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:

$$Z = \frac{X1 + X2 + X3}{X4}$$

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) 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.

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Table 1. Terrace ages, elevations, and uplift rates

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

* 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 sampleddeposit 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

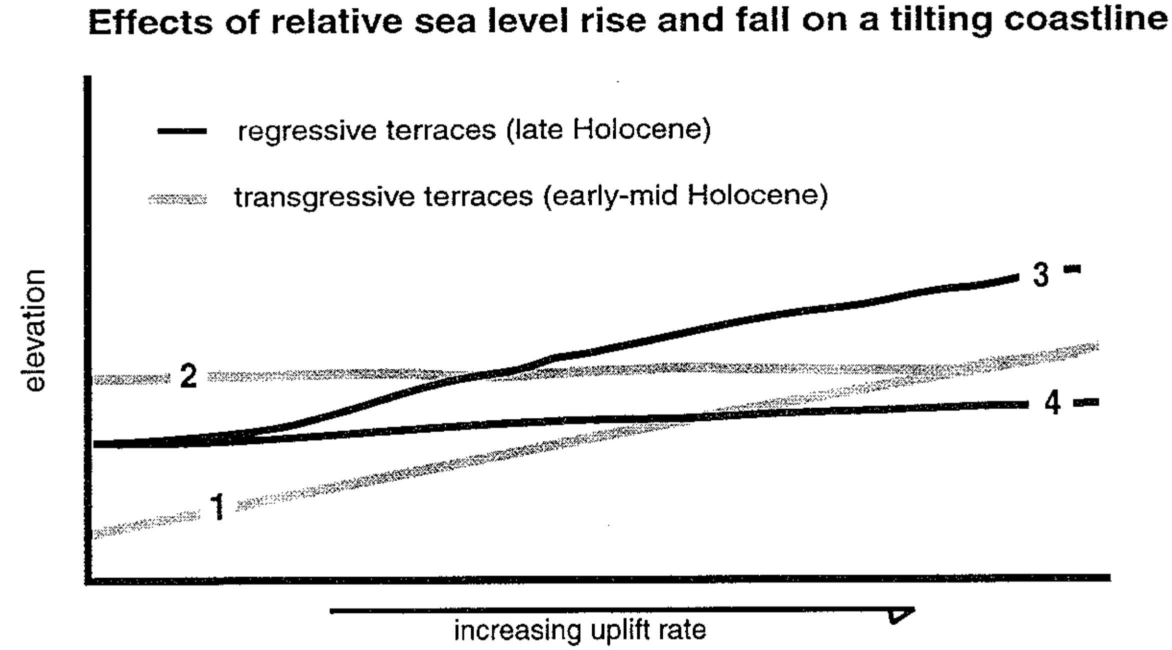

Figure 2. Sea level transgressions and regressions leave different terrace patterns on a tilting coast. During a period of rising sea level with respect to the land, areas of high coastal uplift can keep up with water level, and terraces merge in the direction of highest uplift (gray line). When the 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.

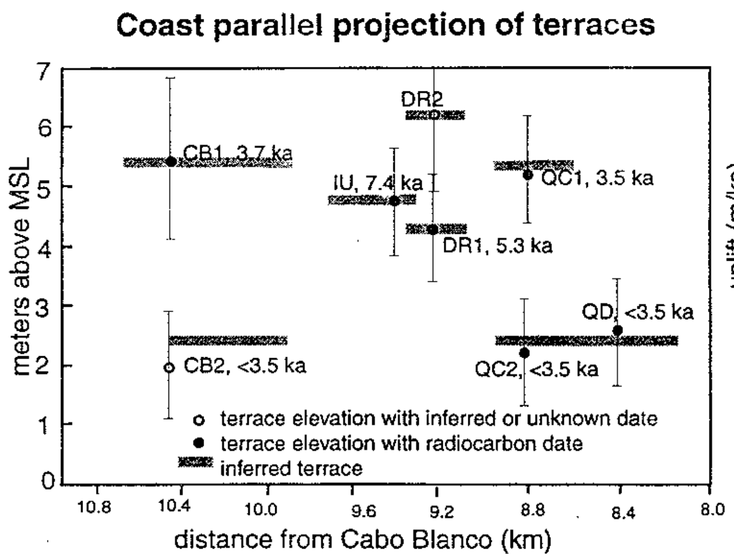

Figure 1. Terrace elevations in my field area. View is looking at the coast from offshore. Note lateral discontinuity between sampled survey lines. Distance along coast is measured along the coast parallel line from Figure 3, and site labels are from Table 1.

