The Geomorphic Footprint of Megathrust Earthquakes:
A Field Investigation of Convergent Margin Morphotectonics,
Nicoya Peninsula, Costa Rica

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A Proposal for a 2013-2014 Keck Geology Consortium Research Project

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Project Details:
Number of students: 9
Approximate dates: June 24 – July 20, 2013
Locations:
1) Nicoya Peninsula, Costa Rica
2) Observatorio Volcanológico y Sismológico de Costa Rica (OVSICORI), Universidad Nacional (UNA), Heredia, Costa Rica.

Introduction:
We are proposing a 9-student Keck project to investigate the morphotectonic footprint of earthquake-generated uplift on the Nicoya Peninsula, Costa Rica. This project is designed to expand upon preliminary geomorphic, geodetic, and seismologic data showing patterns of coseismic rupture and coastal uplift generated by the recent Mw7.6 Nicoya earthquake of 5 September 2012 (NSF Rapid Earthquake Response Team, unpublished data). Project students will build upon several decades of prior research on subduction generated coastal uplift on the Nicoya Peninsula (e.g., Marshall et al., 2012), including a highly successful 1998 Keck project (Gardner et al., 2001). Project faculty members have substantial experience researching this problem and supervising student fieldwork in this region (see Marshall et al., 2009 for details). The participating students will conduct fieldwork on the Nicoya Peninsula, learning research techniques of tectonic geomorphology, paleoseismology, and GPS geodesy. Following fieldwork, the students will process project data and samples at the Costa Rican Volcanologic and Seismologic Observatory (OVSICORI). The project will conclude with student presentations of preliminary data during a mini-research symposium at the Universidad Nacional campus.
Figure 1. Digital elevation model of Central America and seafloor of the Cocos, Nazca, and Caribbean plates (IFM-GEOMAR). The Middle America Trench marks the convergent margin where the Cocos Plate subducts northeastward at 8-10 cm/yr beneath the Caribbean Plate and Central America volcanic arc. This image reveals a sharp contrast on the Cocos Plate between smooth seafloor formed at the East Pacific Rise (EPR) and rough, hotspot-thickened seafloor formed at the Cocos-Nazca spreading center (CNS). This boundary intersects the Middle America Trench offshore of Costa Rica's Nicoya Peninsula. Rectangle outlines area of Fig. 2.

Tectonic Background and Project Impetus:

Megathrust earthquakes along subduction zones are among Earth's most powerful and deadly natural hazards. During the past decade alone, more than a quarter-million people have lost their lives to megathrust earthquakes and tsunami in Sumatra (2004, M9.3), Chile (2010, M8.8), and Japan (2011, M9.0) (e.g., Lay et al., 2005; Ando et al., 2011). Such catastrophic events are also notable for sudden geomorphic changes that they bring to coastlines through either coseismic uplift or subsidence (e.g., Plafker, 1972). Sudden earthquake-induced changes in land level result in either emergence or submergence of the coast, shifting the relative position of the shoreline, and all subsequent tides. Evidence of past events is often preserved in the sedimentary record of beaches and coastal wetlands, and by such features as emerged tidal platforms and coral heads (e.g., Atwater, 1987; Taylor et al., 1987; Nelson, 1996; Natawidjaja, 2006). Geomorphic and stratigraphic analysis of these features (coastal paleoseismology) is a powerful tool for unraveling the past earthquake history of convergent margin coastlines (e.g., Sieh, 2006; Satake and Atwater, 2006). In addition, understanding how earthquake induced changes in land level affect the long-term growth and decay of coastal topography is a fundamental question in the field of tectonic geomorphology (e.g., Bull, 1985; LaJoie, 1986).

An excellent place to study these processes is the Nicoya Peninsula on the Pacific coast of Costa Rica, Central America (Figs. 1-3). The Nicoya Peninsula is unique because it is one of the few landmasses along the Pacific Rim located directly above the seismogenic zone of a subduction megathrust fault. Due to its proximity to the subduction zone, the peninsula is particularly sensitive to vertical movements related to the earthquake cycle (Marshall and Anderson, 1995; Feng et al., 2012). Costa Rica is part of the Central American convergent plate margin, where the Cocos oceanic plate subducts beneath
the Caribbean plate at the Middle America Trench (von Huene et al., 2000). The two plates converge at a rapid rate (~9 cm/yr) along the Nicoya Peninsula (DeMets et al., 2010), resulting in a high seismic potential, as demonstrated by repeated large magnitude (>M 7.5) earthquakes over the past few centuries (Fig. 4), including events in 1853 (M≥7.5), 1900 (M≥7.5), 1950 (Ms=7.7), and 2012 (Mw=7.6).

