081</td>
<td></td>
<td></td>
<td>-1.2861</td>
<td>-1.2872</td>
</tr>
<tr>
<td>GPS</td>
<td></td>
<td></td>
<td></td>
<td>5,896</td>
<td>5,896</td>
<td></td>
<td>0.0011</td>
</tr>
</tbody>
</table>

Table 1. Elevation differences between monuments, data from Todd and Enrique, the geometric leveling have difference in millimeters, while trigonometric leveling has centimeters.

**CONCLUSIONS**

Each technique applied in our surveys has different precision and tolerances. The technique and instrumentation will determine the final precision obtained, and therefore have to be selected based on the required resolution and amount of expected deformation.

For geometric leveling the sources of error are the instrument and staff heights, errors in hitting the target and refraction effects. Errors in trigonometric leveling are proportional to the segment length.

In our trigonometric leveling we recorded 50 measurements of angles and distances, but a post survey analysis of the mean quadratic errors indicated that 10 distance measurements and 10 angle readings (5 in position I and 5 in position II) are enough to obtain an acceptable mean quadratic error. Therefore, for the continuation of the leveling line, we recommend to save time at each locality by taking only 10 readings and thus have a larger coverage per day.

Based on the experience gained in these survey I recommend the extensive use of GPS. The resolution and computational analysis of global positioning system data is becoming more precise every day.

Although geometric leveling gives the best resolution, the distances covered per day depend mainly on topographic conditions (very rough all over the Nicoya peninsula) and is very time consuming making it more expensive. If the expected amount of deformation is large (in the order of cm) trigonometric leveling constitutes a faster and cheaper technique with good enough resolution for the task required. Careful fieldwork, not too long shots and real-time computation in the field could help improve the resolution to the sub-centimeter level.

**ACKNOWLEDGMENTS**

Much thanks goes to my sponsor, Dr. Marino Protti and I would also like to recognize my field partner, Todd Shearer, thank you new friend. Lastly, a big thank you goes to Hazel Miranda, always was with me.
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