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

Jenny Cooke
Department of Geosciences, Trinity University, 715 Stadium Dr., San Antonio, TX 78212-7200
Faculty sponsor: Thomas W. Gardner, Trinity University

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.

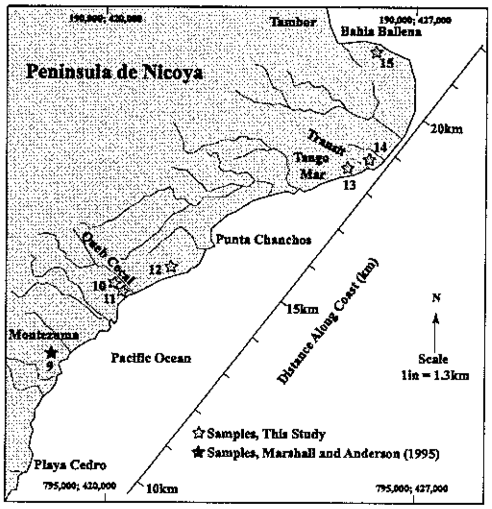


Figure 1. Study area: southeast coast of the Peninsula de Nicoya, Costa Rica. Radiocarbon samples are indicated by stars.

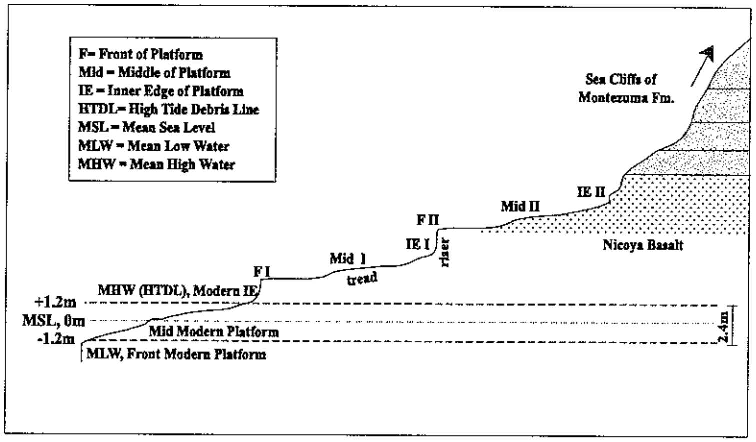


Figure 2. Generalized profile of a marine abrasion platform and facies relationships to mean sea level (MSL). This figure shows the modern abrasion platform as well as abandoned abrasion platforms I and II.

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 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 Protti, 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.

REFERENCES CITED

Bull, W. B., 1984, Correlation of flights of global marine terraces, *in* Morisawa, M., and Hack, J. T., eds, Tectonic geomorphology, Binghamton Symposia in Geomorphology: International Series, 15, p. 129-152.

Gardner, T. W., Verdonck, D., Pinter, N. M., Slingerland, J., Furlong, K. P., Bullard, T. F., and Wells, S. G., 1992, Quaternary uplift astride the aseismic Cocos Ridge, Pacific coast, Costa Rica. Geological Society of America Bulletin, v. 104, p. 219-232.

Gibb, J. G., 1986, A New Zealand regional Holocene eustatic sea-level curve and its application to determination of vertical tectonic movements. *in* Reilly, W. I. and Harford, B. E., eds., Recent crustal movements of the Pacific region, Bulletin - Royal Society of New Zealand, 24, p. 377-395.

Lighty, R. G., Macintyre, I. G., and Stuckenrath, R., 1982, Acropora palmata reef framework: A reliable indicator of sea level in the western Atlantic for the past 10,000 years: Coral Reefs, v1, p.125-130.

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.

Marshall, J. S., and Anderson, R. S., 1995, Quaternary uplift and seismic cycle deformation, Peninsula de Nicoya, Costa Rica. Geological Society of America Bulletin, v. 107. p. 463-473.