Prior to this year (2012), the last major earthquake centered beneath the Nicoya Peninsula was the M7.7 event of 5 October 1950 (Protti et al., 2001). That earthquake killed and injured dozens of people, severely damaged buildings and roads, and produced landslides, liquefaction, and >1.0 m of coseismic uplift along the Nicoya coast (Marshall and Anderson, 1995). Based on geomorphic, seismologic, and geodetic studies over the past several decades (e.g., Nishenko, 1989; Marshall and Anderson, 1995; Gardner et al., 2001; Protti et al., 2001; Marshall et al., 2003-2012; Norabuena et al., 2004; Feng et al., 2012), the Nicoya Peninsula was recognized as a mature seismic gap, with a high probability of rupturing in the near future.

Figure 2. Digital elevation model of southern Central America, showing NASA-SRTM topography for Nicaragua and Costa Rica linked to offshore IFM-GEOMAR multi-beam bathymetry (courtesy of C. Ranero, ICM-CSIC, Barcelona). This image reveals the relationship between the morphology of the subducting Cocos Plate and the morphotectonic structure of the overriding fore arc and volcanic arc of the Caribbean Plate and Panama block.
Figure 3. Digital elevation model of northern Costa Rica showing relationship of onshore topography (NASA-SRTM) and offshore bathymetry (IFM-GEOMAR). Two segment boundaries on the subducting Cocos Plate (Barckhausen et al., 2001) intersect the margin offshore of the Nicoya Peninsula: 1) a morphologic break between smooth and rough seafloor domains (thin dashed line); and 2) a fracture zone trace (thick dashed line) that divides crust formed at the East Pacific Rise (EPR) from that formed at the Cocos-Nazca spreading center (CNS-1 and CNS-2). The southern edge of the Nicoya Peninsula coincides with the Central Costa Rica deformed belt (red dashed line), a diffuse transpressional fault zone between the Caribbean Plate and Panama block inboard of the subducting Cocos Ridge (Marshall et al., 2000).

Figure 4. Geologic map of the Nicoya Peninsula showing boundaries of the Nicoya seismic gap (orange dashed lines), epicenters of large subduction earthquakes (red circles), and aftershock zones of the 1950, 1978, 1990, and 1992 events (red dashed lines). The 1990 and 1992 rupture limits coincide with the edges of the seismic gap. The last major rupture of the Nicoya segment (1950; M=7.7) produced 0.5-1.5 m of coseismic uplift along the central Nicoya coast. Most of this has been recovered by intersiesmic subsidence over the past six decades.
In 1950, the Nicoya coast was a sparsely populated frontier with dense rainforests and isolated rural villages. In recent years, however, this beautiful region has become an epicenter for rapid coastal development driven by Costa Rica's world-renowned tourism trade. Construction of hotels, condominiums, and vacation homes has proceeded with little heed for the lurking earthquake hazard. It has become critical, therefore, that geoscientists develop a clear understanding of the history and impacts of megathrust earthquakes along the Nicoya Peninsula, so that government officials and local residents can better prepare for the next “big one”.

The following story (from Marshall, 2008) provides a graphic account of one man's observations during the 1950 Nicoya Peninsula earthquake. His recollection of dramatic coastal changes is similar to those of other earthquake survivors recorded in a series of interviews 20 years ago (Marshall, 1991).

The sky dawned dark and cloudy on the morning of October 5th 1950. It was rainy season along the Pacific coast of Costa Rica's Nicoya Peninsula. In scattered coastal villages, farmers and ranchers gathered along the shoreline waiting for the cargo launch to arrive from the port city of Puntarenas. Their ox-carts were full of freshly harvested corn, ready for shipment to the mainland. Near the village of Garza, Don Daniel Ruiz Matarita was riding on horseback along the beach with several other men. The horses were skittish, and the nearby rainforest echoed with the roar of nervous howler monkeys. Suddenly, without warning, the ground heaved violently, trees and branches toppled over, and the beach exploded with geysers of water and sand. "Earthquake! We're done for!" shouted one of the men. Their horses bolted in terror, throwing the riders to the ground. Huge chunks of rock toppled off of nearby cliffs, crashing into the water with a tremendous splash. Certain they were doomed, the men prayed for salvation. When the great earthquake finally subsided, Don Daniel and his companions were amazed and thankful to be alive. As they stood up and looked around, they saw that the ocean curiously had withdrawn from the bay, leaving a wide expanse of barren rocks, seaweed, and flopping fish. Seizing the moment, the men snatched up handfuls of sea bass, content at least that their bellies would be full in this time of disaster. In the days following the earthquake, Don Daniel recalls that the sea did not return as they had expected. He heard stories from others that the same thing had happened all along the central Nicoya coast. Don Daniel remembers one place where the drop in sea level was particularly obvious, a rocky headland known to local fisherman as "La Raspa Nalgas" (The Butt Scratcher). Prior to the earthquake, it had been impossible to get around this rocky point on foot, as it was under water at even the lowest tides. But, after the quake one could walk around the headland without entering the water, indicating a drop in tidal levels near a grown man's height. Don Daniel recalls that it took nearly four decades for the ocean to reclaim its former level, quickly during the first few years, then slowly thereafter. High tides now reach further inland in many places than they did before the 1950 earthquake.

