Fault kinematics in the MalPaís sandstones of the Península de Nicoya, Costa Rica

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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

Fig. 1

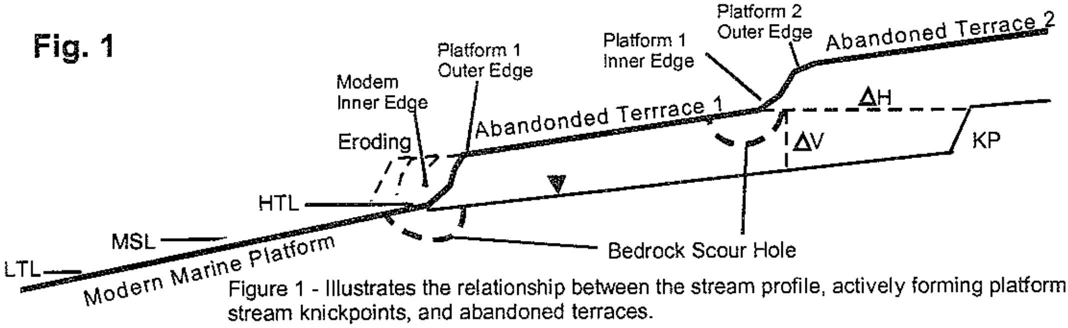
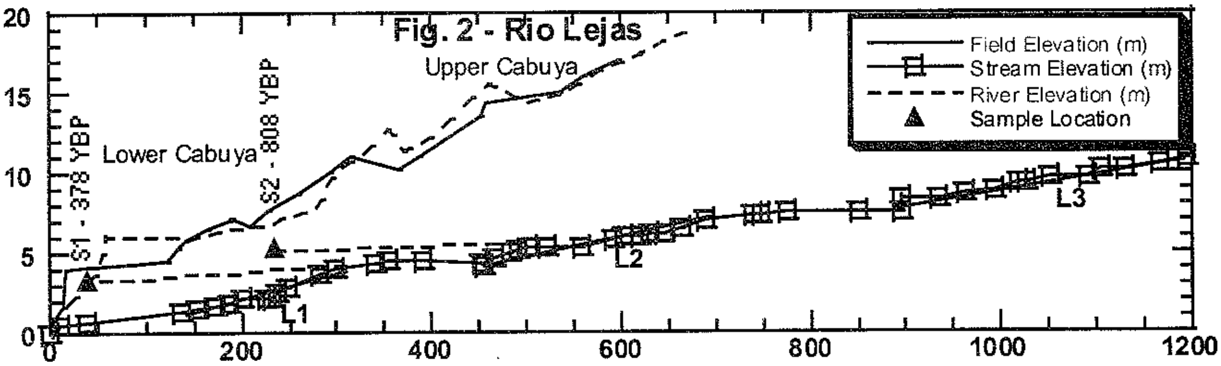
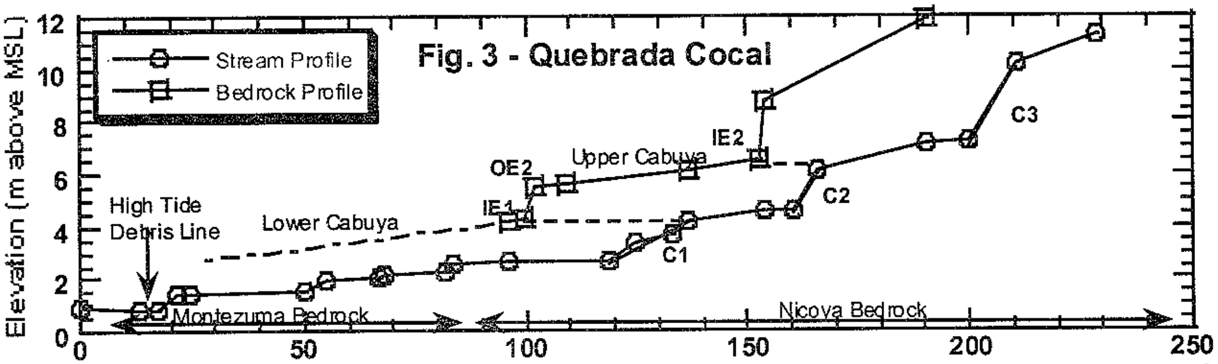


Figure 1 - Illustrates the relationship between the stream profile, actively forming platform, stream knickpoints, and abandoned terraces.





