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.

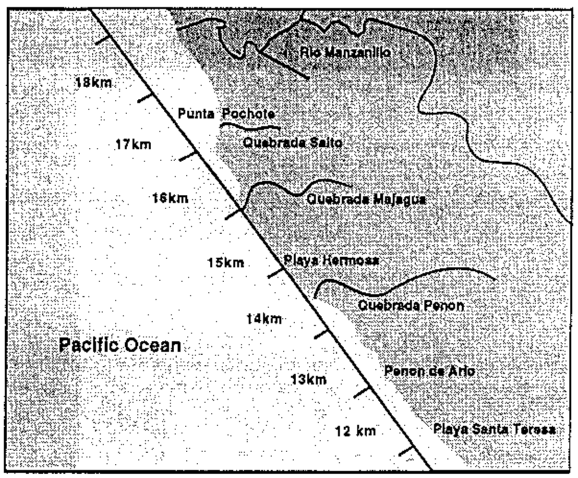


Figure 1: Trench-parallel coastline of the Peninsula de Nicoya, Costa Rica. Distances based on kilometer line drawn from the highest point of Cabo Blanco to the farthest seaward platform of Penon de Ario. My study site encompasses 12.0 - 19.0 km. See Gardner, this volume, Fig. 3 for general location.

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.

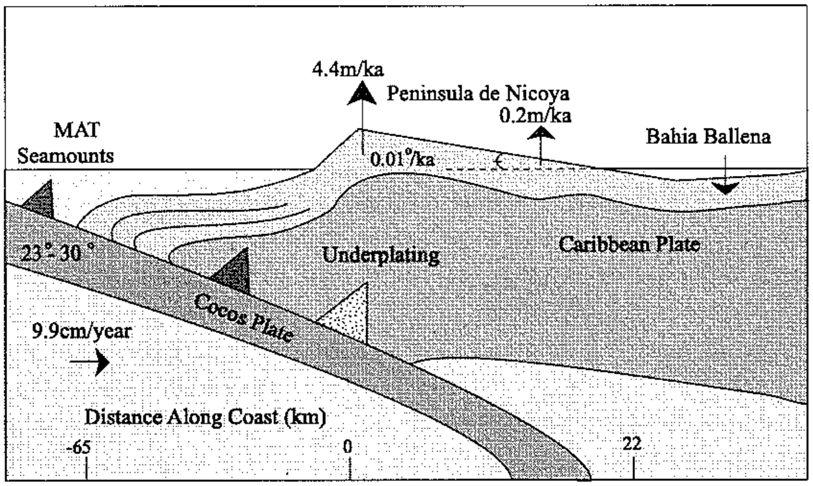


Figure 7. Uplift and rotation of the southeast coast of the Peninsula de Nicoya. Convergence rate from Gardner (this volume, Fig. 2.) Subduction angle from Protti et al. (1995).

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.

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 ^{14}C 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 ^{14}C yr BP. Mean, minimum, and maximum uplift rates were determined using the equation:

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

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.

Sample ID#	Lambert Grid Coordinates	Distance Along Coast (km)	Elevation (m) Raw Survey	*X1* Elevation (m) to MSL	*X2* Depositional Elevations (m)
1NK (CR-NK-5)	181,700mN: 400,200mE	12.1	0.70	1.90, 1.85-1.95	(-) 0.60, 0.00 - 1.20
5NK (CR-NK-10)	182,600mN: 406,500mE	12.6	-0.32	1.50, 1.30 - 1.70	(-) 1.20, 0.60 - 1.80
6NK (CR-NK-11)	183,300mN: 405,950mE	14.4	-0.82	0.38, 0.18 - 0.58	0.00, -1.20 - 1.20
8NK (CR-NK-12)	184,450mN: 404,700mE	15.9	0.74	1.94, 1.89 - 1.99	(-) 1.20, 0.60 - 1.80
9NK (CR-NK-1)	185,300mN: 404,700mE	16.9	52.00	53.20, 52.70 - 53.70	(-) 1.20, 0.60 - 1.80
11NK (CR-NK-2)	185,300mN: 404,700mE	16.7	52.00	53.20, 52.70 - 53.70	(-) 1.20, 0.60 - 1.80
12NK (CR-NK-3)	185,300mN: 404,700mE	16.7	52.00	53.20, 52.70 - 53.70	(-) 0.60, 0.00 - 1.20
2NK (CR-NK-6)	181,700mN: 400,200mE	12.1	-0.07	1.13, 1.08 - 1.18	(-) 1.20, 0.60 - 1.80
3NK (CR-NK-7)	181,700mN: 400,200mE	12.1	0.02	1.22, 1.17 - 1.27	(-) 0.60, 0.00 - 1.20
4NK(CR-NK-9)	182,300mN: 496,650mE	13.0	1.30	2.50, 2.45 - 2.55	(-) 1.20, 0.60 - 1.80
7NK (CR-NK-13)	183,300mN: 405,950mE	14.4	0.58	1.78, 1.58 - 1.98	(-) 0.60, 0.00 - 1.20
10NK (CR-NK-8)	185,700mN: 404,300mE	16.9	0.75	1.95, 1.75 - 2.15	(-) 1.20, 0.60 - 1.80