Such stories provide compelling evidence for abrupt coseismic uplift followed by gradual postseismic and interseismic subsidence. The return of tides to their pre-1950 levels indicates that the Nicoya Peninsula is locked and loaded for the next major earthquake. Similar movements have been observed along convergent margin coastlines worldwide. Famous examples in the geomorphic literature include Chile, Alaska, Japan, Cascadia, Vanuatu, and Indonesia (Plafker, 1972; Matsuda et al., 1978; Bull, 1985; LaJoie, 1986; Atwater, 1987; Taylor et al., 1987; Sieh, 2006). As the locked interface between two converging tectonic plates snaps free, the upper plate springs forward releasing stored elastic energy in the form of seismic waves (the earthquake). The seaward edge of the plate nearest the subduction trench rebounds upward, resulting in sudden coseismic uplift (and often a tsunami). In contrast, the landward region further from the trench subsides as strain is released. As the plates become locked again and elastic strain begins to build, gradual interseismic movements generally occur in the opposite direction (subsidence in the coseismic uplift zone and vice versa). This cycle of vertical motion in response to elastic strain accumulation and release is an integral part of the way subduction zones work, and is a dramatic manifestation of the forces that generate deadly megathrust earthquakes and tsunami.

An interesting question for geomorphologists is how this short-term cycle of elastic motion translates into longer-term permanent deformation that generates topographic relief. How much of the seismic cycle deformation is non-recoverable and permanent? Does coastal topography mirror earthquake cycle deformation patterns? Are earthquake rupture zones long-lived features or are they transient, changing
location and shape through time? What other processes contribute to the creation of permanent coastal topography along convergent margins?

Along the Nicoya Peninsula's seaward-facing coastline (Fig. 3), net Quaternary uplift is recorded by emergent marine terraces (ancient shorelines) and uplifted alluvial fill (ancient river deposits) (Hare and Gardner, 1985; Marshall and Anderson, 1995; Gardner et al., 2001; Marshall et al., 2001). Along the peninsula's landward-facing gulf coast, net subsidence results in drowned rivers and broad mangrove estuaries. Ongoing geomorphic, paleo-geodetic, and paleoseismic studies (e.g., Marshall et al., 2012) are revealing upper plate deformation patterns that provide important clues about seismogenic zone segmentation and the periodicity of megathrust earthquakes beneath the Nicoya Peninsula. Field mapping, surveying, and isotopic dating of uplifted paleo-shorelines, river deposits, and wetland sediments allows for calculation of Holocene and Pleistocene uplift rates. Preliminary results (Fig. 5; Marshall et al., 2007, 2008, 2010, 2011, 2012) indicate that sharp variations in uplift patterns on the Nicoya Peninsula coincide with three distinct domains of subducting seafloor identified through offshore geophysical studies. These seafloor segments (Fig. 3), designated EPR, CNS-1, and CNS-2, each originated at distinct oceanic spreading ridges and exhibit contrasts in crustal thickness, surface roughness, and heat flow. Such contrasts may exert important controls on seismogenic zone geometry, seismic coupling, and earthquake rupture behavior.