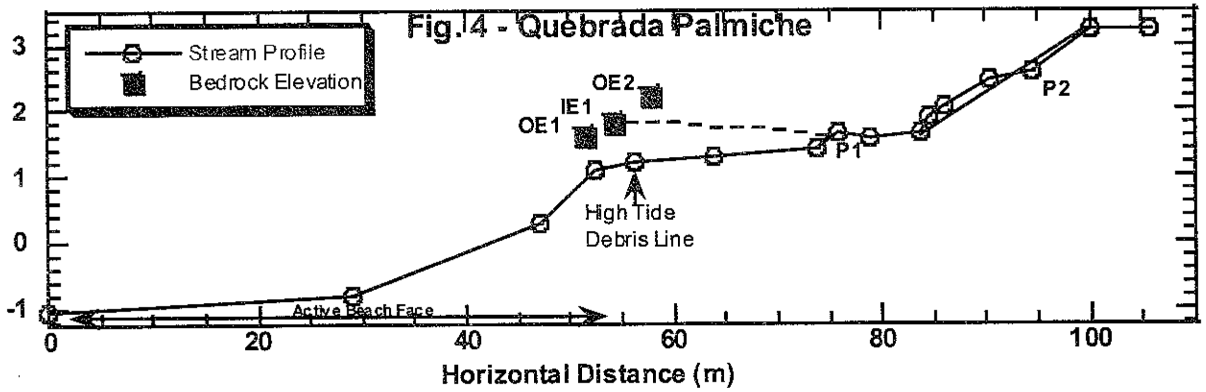


Figure 2 – Rio Lejas stream and terrace profile. Notation as follows KP's (L1, L2, & L3) and radiocarbon dated shell samples (S1 & S2). Field and river bank profiles were surveyed adjacent to the river (Bee, this volume).
Figure 3 – Quebrada Cocal stream and marine terrace risers. KP's are labelled C1,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

sandstone, with a large number of benthic foraminiferas, possibly indicating that this was an ancient turbidite flow. Faults within this region are well defined and bedding is coherent throughout with fairly gentile synclines and anticlines. The Barrigona subunit shows laminar cross-bedding and is a slightly more bluish-gray. *Mora* [1985] described evidence of bioturbation, with an abundance of mollusks and large foraminiferas in this subunit, though I saw no fossil material within this subunit at all. The region appeared to have a great deal of soft-sediment flow, which may have been what *Mora* [1985] described as bioturbation. Nearly all faults were soft-sediment faults and there were no apparent bedding planes. The Sta. Teresa shows primarily trough cross-bedding of sandstone beds including lithoclasts and bioclasts and appears slightly purple in hand sample. One exposure within this subunit is incoherent, showing no clear bedding planes and no obvious fault planes. The contact between the coherent and incoherent bedding is roughly N80E, 80SE, with the downdrop block towards the coast. At the far north end of the field site, fault planes could once again be seen and measured on seastacks, which provided three dimensions by which to measure the faults.

FAULT DATA

Two main types of faults were noted within the field area. The first is a soft-sediment fault that formed before the rock had fully lithified. These faults often contain a darker gouge-like layer that is not always visible in thin section. In some of the soft-sediment faults this layer does display cataclasis, and in others there is very little difference between this layer and the host rock. The soft-sediment faults also commonly appear in zones of parallel faults. All other faults have formed since lithification. These include normal and strike-slip faults. A few reverse and calcite filled extensional fractures were seen, but reverse faults only comprised 2% of the total faults measured and the extensional fractures comprise only 5%. By far the most predominant were the extensional faults, and there was a relatively equal proportion of right- and left-lateral faulting. Figures 1 and 2 are examples of normal and soft-sediment faults.

The orientation of the faulting shows a few trends. Most faults strike N60E, N20E or due north, with very steep to vertical dips. In the northern sites, the faults trend more westward, still maintaining steep dips. Below is a chart of average fault orientations:

Site	Strike-slip	Normal	Soft sediment	N=
1	N60E; N5E; N30W; N20E		N50W	42
2	N60E	N30E 50SE		11
3		N72E 60NW; N18E 60SE		7
4	N60E	N80W 70SW; N20E 70SE		22
5	N65E; N3W		N10E; N15E	5
6	N30W; N50W; N30E;		N70W; N39W 80SW	14
7	N8E	N45W 50NE; N8W 70 SW		32
8	N10E	N35W 50SW		17
10		N15W 70SW; N50E 80SE		12
11	No common trends			10

Table 1: Average orientations of faults at each of the field sites. Sites 1-5 are located at the southern end of the field area between MalPaís and Punta Barrigona and sites 6-11 are north of Santa Teresa. Site 9 contained no measurable faults. Sites 12 and 13 are located between sites 5 and 6 and contain very little data. All strikes in the strike-slip column have no dip values because all have vertical (90°) dips. N is the total number of faults measured within the area.

Stereonets for the faults at the southernmost site within the field area and a site at the northern end are shown in figures 3 and 4. In each of these stereonets, the poles to the fault planes are plotted to show the clustering of faults. In the southern site, fault poles are clustered in the northwestern and southeastern regions, and most are near vertical. In the northern site, there are more clusters of faults, with a greater range of strikes as well as dips.

