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

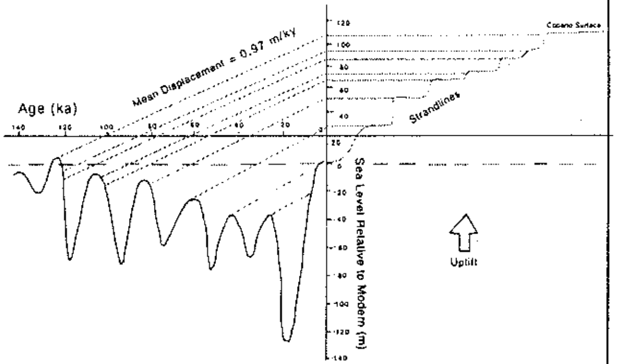
Stream profiles were surveyed with a pocket transit and hip chain. Each stream crosses the abandoned Holocene marine platforms and rises onto the uplifted Cobano surface, lithology from Gardner, this volume, Fig. 3. Associated stream terraces and marine terraces were connected to the profile using a 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

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 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.

	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

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 log 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.

Knickpoint Shape. KP morpology 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 and 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 drop, 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

Burbank, Douglas W.; Leland, John; Fielding, Eric; Anderson, Robert S.; Brozovic, Nicholas; Reid, Mary R.; Duncan, Christopher, 1996, Bedrock incision, rock uplift and threshold hillslopes in the northwestern Himalayas, Nature, v. 379, p. 505-510.

Hills, E. S., 1972, Shore platforms and wave ramps: Geological Magazine, v. 109, p. 81-88.

Marshall, J.S., 1991, Neotectonics of the Nicoya Penisula, Costa Rica: A Look at Forearc Response to Subduction at the Middle America Trench, [M.S.Thesis]: Santa Cruz, California, University of California, 196 p.

Marshall, J. S. and Anderson, R. S., 1995, Quaternary uplift and seismic cycle deformation, Penisula de Nicoya, Costa Rica, v. 107, p. 463-473.

Table 1	Lejas	Cocal	Palmiche
Distance from Cabo Blanco (km)	4.5	8	11
Total length (km)	30	3.5	0.9
Drainage area (km2)	21	1.6	0.5
Discharge (m3/s)	2.7	0.2	6.0E-03
Slope of surveyed section	9.0E-03	0.07	0.04

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 togographic maps.

Table 2	**S1**	**S2**	**C1**	**C2**	**P1**
Distance intertidal pool to base of KP (m)	136	452	147	187	18
Horizontal distance from inner edge (m)	198.6	264.0	43.3	21.3	30.2
Vertical distance from inner edge (m)	1.700	2.395	1.620	2.110	0.695
Age of abandonment of inner edge (YPB)	378	808	2400	4400-5200	2400
Height (m)	3.00	--	1.29	1.54	0.215
Length (m)	218.5	--	17.6	4.9	1.9
Length:Height ratio	72.8	--	13.6	3.2	8.8
Vertical incision rate (mm/yr)	4.5	3	0.7	0.5-0.4	0.3
Horizontal retreat rate (m/yr)	0.525	0.327	0.018	0.005-0.004	0.013
Vertical rate/drainage area (mm/yr/km2)	0.2	0.1	0.4	0.3	0.6
Horizontal rate/drainage area (m/yr/km2)	0.02	0.02	0.01	0.003	0.03

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.