Figure 5a-c. a) Digital elevation model of Nicoya Peninsula (NASA-SRTM) showing areas of uplifted marine and fluvial terraces within late Pleistocene Iguanazu, Carrillo, Cobano, and La Mansion geomorphic surfaces (red areas); and Holocene Garza and Cabuya surfaces (yellow areas). Rectangles outline coastal study areas of Marshall et al., 2012. Dashed white lines mark prominent structural lineaments that form boundaries of 8 mountain blocks (A-G) with varying topographic relief (e.g., Hare and Gardner, 1985). b) Map of Nicoya Peninsula showing rupture area for 1950 M7.7 earthquake (Guendel, 1986) and model for locked slip on plate interface based on GPS velocity field shown by vectors (Norabuena et al., 2004). Note coincidence of
earthquake rupture zone, patch of maximum locking, and area of prominent topographic relief extending from block C to block F. c) Summary diagram showing uplifted coastal terrace elevations, age data, and uplift rates within each study area. Numbers in circles indicate specific study sites for Pleistocene and Holocene terraces. Terrace ages are based on sea level curve correlations and isotopic dates (OSL and 14C, as indicated). Differences in uplift rates for each study area reflect morphologic and thermal variations in the subducting Cocos plate seafloor across the EPR, CNS-1, and CNS-2 segment boundaries. The highest uplift rates occur within block G directly inboard of subducting Fisher seamount chain (Figs. 2 & 3). Outside of this area, the most rapid uplift occurs in blocks C-E inboard of locked patch and within 1950 and 2012 rupture zones (see Fig. 6 for 2012 rupture area). An abrupt decrease in uplift rate occurs northwest of the locked zone across the lineament separating blocks B and C. This suggests that the northwestern end of the peninsula may lie within a distinct segment of the plate margin.

The 2012 Nicoya Earthquake

On 5 September 2012, after 62 years of strain accumulation, a major megathrust earthquake (M$_w$=7.6) ruptured the Nicoya seismic gap. This large event was centered 12 km offshore of the central Nicoya coast, with a hypocentral depth of 18 km. Near the hypocenter, the maximum slip exceeded 2 m, and the rupture spread outward along the plate interface to encompass >3000 km$^2$ of the Nicoya seismogenic zone. More than 1700 aftershocks were recorded within the first 5 days (OVSICORI-UNA), outlining two distinct rupture patches, one centered on the central coast, and the other beneath the southern tip of the peninsula (Fig. 6).

![Figure 6 a-b. a.) Earthquake epicenter map and seismogenic zone profile for Costa Rica (by LIS-UCR) showing location of 2012 M$_w$=7.6 Nicoya earthquake (red circle) with respect to two years of prior seismicity (2010-2012). b.) Map of Nicoya Peninsula earthquakes for September 2012 (recorded by OVSICORI-UNA) showing distribution of aftershocks and triggered events (red dots) associated with the 5 September 2012 mainshock (blue star). Note two distinct rupture patches outlined by aftershocks beneath the central and southern portions of the peninsula.](image-url)
The 2012 Nicoya earthquake was felt throughout much of Central America and resulted in widespread damage ($45 million) to homes, public buildings, schools, and health centers in Costa Rica. As the result of intensive prior research and public outreach, Costa Rican citizens had substantial awareness of the seismic hazard associated with the Nicoya Peninsula. For this reason, the population reacted appropriately and the number of casualties was relatively low (no deaths and ~200 injured).

Following the 2012 Nicoya earthquake, an NSF rapid response team collected preliminary geomorphic and geodetic data to constrain patterns of coseismic deformation across the peninsula. Geomorphic spot measurements at a dozen field sites indicates that the earthquake produced 0.1 to 0.8 m of coseismic uplift along the central Nicoya coast (Fig. 7). Inversion modeling of preliminary GPS data from the OVSICORI geodetic network yielded consistent results (Fig. 8), showing maximum uplift adjacent to the earthquake epicenter and decaying outward with both coast parallel and coast perpendicular distance. Preliminary models based on seismic wave inversion (Fig. 9) show a bull's eye of maximum slip (>2m) adjacent to the hypocenter, surrounded by a broader area of decreasing slip across >3000 km² of the seismogenic zone beneath the central coast. This rupture pattern is roughly similar to the area of pre-earthquake locking suggested by GPS modeling (Fig. 8).

Figure 7 a-b. Pre & post-earthquake photographs of high tide at Playa Carrillo estuary, showing the magnitude of 5 September 2012 coseismic uplift directly inland of earthquake epicenter: a) July 5, 2012, 3:50 pm, +3.0m tide, b) Sept 13, 2012, 12:30 pm, +2.4m high tide. The tide pictured at left was the highest tide for the 2 months preceding the earthquake. Note the coconut debris line left by this tide still visible in the post-earthquake photo at right. While the pre-earthquake high tide at left is 0.6m higher than the post-earthquake high tide at right, the surveyed difference in these tidal levels is ~1.4m, indicating uplift of ~0.8m (Marshall et al., unpublished data).
Figure 8 a-b. a.) Map of Nicoya GPS network (from Feng et al., 2012) showing continuous stations (yellow circle) and campaign sites (red diamonds). Blue vectors show horizontal velocities relative to stable Caribbean plate between 1996 and 2010. 2-D 2s error ellipses represent 86.5% confidence. b.) Preliminary rapid GPS solution for continuous stations showing horizontal (black) and vertical (blue) displacement vectors for the 5 September 2012 Mw 7.6 Nicoya earthquake (solution by JPL, based on data from OVSICORI-UNA). Red beach ball shows preliminary focal mechanism for mainshock. Contoured colors show modeled distribution of pre-earthquake locking on megathrust fault.