DISCUSSION

The development of the deformation of the MalPaís sandstones along the Pacific coast of the Península de Nicoya can be broken down into at least two events, though it is likely there was a significant amount of activity in between. During deposition but before lithification, soft-sediment faulting occurred. This suggests an unstable depositional environment. These faults do not show any common orientations within the field area, but all lay parallel to the general trend of the shoreline at the individual site. This may indicate that the sediments where these soft-sediment faults are common may have undergone post-depositional slumping or been deposited in a turbidity current. The benthic foraminifera found in thin section also implies that these may be turbidite deposits.

Following lithification of the sediments, tectonics played a larger role in the deformation of the rock. The southern end appears to have undergone at least two more faulting events. The most recent event is seen in the conjugate set oriented N60E and approximately due north, indicating that the primary compressive stress is roughly trench perpendicular. Three conjugate sets in this orientation were observed, and none were cut by any other faults. The other faults seen in these orientations were also strike-slip, with a majority of them striking N60E. Roughly half of them left lateral and the other half right lateral. This may be explained by left-lateral faulting occurring in the compressional environment, and later during a period of extension, some of the faults were reactivated as right lateral. Cross-cut by these faults are a set of normal faults, mostly striking N20E and dipping steeply to the southeast. This illustrates an earlier extensional environment.

The north end has significantly more fault sets, and they are also not as clearly defined into clusters. There is a larger distribution of fault orientations, so may have undergone more changes in the tectonic history. As in the south, they show periods of extension and compression, though in different orientations. The strike-slip faults are closer to N10E, and there are several sets of normal faults.

Finally, the contact between the coherent and incoherent bedding appears to be fairly recent, as there is little to no faulting within the incoherent beds and no through-going features across the contact. This may have been caused by later slumping, and the contact is the headwall of the slump.

CONCLUSIONS

The deformation of the MalPaís sandstone since the Miocene that can be seen today was probably caused by a depositional environment of slumping and/or turbidity currents, bioturbation and tectonics from the subduction of the Cocos Plate beneath the Caribbean Plate. Before lithification, slumping caused soft sediment faulting throughout the region. After lithification, the predominance of normal faults strongly suggests that extension from seafloor topography has led to a flexure of the land, and it is expressed differently in the north and in the south. Finally, compression from the subduction of the plate followed, with some extension possibly following reactivating existing fault planes.

Because the subunits of the MalPaís were deposited at different times, it is difficult to make any correlation through time throughout the field area. Therefore, I cannot relate deformation to the movement of the triple junction.

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I'd like to thank Tom Gardner, Ed Beutner, Linda Reinen, and Don Zenger for all of their help throughout the project. I'd also like to thank Carrie Elliot for her help teaching me how to use all the machines for thin sections.

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Figure 1: Image of a normal fault. Field book for scale.

Figure 2: Image of soft-sedimentary faults. Faults are the gray bands running horizontally across the image. Hammer for scale.

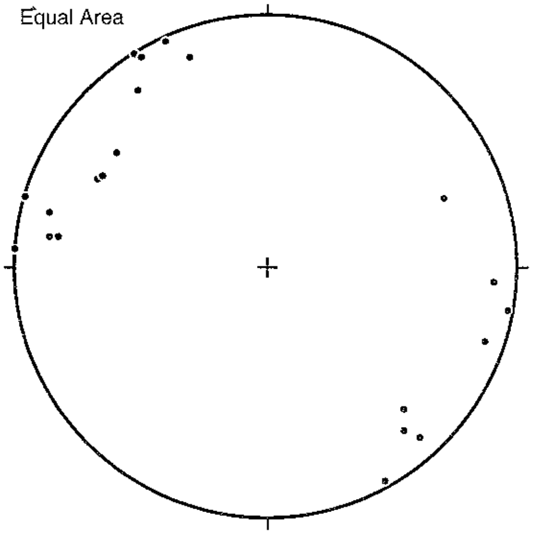

Figure 3: Stereonet plot of the poles to the fault planes at site 1, which is located at the southernmost tip of the field area. Note the clustering of points around the northwestern and southeastern regions.

