Rate and style of Holocene uplift in response to subducting seamounts, Malpaís area, Península de Nicoya, Costa Rica

Reed J. Burgette
Department of Geology, Whitman College, Walla Walla, WA 99362
Faculty sponsor: Kevin Pogue, Whitman College

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 treads 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.

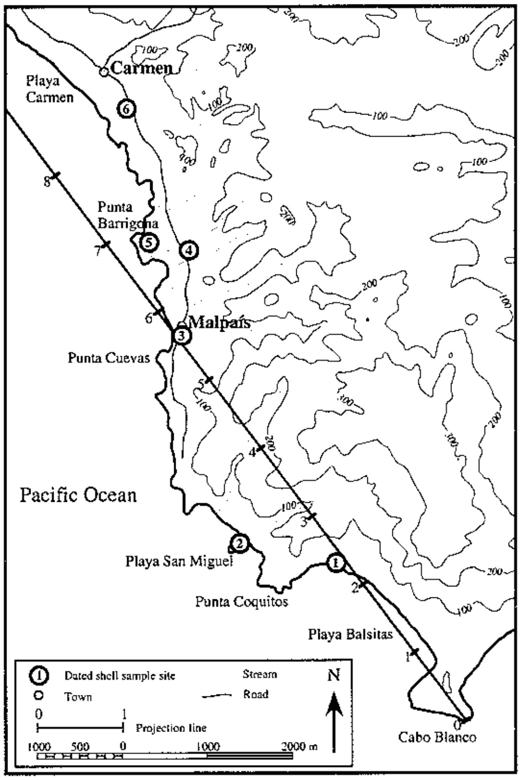
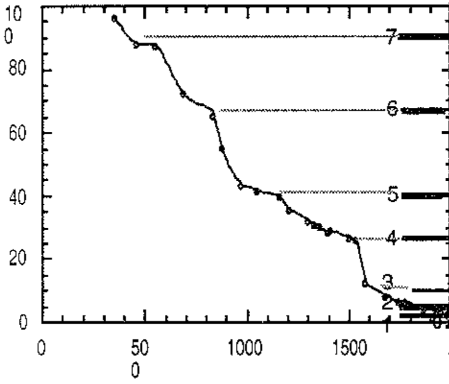
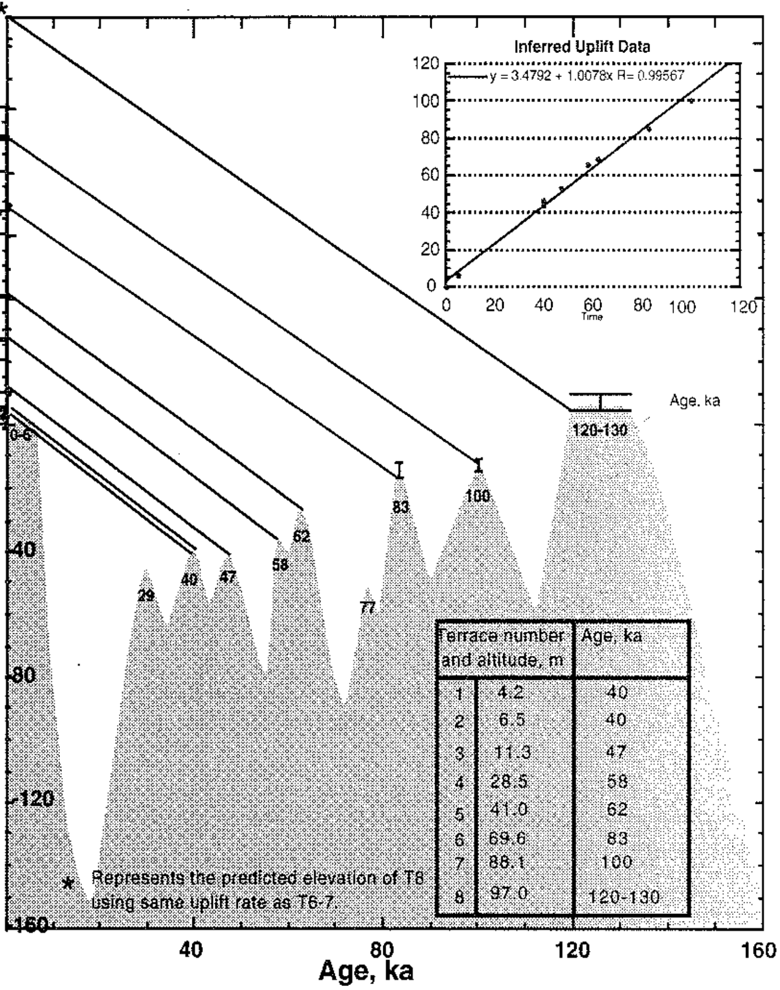


Figure 1. Map of the Malpaís area of the trench-parallel southwestern coast of the Península de Nicoya.