Figure 9. Map of the Nicoya Peninsula with preliminary dislocation model (based on seismic wave inversion) showing slip distribution for the 5 September 2012 Mw 7.6 Nicoya earthquake (by Laboratorio de Ingeniería Sismica, Universidad de Costa Rica [UCR-LIS]). Colored contours (key at right) show variable slip decaying from a maximum of >2m near the hypocenter. Area of maximum slip corresponds with area of greatest observed coseismic uplift along the coastline (both geomorphic and GPS data).
**Proposed Keck Project:**

Ongoing geomorphic field research on the Nicoya Peninsula is revealing patterns of both short-term elastic seismic cycle motions, as well as long-term net morphotectonic deformation associated with subduction (e.g., Fig. 5, Marshall et al., 2012). This research, in conjunction with instrumental seismology, geodesy, and marine geophysical studies (see NSF MARGINS website), is helping to advance our understanding of megathrust earthquake processes and seismic hazards along the Nicoya Peninsula convergent margin. While the recollections of older residents like Don Daniel Ruíz Matarita provide us with a dramatic window into the human experience of major Nicoya earthquakes, geoscientists are now helping elucidate a scientific picture of the natural forces behind such events. The recent 2012 Nicoya earthquake provides an unprecedented opportunity to advance our understanding of earthquake processes and their impacts on the geology and geomorphology of this active convergent margin.

The Keck research project proposed here will build upon preliminary post-earthquake field studies by filling critical data gaps, addressing key questions about how earthquake-generated uplift impacts coastal geomorphology, and investigating how seismic cycle motions contribute to net deformation and topographic growth. Project students will gain valuable professional experience applying modern field techniques of coastal geomorphology, paleo-seismology, and GPS geodesy. Their efforts and research results will contribute to the growing body of scientific knowledge on convergent margin morphotectonics. Project results will be compiled and incorporated into student co-authored professional presentations and publications.

**Hypothesis to be Tested and its Significance:**

We hypothesize that megathrust earthquakes along the Nicoya convergent margin leave a characteristic geomorphic footprint on the coastal landscape. Earthquake induced changes in land level (coseismic uplift and interseismic subsidence) shift the relative position of the shoreline, producing distinctive morphologic changes that can be observed and measured in the field. We further hypothesize that the magnitude and pattern of seismic cycle deformation is related to the earthquake rupture geometry and slip distribution, which is in turn controlled by subduction zone characteristics such as convergence rate, obliquity, slab dip, plate roughness, heat flow, and fluid flux.

The proposed research will address fundamental questions on the morphotectonics of convergent plate margins and the segmentation of megathrust earthquake rupture zones. Key questions related to our hypotheses include: How do short-term elastic seismic cycle displacements translate into longer-term permanent deformation that generates topographic relief? How much of seismic cycle deformation is non-recoverable and permanent? Does coastal topography mirror earthquake cycle deformation patterns? Are earthquake rupture zones long-lived features or are they transient, changing location and shape through time? What other processes contribute to the creation of permanent coastal topography along convergent margins? How do variations in uplift patterns relate to along-strike differences in subducting plate age, roughness, and thickness that control seismogenic zone segmentation?

**Project Teaching and Learning Goals:**

The Costa Rica project will combine research techniques of tectonic geomorphology, paleoseismology, and geodesy to characterize the earthquake history and patterns of seismic cycle deformation on Costa Rica’s Nicoya Peninsula.