Pinter, N., and Gardner, T. W., 1989, Construction of a polynomial model of sea level: Estimating paleo-sea level over time: Geology, v. 17, p. 295-298.

von Huene, R., and 16 others, 1995, Morphotectonics of the Pacific convergent margin of Costa Rica,*in* Mann, P., ed., Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America: Boulder, Colorado, Geological Society of America Special Paper 295, p. 291-307.

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.

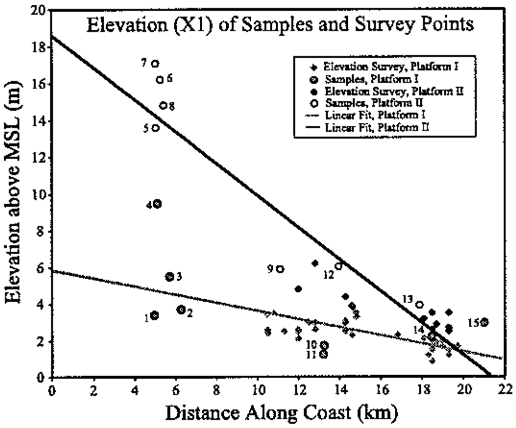


Figure 3. X1 is the elevation above MSL of radiocarbon samples and inner edge survey points. Samples 1-9 are from Marshall and Anderson (1995); samples 10-15 are from this study.

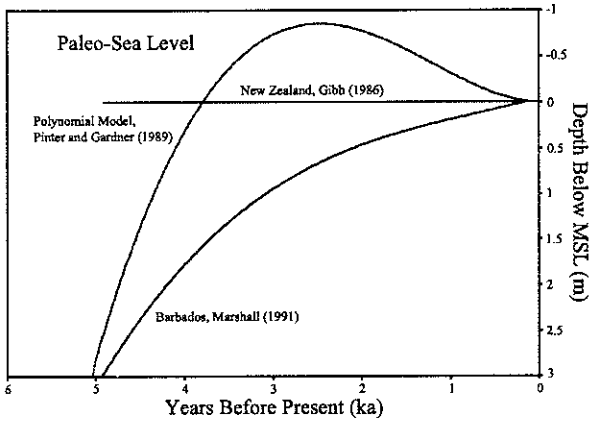


Figure 4. Paleo-sea level, X3, for three Holocene sea level curves.

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 +/- 0.6 m. At this high-energy environment, the release of CO_2 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).

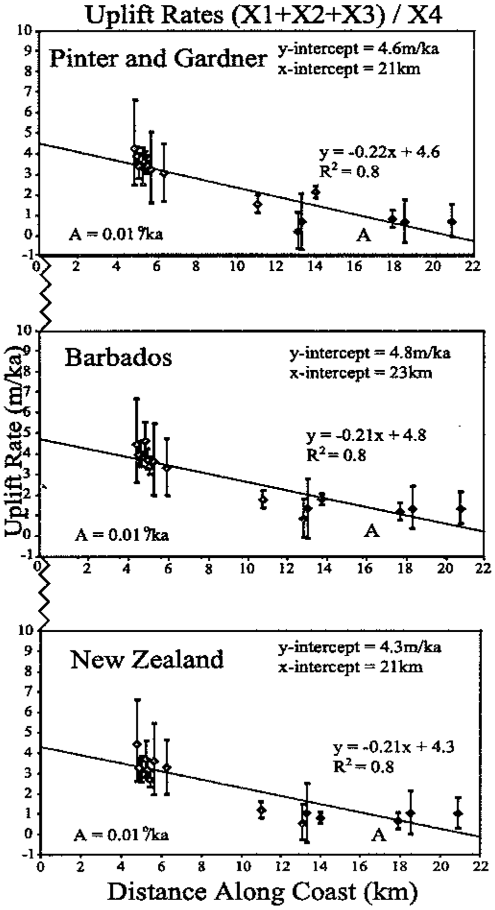
X4, calibrated radiocarbon age (ka). For this study, six shell and beachrock samples were dated by Beta Analytic, a radiocarbon dating service (Fig. 6). A spatial and temporal distribution of samples were collected so that the radiocarbon dates would yield ages of platforms I and II at various distances 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 Tango 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).