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.





Terrace number and altitude, m		Age, ka
1	4.2	40
2	6.5	40
3	11.3	47
4	28.5	58
5	41.0	62
6	69.6	83
7	88.1	100
8	97.0	120-130

* Represents the predicted elevation of T8 using same uplift rate as T6-7.

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

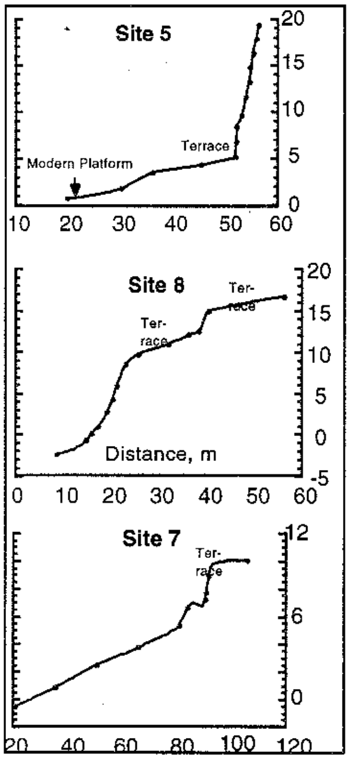
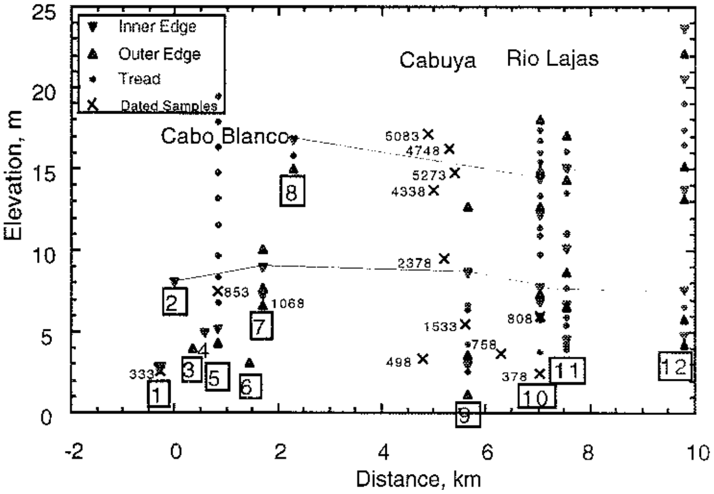


Figure 2. Holocene Terrace elevations along Nicoya coast



Uplift rate is determined using the following equation:

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

(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 this 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-tidal 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 at 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 $\delta^{13/12}$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 Península de Nicoya.