- **Fieldwork.** Student researchers will gain substantial experience in conducting geologic/geomorphic field studies. Particular skills include:
  1) developing research strategies and planning fieldwork
  2) preparing base maps and reviewing aerial photography
  3) conducting fieldwork and recording observations/data in notes and digital photographs
  4) field mapping of outcrops, landforms, and deposits on base maps and air photos
  5) locating field sites and topographic surveying using Brunton compass, hand-held GPS, laser range finder, barometric altimeter, hand level, tape measure, and stadia rod
6) measuring and describing stratigraphic columns and soil profiles
7) collecting, describing, and archiving field samples (rocks, fossils, sediment cores) for hand
inspection, thin section analysis, and isotopic age dating (e.g., 14C, OSL, CRN)

**Sample preparation and lab analysis.** The students will also learn how to prepare field samples for
age dating, petrographic, and geochemical analysis. Particular skills included:
1) preparing sample databases in Excel software
2) selecting, cutting, and packing samples for shipping to geochronology labs
3) selecting, cutting, and packing thin section blanks for shipping to thin section lab

**Data analysis and figure drafting.** The students will also gain substantial experience in analyzing
and interpreting field data, and in producing maps, figures, and illustrations. Particular skills included:
1) generating topographic base maps and DEM from digital data using ArcGIS software
2) drafting geologic/geomorphic maps of study sites using Adobe Illustrator software
3) processing raw topographic survey data using Excel spreadsheets and tide tables
4) drafting topographic profiles from survey data using Excel and Kaleidagraph software
5) cataloging digital field photographs and selecting representative study site photos

**Presentation of research results.** The students will also develop presentation skills through talks and
posters (mini-project symposium at OVSICORI, Annual Keck Symposium, and other professional
conferences). Particular skills included:
1) interpreting field data and illustrations to arrive at focused conclusions
2) writing and submitting abstracts presenting project results
3) organizing research results & illustrations for effective poster & Powerpoint presentations
4) writing poster text and figure captions
5) designing and drafting final poster layout and printing on large format plotter
6) preparing Powerpoint slide presentations
8) presenting posters and Powerpoint talks at professional conferences, summarizing research results
to poster visitors and session audiences, answering questions and discussing significance of results

**Student Research Projects:**

Students will test the overarching hypothesis by completing one of the following geomorphic,
paleoseismic, or geodetic projects.

**Coseismic Coastal Uplift and Impacts on Beach Morphology (2 students)**

Preliminary geomorphic field measurements and GPS data indicate that the 2012 Nicoya earthquake
generated up to 1.2 m of coseismic uplift along the central Nicoya coastline (Marshall, Newman, and
Protti, unpublished data). Students working on this project will investigate this coastal uplift through
detailed site investigations, collecting additional geomorphic field data, and surveying coastal landforms
to further constrain the magnitude and pattern of uplift. Students will use laser range finders, barometric
altimeters, hand held GPS, and stadia rods to survey topographic profiles and measure uplift. Students
will also investigate the impacts of recent coseismic uplift on the morphology of beaches and rocky
shorelines by measuring uplift-related geomorphic changes, including modification of beach profiles,
stream incision, shifts in tidal levels, changes in wave erosion, and displacement of tidal ecozones (e.g.
mortality of sessile organisms).

**Coastal Wetland Stratigraphy and Paleoseismic Records (2 students)**

To investigate the history of paleo-earthquakes on the Nicoya Peninsula, students will use hand-
gouge augers to extract sediment cores from coastal wetlands. These cores will be examined for evidence
of previous coseismic land level changes (e.g. abrupt changes in grain size, soil color, etc.). A pilot
sediment coring study (Spotila et al., 2010) revealed compelling evidence of abrupt stratigraphic breaks,
consistent with coseismic uplift in several Nicoya wetlands. In this project, we will target additional
wetland sites for paleoseismic records in areas of known vertical motion during the 2012 earthquake. The
core stratigraphy will be measured, photographed, and described in detail. Organic samples will be
collected from cores for radiocarbon dating. In addition, students will document the impact of the recent coseismic uplift on wetland morphology and sedimentation. This will provide important reference data for interpreting stratigraphic evidence of past events.

**Geomorphology and Petrology of Uplifted Holocene Beachrock Horizons (2 students)**

To study Nicoya Peninsula coastal uplift, students will examine Holocene-age carbonate beachrock deposits, a common feature of tropical coastlines. These tabular horizons of lithified beach sediment extend laterally along the shoreline, creating a natural pavement similar to a concrete sidewalk. Beachrock forms by precipitation of carbonate cement (calcite and aragonite) within intergranular pore spaces of beach sediments in the groundwater excursion zone between high and low tide. These horizons form preferentially where groundwater is abundant near streams and wetlands. As earthquakes elevate the coastline, beachrock horizons are moved upward on the beach face and eventually into the landscape beyond. By surveying their current elevation above sea level and collecting samples for age dating, we will use beachrock horizons as timelines to track the history of net Holocene uplift. Students will survey beachrock outcrops using laser range finders, hand held GPS, and stadia rods. Sites will be photographed and described in detail, and samples will be collected for radiocarbon dating and thin section analysis.