Sample	X1(m)	X2(m)	X3(m): P&G	X3(m): BB	X3(m): NZ	X4 (ka)
1	3.4+/-0.2	-1.2+/-0.6	3.8+/-0	0.0+/-0	0.0+/-0	0.5+0.04/-0.05
2	3.7+/-0.2	-1.2+/-0.6	-0.2+/-0	0.0+/-0	0.0+/-0	0.76+0.10/-0.06
3	5.5+/-0.2	0.0+/-1.2	-0.6+/-1	0.0+/-1	0.0+/-1	1.53+0.05/-0.09
4	9.5+/-0.2	-0.6+/-0.6	-0.8+/-1	2.0+/-1	0.0+/-1	2.38+0.08/-0.04
5	13.7+/-0.2	0.0+/-1.2	1.0+/-1	3.5+/-1	0.0+/-1	4.34+0.09/-0.08
6	16.2+/-0.2	-1.2+/-0.6	2.0+/-1	2.5+/-1	0.0+/-1	4.75+0.12/-0.17
7	17.1+/-0.2	-0.6+/-0.6	3.1+/-1	3.5+/-1	0.0+/-1	5.08+0.19/-0.15
8	14.8+/-0.2	-0.6+/-0.6	3.8+/-1	3.5+/-1	0.0+/-1	5.27+0.06/-0.19
9	6.0+/-0.2	-0.6+/-0.6	1.5+/-1	2.5+/-1	0.0+/-1	4.56+0.10/-0.10
10	1.70+/-0.05	0.0+/-1.2	-0.6+/-1	0.4+/-1	0.0+/-1	1.63+0.09/-0.06
11	1.28+/-0.05	0.0+/-1.2	-0.8+/-1	0.6+/-1	0.0+/-1	2.37+0.05/-0.04
12	6.16+/-0.05	-1.2+/-0.6	8.2+/-1	6.0+/-1	0.0+/-1	6.23+0.07/-0.09
13	3.90+/-0.01	-1.2+/-0.6	0.6+/-1	2.0+/-1	0.0+/-1	4.13+0.05/-0.05
14	2.26+/-0.05	-0.6+/-0.6	-0.6+/-1	0.4+/-1	0.0+/-1	1.62+0.10/-0.07
15	2.96+/-0.05	-0.6+/-0.6	-0.8+/-1	0.6+/-1	0.0+/-1	2.33+0.05/-0.15

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.

◇ Marshall and Anderson (1995)
◆ This Study

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.

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°/100,000years, 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 125ka (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.

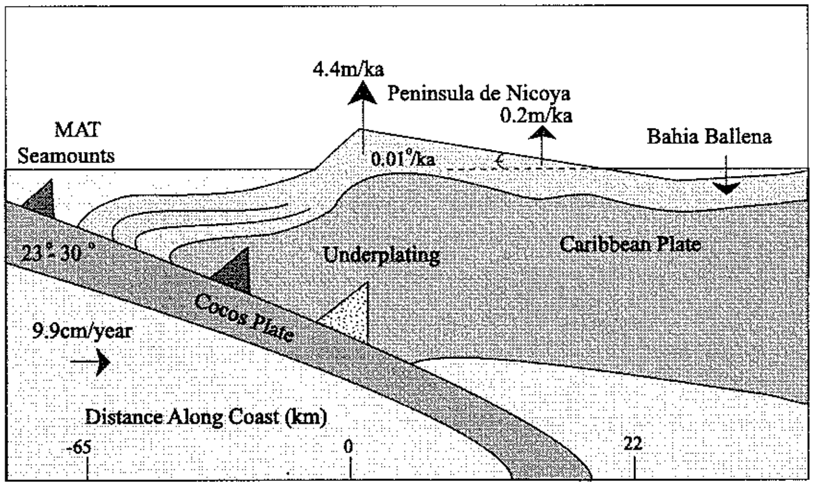


Figure 7. Uplift and rotation of the southeast coast of the Peninsula de Nicoya. Convergence rate from Gardner (this volume, Fig. 2.) Subduction angle from Protti et al. (1995).