Sample ID #	*X3* Paleo Sea Level (m) Pinter/Garder	*X3* Paleo Sea Level (m) Barbados	*X3* Paleo Sea Level (m) New Zealand	Conventional 14C Age (yr BP)	*X4* Calibrated 14C Age (yr BP)
2NK (CR-NK-6)	4.0, 0.3 - 5.0	3.5, 2.5 - 4.5	0.0, -1.0 - 1.0	5070 +/- 70	5478, 5543-5378
3NK (CR-NK-7)	0.5, -0.5 - 1.5	2.5, 1.5 - 3.5	0.0, -1.0 - 1.0	2590 +/- 60	2333, 2368-2208
4NK (CR-NK-9)	0.0, -1.0 - 1.0	0.5, -0.5 - 1.5	0.0, -1.0 - 1.0	1250 +/- 60	513, 543-478
7NK (CR-NK-13)	0.0, -1.0 - 1.0	0.5, -0.5 - 1.5	0.0, -1.0 - 1.0	830 +/- 50	1468, 1553-1403
10NK (CR-NK-8)	0.0, -1.0 - 1.0	1.5, 0.5 - 2.5	0.0, -1.0 - 1.0	1900 +/- 60	1103, 1178-1028

Sample ID#	Uplift Rate (m/ky) Pinter/Gardner	Uplift Rate (m/ky) Barbados	Uplift Rate (m/ky) New Zealand	Comments
2NK (CR-NK-6)	0.71, -0.076 -1.10	0.64, 0.32 - 0.94	0.21, -0.31 - 0.29	Collected near water table.
3NK (CR-NK-7)	0.74, 0.22 - 1.80	1.30, 0.62 - 2.16	0.27, -0.43 - 1.0	Best sampling site, although scarce shells.
4NK (CR-NK-9)	2.50, -0.64 - 6.20	3.51, 2.49 - 7.21	2.53, 1.67 - 6.17	Discard. Possible modern contamination.
7NK (CR-NK-13)	0.80, -0.40 - 2.10	1.14, -0.077 - 2.48	0.80, -0.40 - 2.12	Large embayment (abandoned bedrock weathered to clay).
10NK (CR-NK-8)	0.68, -0.90 - 2.30	0.68, -0.89 - 2.16	0.68, -0.89 - 2.48	Base of Pleistocene terrace transect.

Based on Pinter/Gardner (1989), Barbados (Fairbanks, 1989) and New Zealand (Gibb, 1986) sea level curves.

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*).

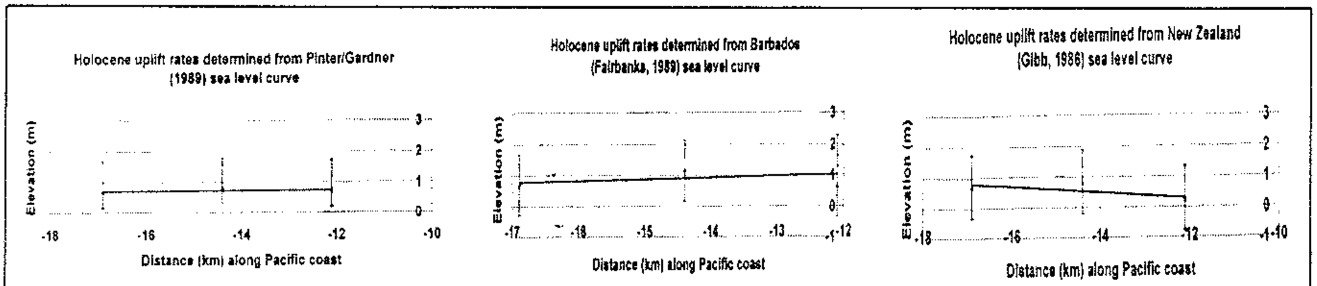


Figure 2: Holocene uplift rates determined from measured terrace elevation, depositional depth, paleo-mean sea level, and calibrated radiocarbon dates.