**Geodetic Evaluation of Co-Seismic and Post-Seismic Deformation (3 students)**

The Costa Rican Volcanologic and Seismologic Observatory (OVSICORI-UNA) operates a dense network of 13 continuous GPS receivers on the Nicoya Peninsula (in collaboration with Georgia Tech University, University of South Florida, and U.C. Santa Cruz). In addition, there are more than 15 campaign GPS monuments located throughout the peninsula. Students will work under the direction of Dr. Marino Protti (Senior Research Geophysicist, OVSICORI) to install campaign GPS receivers, service continuous GPS stations, download data, and process/evaluate horizontal and vertical GPS motions to interpret seismotectonic deformation related to the 2012 Nicoya earthquake.

**Preferred student background:**

Students should be prepared for working in challenging field conditions. Fieldwork in a tropical setting requires astute observational skills, creative thinking, and an ability to work with limited geologic exposure. Demonstrated experience in field methods is strongly preferred. Students should have taken core courses in geomorphology, mineralogy/petrology, structural geology, and tectonics. Additional coursework in sedimentary geology, stratigraphy, geophysics, optical mineralogy, or GIS is desirable.

**Schedule:**

The tentative project dates are June 24 to July 20, 2013. The following schedule is proposed:

**Week 1 (June 24-30)**
- Travel to Costa Rica (Lodging at Hotel Valladolid, Heredia)
- Orientation meeting and introduction to project at OVSICORI-UNA in Heredia.
- Travel from Heredia to Playa Sámara, Nicoya Peninsula. (Lodging at Villas Kalimba)
- Introductory field trips to areas of coseismic coastal uplift, selection of student projects and field sites.
- Begin fieldwork (see next week for details)

**Week 2 (July 1-7)**
- Geomorphology teams conduct coastal fieldwork in maximum uplift zone: Islita-Carrillo-Sámara.
- Geodesy team conducts GPS campaign throughout peninsula.

**Week 3 (July 8-14)**
- Project group moves base of operations to Playa Nosara. (Lodging at Lagarta Lodge)
- Coastal fieldwork in additional areas of coseismic uplift: Garza-Nosara-San Juanillo.
- Continued GPS campaign throughout peninsula.

**Week 4 (July 15-20)**
- Geomorphology teams finalize coastal fieldwork in Garza-Nosara-San Juanillo area
- Geodesy team finalizes GPS campaign, downloads data from continuous GPS stations
- Travel from Nosara to Heredia (Lodging at Hotel Valladolid)
- Final 3 days at OVSICORI: Students compile and process project data and samples
• Students present preliminary results in Nicoya Project Mini-Symposium at OVSICORI
• Return travel to U.S.

**Logistics:**

*Travel to Costa Rica:* Participants will fly from U.S. airports to San José, Costa Rica (a popular tourist destination with many affordable flight options). Project faculty will meet arriving students and transport them to nearby hotel.

*Lodging and Meals:* Participants will stay at two reputable eco-tourist lodges used by the project director during prior Nicoya Peninsula fieldwork with students (see Marshall et al., 2009 for details). These hotels provide a safe and comfortable home base and easy access to field areas. Hotel owners have offered affordable group rates for blocks of rooms and group meals.

*Vehicles and Field Equipment:* Two 5 passenger SUVs (e.g., Mitsubishi Montero) will be rented at a discounted monthly rate from Dollar Rent-A-Car for the duration of the project. Protti has arranged for a third field vehicle from OVSICORI. Roads in the field area are both paved and unpaved, but all in good condition, providing easy access to field sites. The faculty’s home institutions will provide all necessary field equipment (e.g., maps, Bruntons, GPS, laser-range finders, survey gear, shovels, soil auger, sledges).

*Laboratories:* During the final days of the project, the students will compile and process field data and samples in the laboratories of OVSICORI, located on the campus of the Universidad Nacional (UNA) in Heredia (near the capital city San José). In the OVSICORI computer labs, the students will process GPS and topographic survey data, and generate data plots and maps. Samples collected for age dating will be prepped and shipped to the geochronology labs at Beta Analytic (14C) and the University of Cincinnati (CRN and OSL), both key collaborators on Marshall and Gardner’s prior Nicoya research.