Fig. 1

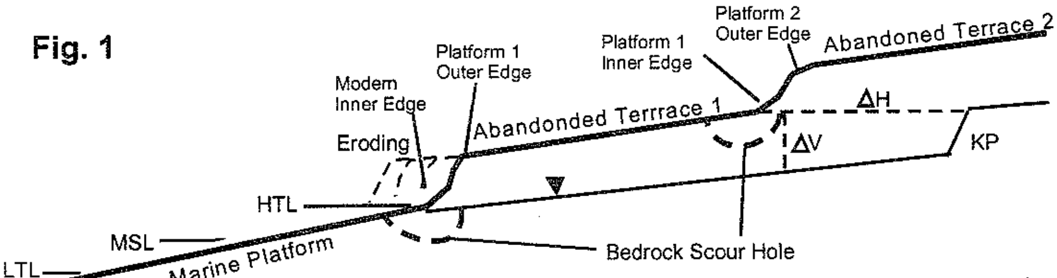
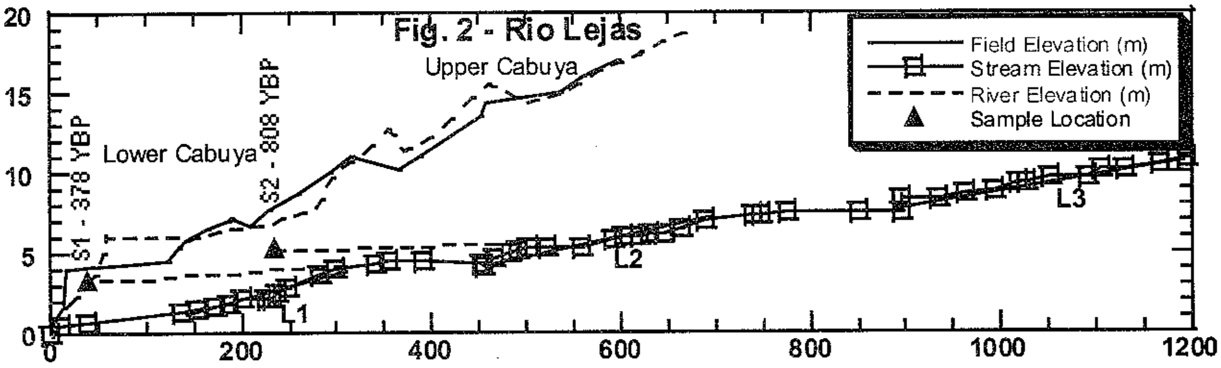
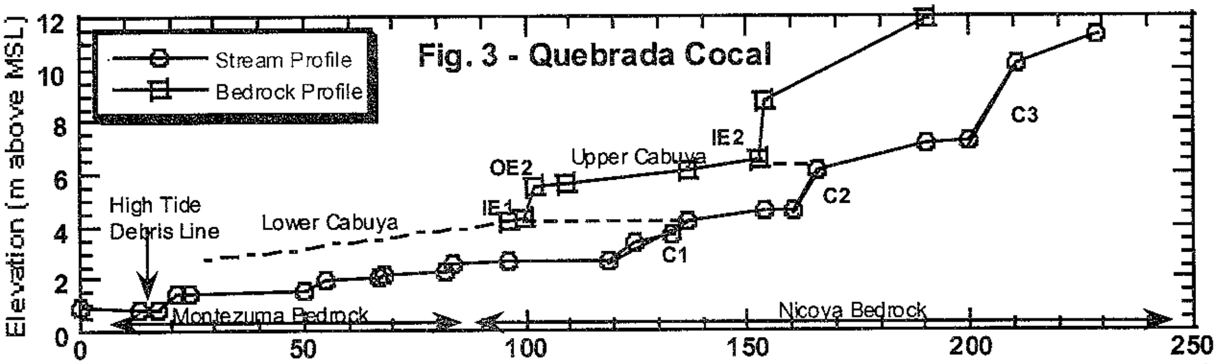


Figure 1 - illustrates the relationship between the stream profile, actively forming platform, stream knickpoints, and abandoned terraces.





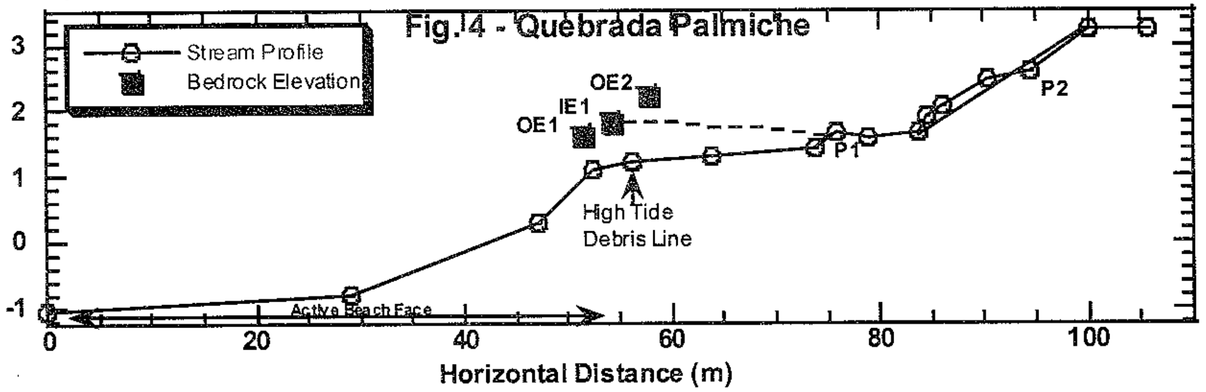


Figure 2 – Rio Lejas stream and terrace profile. Notation as follows KP's (L1, L2, & L3) and radiocarbon dated shell samples (S1 & S2). Field and river bank profiles were surveyed adjacent to the river (Bee, this volume).
Figure 3 – Quebrada Cocal stream and marine terrace risers. KP's are labelled C1, 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 MalPaís sandstones of the Península de Nicoya, Costa Rica

Alexandra E. Krull
Dept. of Geology, Pomona College, Claremont, CA 91711
Faculty Sponsor: Linda Reinen

INTRODUCTION

The Pacific coast of the Península 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 is 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 MalPaís sandstone. It records a deformational history from just over 20 Ma. This is exposed along the Pacific coast from approximately 2km north of Cabo Blanco to 2 km north of Santa Teresa (Gardner, this volume, Figure 3). Three subunits of the MalPaís sandstones have been noted my *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 Península 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-smooth 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 MalPaís sandstones. All data were collected on faults in the Miocene silt and sandstones of the MalPaís 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 MalPaís 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