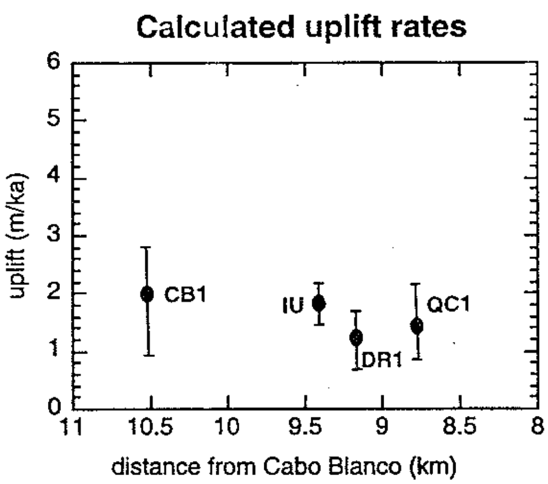

Figure 3 Uplift rates plotted along the coast-parallel line of Figure 3. Terraces in my area did not show an increase in uplift in either direction. Sample numbers are from Table 1.

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.

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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.

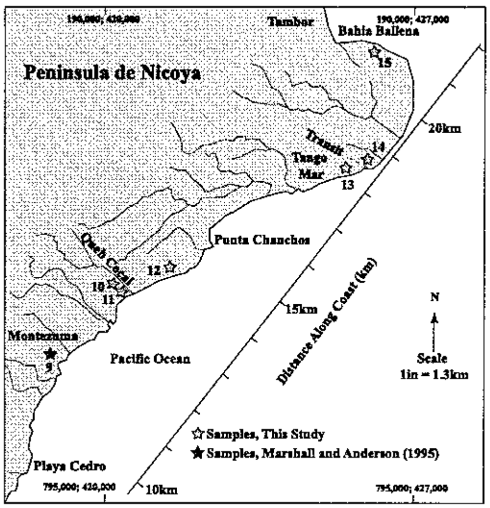

Figure 1. Study area: southeast coast of the Peninsula de Nicoya, Costa Rica. Radiocarbon samples are indicated by stars.

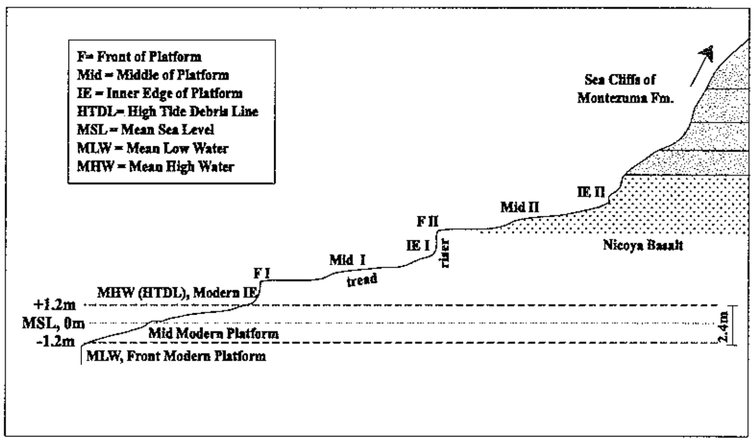

Figure 2. Generalized profile of a marine abrasion platform and facies relationships to mean sea level (MSL). This figure shows the modern abrasion platform as well as abandoned abrasion platforms I and II.

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