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

Fisher, D.M., Gardner, T.W., Marshall, J.S., Sak, P.B., and Protti, M., 1998, The effects of subducting seafloor roughness on fore arc kinematics, Pacific Coast, Costa Rica: Geology, v. 26, n.5, p. 467-470.

Gardner, T.W., Verdonck, D., Pinter, N.M., Slingerland, R., Furlong, K.P., Bullard, T.F., and Wells, S.G., 1992, Quaternary uplift astride the aseismic Cocos Ridge, Pacific coast, Costa Rica: Geological Society of America Bulletin, v. 104, p. 219-232.

Gibb, J.G., 1986, A New Zealand regional Holocene sea-level curve and its application to determination of vertical tectonic movements: A contribution to IGCP-Project 200, R. Society of New Zealand Bulletin, v. 24, p. 377-395.

Lundberg, N., 1982, Evolution of the slope landward of the Middle America Trench, Nicoya Peninsula, Costa Rica *in* Leggett, J.K., ed., Trench-fore arc Geology: Sedimentation and tectonics on modern and ancient active plate margins: London, Geological Society of America, p. 131-147.

Marshall, J.S., 1991, Neotectonics of the Nicoya Peninsula, Costa Rica: A look at fore arc response to subduction at the Middle America Trench, [M.S. Thesis]; Santa Cruz, California, University of California, 196p.

Marshall, J.S., and Anderson, R.S., 1995, Quaternary uplift and seismic cycle deformation, Peninsula de Nicoya, Costa Rica: Geological Society of America Bulletin, v. 107, p. 463-473.

Pinter, N., and Gardner, T.W., 1989, Construction of a polynomial model of glacio-eustatic fluctuation: Estimating paleo-sea levels continuously through time: Geology, v. 17, p. 295-298.

Protti, M., Guendel, F., and McNally, K., 1995, Correlation between the age of the subducting Cocos Plate and the geometry of the Wadati-Benioff zone under Nicaragua and Costa Rica, *in* Mann, P., ed., Tectonic development of the Caribbean Plate boundary in southern Central America, Geological Society of America Special Paper 295: Boulder, Geological Society of America, p. 309-326.

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

Natalie M. Kehrwald
Department of Geology, Colorado College, Colorado Springs, CO 80946
Faculty sponsor: Eric M. Leonard, Colorado College

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 ^{14}C 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.

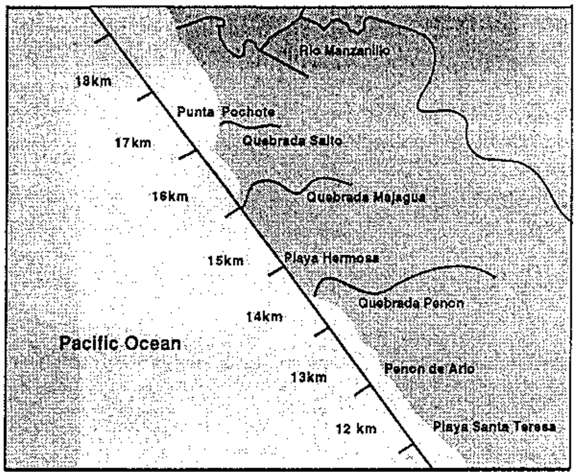


Figure 1: Trench-parallel coastline of the Peninsula de Nicoya, Costa Rica. Distances based on kilometer line drawn from the highest point of Cabo Blanco to the farthest seaward platform of Penon de Arlo. My study site encompasses 12.0 - 19.0 km. See Gardner, this volume, Fig. 3 for general location.