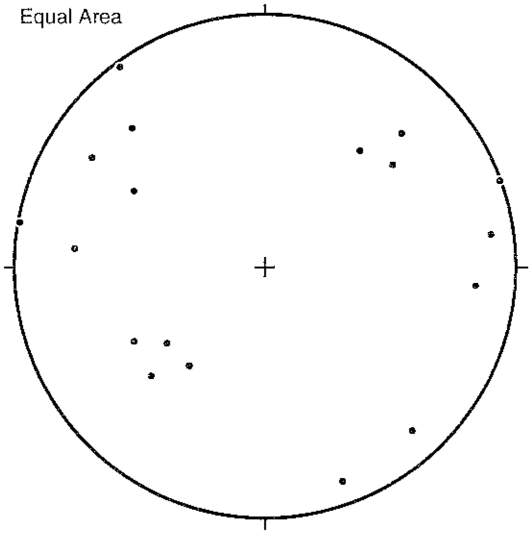

Figure 4: Stereonet plot of the poles to the fault planes at site 7, near the northern end of the field area, just south of the coherent/incoherent boundary. Note there are several clusters of points illustrating the more diverse range of fault orientations in the north.

Faults and folds in the Cabo Blanco Formation, Peninsula de Nicoya, Costa Rica

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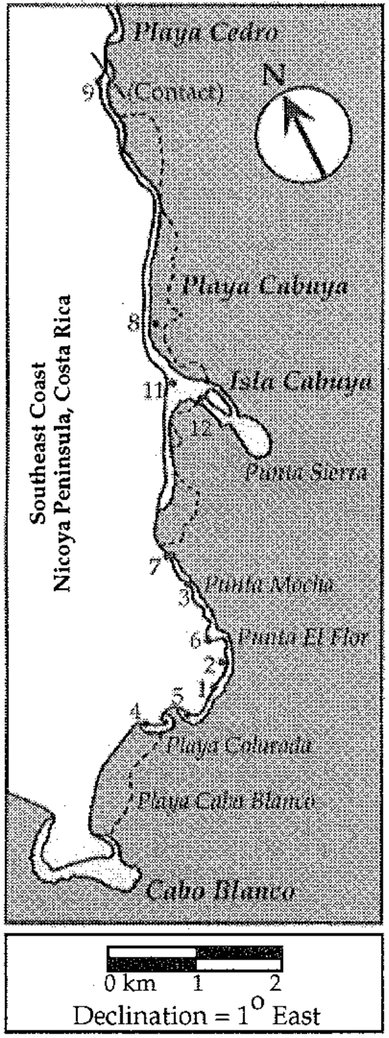
PURPOSE

The Cabo Blanco Formation is a sedimentary unit of interbedded deep water marine, hemipelagic mudstones and fine grained terrigenous turbidites deposited from Paleocene to lower Eocene times. Crustal uplift has exposed the Cabo Blanco on marine terraces along the southeastern shore of the Peninsula de Nicoya , Costa Rica (Figure 1). Faults and folds exposed on the terraces and in adjacent sea cliffs record the deformational history of this unit. The purpose of this project was to unravel the deformational history and to develop an explanation for deformation of the Cabo Blanco Formation. Understanding the strains involved in producing these faults and folds will provide insight as to the interactions between the Cocos and Caribbean plates that have affected the Cabo Blanco since Paleocene times.

Figure 1: Location map.



TECTONIC SETTING

The Middle American Trench (MAT) strikes about N50W and lies nearly 70 km southwest of the Peninsula de Nicoya. At the MAT the Cocos plate is subducting below the Caribbean plate at a rate of approximately ~9 cm/yr. Convergence between these plates along an azimuth of N29E (Lundberg, 1982) indicates subduction is slightly oblique. The time at which subduction initiated along the MAT remains uncertain, and is part of a larger dispute over the tectonic history of the entire Caribbean region. The presence of volcanic rocks and volcaniclastic sediments of late Cretaceous age landward of the trench suggests that subduction began between 60 to 70 Ma (Lundberg, 1982: McIntosh, 1993). However, it has also been postulated that present MAT subduction initiated as late as the Oligocene, forming the Talamanca volcanic belt (de Boer, 1979). Trench-related compression has caused the Caribbean crust to warp as a broad anticline, uplifting the forearc. Regional uplift began during the Paleogene and has remained active during Quaternary times (Lundberg, 1982; Gardner et al., 1992). The initial age of MAT subduction is important for distinguishing the origin of the sediments that comprised the Cabo Blanco turbidites. Assuming that subduction began prior to the deposition of the Cabo Blanco sediments, this unit can be restricted to the parautochtonous landward slope along the Caribbean margin. However, if subduction initiated following the deposition of sediments, the source and site of initial deposition is less constrained relative to the trench.

METHODS

Field observations included measuring and classifying faults, folds, and bedding at 11 separate localities. All measurements were made using a Brunton compass. Fault orientations, striations and sense-of-slip, cross-cutting relationships, and character of fill were determined. Axial surfaces were determined from combining hingeline and axial trace measurements on folds. Sense of rotation was also determined. Stereonet and Faultkin were used to plot fault and fold sets and to make location comparisons. Hand samples were collected and prepared for thin-section analysis. Samples were appropriately cut and observed for evidence of microstructural deformation and composition.