**Safety:** The project director and faculty have substantial prior experience working with students on Costa Rica fieldwork (e.g., Marshall et al., 2009). All are aware of common field hazards and necessary safety precautions. Safety training will be a critical aspect of this project. Students will be instructed to be vigilant and aware of all potential hazards. Common field hazards include dehydration, heat exhaustion, sunburn, rugged terrain (cliffs, rocky shore platforms, streams/rivers), plants (thorny, sharp, or stinging shrubs/trees), and insects/animals (fire ants, wasps/bees, scorpions, mosquitoes, snakes, sting rays, angry monkeys). Students will always work in teams under the supervision of project faculty. Cell phones or radios will be used for communication. All participants will carry a Spanish language letter from OVSICORI explaining the purpose of fieldwork and requesting assistance if needed. Water and first-aid kits will be kept in field vehicles, along with maps and contact information for nearby emergency medical facilities. Only faculty will drive field vehicles and seat belt use will be enforced.

**Faculty Experience:**

**Jeff Marshall** is a Professor of Geological Sciences and University Coordinator for Undergraduate Research at Cal Poly Pomona. He is a geomorphologist with expertise in neotectonics, geologic hazards, and the geomorphology of rivers and coastlines. He has over 20 years experience investigating the morphotectonics of the Middle America convergent margin, including more than a decade of mentoring undergraduate field research on the Nicoya Peninsula (most recently a 3-year REU project funded by NSF MARGINS and the Kellogg Foundation). Dr. Marshall studied geology and earth surface processes at UC Santa Barbara (BS), UC Santa Cruz (MS), and Penn State (PhD). Prior to joining Cal Poly’s faculty in 2001, Marshall was a visiting instructor/assistant professor for 3 years at Franklin & Marshall College, where he gained substantial experience working with the Keck Geology Consortium.

Marshall’s Prior Keck Geology Consortium Experience:

*Project Faculty* – Nicoya Peninsula, Costa Rica Coastal Tectonics Project (1998-99)
*Workshop Faculty* – Workshop for Costa Rica Tectonics Project, Trinity University (1999)
*Participant* – Keck Geology Consortium Annual Symposium, Carleton College (1999)
*Faculty Sponsor/Site Visitor* – Florida Barrier Islands Project (1999-2000)
Tom Gardner is a Professor of Geosciences at Trinity University, San Antonio, Texas. He is a geomorphologist with expertise in active tectonics, stratigraphy, fluvial geomorphology, and coastal processes. He has over 30 years experience researching active tectonics and supervising student fieldwork in Central America, including directing Keck projects in Costa Rica (1998) and Panama (2010). Dr. Gardner studied geology and geomorphology at Franklin & Marshall College (BS), Colorado State (MS), and University of Cincinnati (PhD). Prior to his appointment at Trinity as the Herndon Distinguished Professor of Geology, Gardner was a Professor in the Geosciences Department at Penn State University.

Gardner's Prior Keck Geology Consortium Experience:
- **Project Faculty** – Wyoming Geology Project (1996-97)
- **Participant** – Keck Geology Consortium Annual Symposium, College of Wooster (1997)
- **Project Faculty** – Shenandoah Valley Geomorphology Project (1997-98)
- **Participant** – Keck Geology Consortium Annual Symposium, Amherst College (1998)
- **Project Director** – Nicoya Peninsula, Costa Rica Coastal Tectonics Project (1998-99)
- **Participant** – Keck Geology Consortium Annual Symposium, Carleton College (1999)
- **Project Faculty** – San Andreas Fault Neotectonics Project (1999-2000)
- **Participant** – Keck Geology Consortium Annual Symposium, Whitman College (2000)
- **Project Faculty** – Minnesota Watershed Project (2000-01)
- **Project Faculty** – Keck Geology Consortium Annual Symposium, NASA Goddard Center (2001)
- **Project Director** – Australia Coastal Tectonics Project (2002-03)
- **Participant** – Keck Geology Consortium Annual Symposium, Beloit College (2003)
- **Project Director** – Panama Volcano Geomorphology Project (2010-11)
- **Participant** – Keck Geology Consortium Annual Symposium, Union College (2011)

Marino Protti is a Research Geophysicist with the Observatorio Volcanológico y Sismológico de Costa Rica, Universidad Nacional (OVSICORI-UNA). Dr. Protti is a seismologist and geodesist with expertise in subduction zone seismotectonics and instrumental monitoring of earthquake and volcanic hazards. He is the lead investigator in charge of the Nicoya Peninsula seismic and geodetic network, and is involved in public education and government advising on geologic hazards in Costa Rica. Dr. Protti studied geology and geophysics at the Universidad de Costa Rica (BS) and UC Santa Cruz (MS & PhD).

Protti's Prior Keck Geology Consortium Experience:
- **Project Faculty** – Nicoya Peninsula, Costa Rica Coastal Tectonics Project (1998-99)
- **Participant** – Keck Geology Consortium Annual Symposium, Carleton College (1999)
**References Cited:**