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 hand 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*).

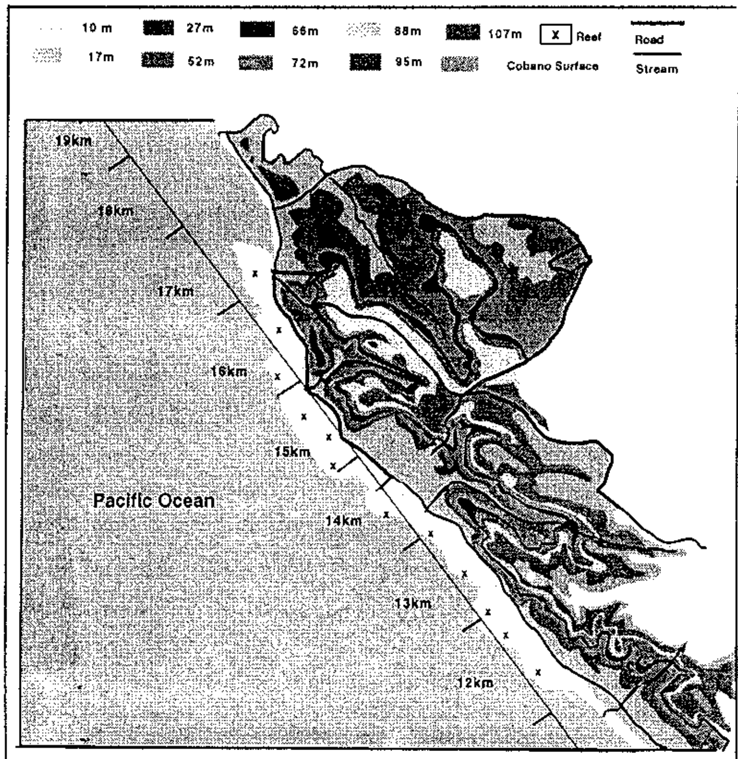
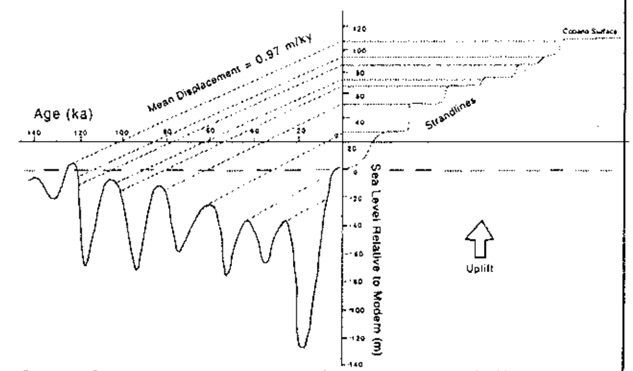


Figure 3: Marine terrace elevations for the Pacific Coast, Peninsula de Nicoya, Costa Rica

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*).

FIGURE 4:UPLIFT RATES BASED ON PINTER AND GARNDER (1989) SEA LEVEL CURVE



Emergent Pleistocene terraces correlated with sea-level highstands. Modern strandline heights are compared to the elevation at which they formed. The slope of the line connecting paleo-sea level and current elevation denotes the rate of uplift.

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.

	Pinter and Gardner (1989) uplift rates	New Zealand (Gibb, 1986) uplift rates	Barbados (Fairbanks, 1989) uplift rates
Model 1	1.30 m/ky	1.10 m/ky	1.32 m/ky
Model 2	0.97 m/ky	0.98 m/ky	1.10 m/ky

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

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, platform uplift rates can be determined. The terraces from 12.0 to 19.0km lie at 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 .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. Garnder, this volume, for full listing.

Fischer, D., Gardner, T., Marshall, J., Montero, W., 1994, Kinematics associated with late Cenozioc deformation of central Costa Rica: Western boundary of the Panama microplate. *Geology*, v.22, p.263-266.

Gardner, T., Verdonck, D., Pinter, N., Slingerland, R;, Furlong, K., Bullard, T., Wells, S., 1992, Quaternary uplift astride the aseimic Cocos Ridge, Costa Rica, *Geologic Society of America*, v. 104, p.219-232.

La Joie, Kenneth, 1986, Coastal Tectonics, *in* Wallace, R.E., *Active Tectonics, Studies in Geophysics*, National Academy Press, Washington D.C., p.95-124.

Merritts, D. and Bull, Wl, 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

Erin R. Kraal
Department of Geology, Washington and Lee University, Lexington, VA 25540
Faculty Sponsor: David Harbor, Washington and Lee University

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