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

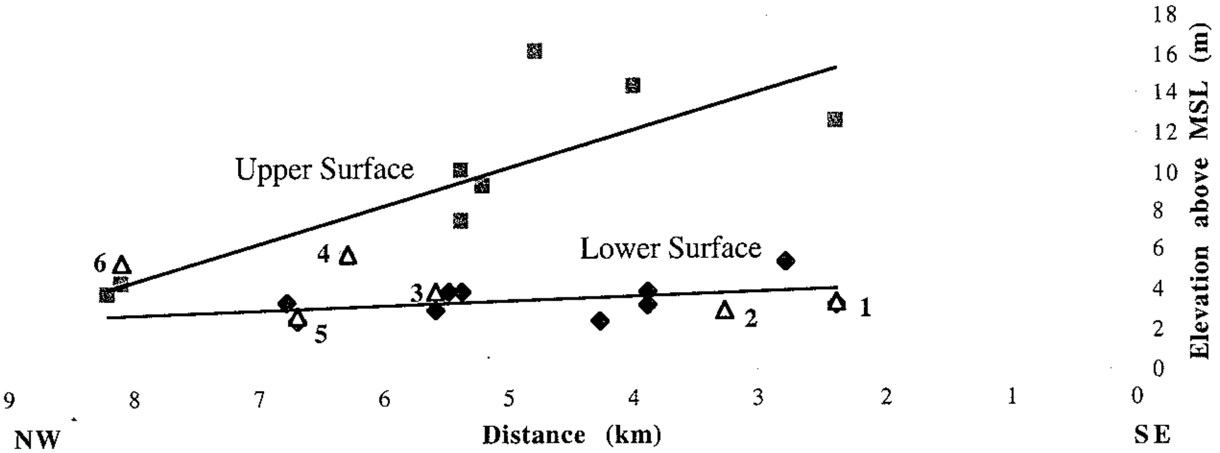


Figure 2. Regression trends for bedrock terrace elevations along the Malpaís area coast of the Península de Nicoya. Lower surface elevations are measured at the inner edge, and represent the highest points on the surface (black diamonds). The upper terrace inner edge is obscured by colluvium, and these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

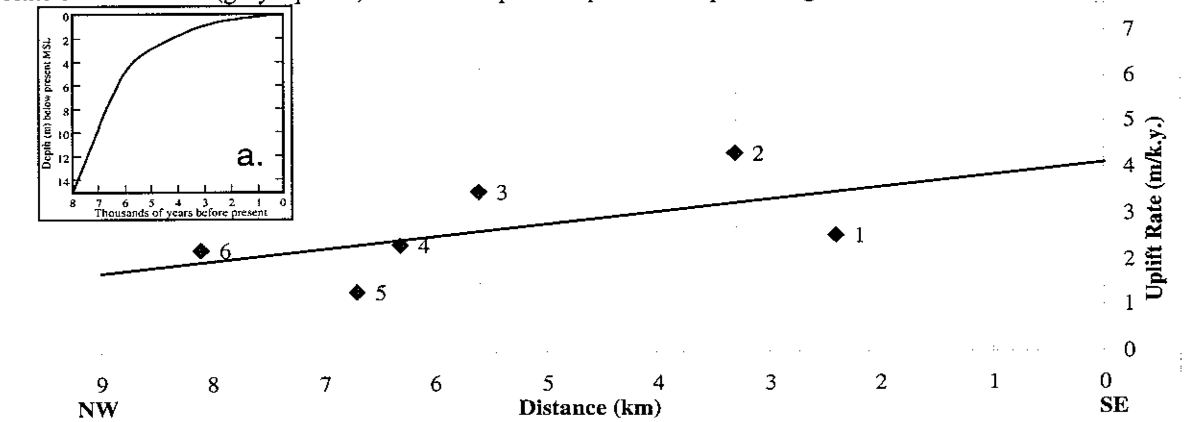


Figure 3. Uplift rates calculatedfrom six datedshell samples along the trench-parallel coast from Cabo Blanco (0 km) northwest to Carmen (8.6 km). Inset **Figure 3a** is the Barbados Holocene sea level curve determined by Marshall (1991) used to calculate uplift rates.

Uplift rates along the trench-parallel coast decreaseto 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 trendof 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 terracesare 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.

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REFERENCES CITED

Gardner, T. W., Verdonck, D., Pinter, N., Slingerland, R., Furlong, K., Bullard, T. F., and S. G. Wells, 1992, Quaternary Uplift Astride the Aseismic Cocos Ridge, Pacific Coast of Costa Rica, Geol. Soc. Am. Bull., 104, p. 219-232.

Lajoie, K. R., 1986, Coastal tectonics, *in* Studies in geophysics series: Active tectonics: Washington D.C., National Academy Press, p. 95-124.

Marshall, J. S., 1991, Neotectonics of the Nicoya Peninsula, Costa Rica: A look at forearc response to subduction at the Middle America Trench [Master's thesis]: Santa Cruz, California, University of California, 196 p.

von Huene, R. and 16 others, 1995, Morphotectonic features of the Costa Rican Pacific margin surveyed during the Sonne 76 cruise, *in* P. Mann, ed., Geologic and Tectonic Development of the Caribbean Plate Boundary: Geol. Soc. Am. Spec. Paper, No. 295 p. 291-307.

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

Emily O. Burton
Department of Geology, Carleton College, 1 N. College St., Northfield, MN 55057
Faculty sponsor: David Bice, Carleton College

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)