

PROCEEDINGS OF THE TWENTY-SEVENTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

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**KECK GEOLOGY CONSORTIUM
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Keck Geology Consortium: Projects 2013-2014
Short Contributions— Earthquake Geomorphology, Costa Rica Project

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TOM GARDNER, Trinity University
MARINO PROTTI, Universidad Nacional de Costa Rica
SHAWN MORRISH, Cal Poly Pomona

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Research Advisor: David Harbor

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ANTHONY MURILLO GUTIÉRREZ, Universidad Nacional de Costa Rica (UNA)

Research Advisor: Marino Protti

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THE GEOMORPHIC FOOTPRINT OF MEGATHRUST EARTHQUAKES: MORPHOTECTONICS OF THE 2012 M_w 7.6 NICOYA EARTHQUAKE, COSTA RICA

JEFF MARSHALL, Cal Poly Pomona

TOM GARDNER, Trinity University

MARINO PROTTI, Universidad Nacional de Costa Rica

SHAWN MORRISH, Cal Poly Pomona

INTRODUCTION

Megathrust earthquakes along subduction zones are among Earth's most powerful and deadly natural hazards. During the past decade, more than a quarter-million people lost their lives to megathrust earthquakes and tsunamis in Sumatra ($M_{9.3}$, 2004), Chile ($M_{8.8}$, 2010), and Japan ($M_{9.0}$, 2011). Such catastrophic events are also notable for sudden geomorphic changes along coastlines caused by coseismic uplift or subsidence (e.g., Plafker, 1972; Atwater, 1987). 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 preserved in the sedimentary record of beaches and coastal wetlands, and by such features as emerged tidal platforms and coral reefs (e.g., Taylor et al., 1987; Nelson et al., 1996; Natawidjaja et al., 2006). Geomorphic and stratigraphic analysis of these landforms allows geoscientists to unravel the paleoseismic history of convergent margin coastlines (e.g., Sieh, 2006; Satake and Atwater, 2006), and to investigate how earthquake induced crustal displacements affect the long-term growth and decay of coastal topography (e.g., Bull, 1985; LaJoie, 1986; Sato and Matsuura, 1992; Marshall and Anderson, 1995; Rehak et al., 2008).

An excellent place to study these processes is the Nicoya Peninsula (Fig. 1) on the Pacific coast of Costa Rica, Central America (Marshall, 2007; Marshall, 2008). 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 megathrust fault. Due to its proximity to the fault, the peninsula is particularly sensitive to vertical movements related to the earthquake cycle (Marshall and Anderson, 1995; Feng et al., 2012; Protti et al., 2014). 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 (~ 8 cm/yr) along the Nicoya Peninsula (DeMets et al., 2010), resulting in a high seismic potential, as demonstrated by repeated large magnitude ($>M_{7.0}$) earthquakes over the past few centuries, including events in 1853 ($M_{\geq 7.0}$), 1900 ($M_{\sim 7.2}$), 1950 ($M_w 7.8$), and 2012 ($M_w 7.6$).

The objective of this Keck research project was to investigate the morphotectonic footprint of earthquake-generated uplift produced by the recent 2012 $M_w 7.6$ Nicoya Earthquake (Fig. 2). Our overarching hypothesis was that megathrust earthquakes along the Nicoya convergent margin leave a characteristic geomorphic signature on the coastal landscape. Earthquake induced changes in land

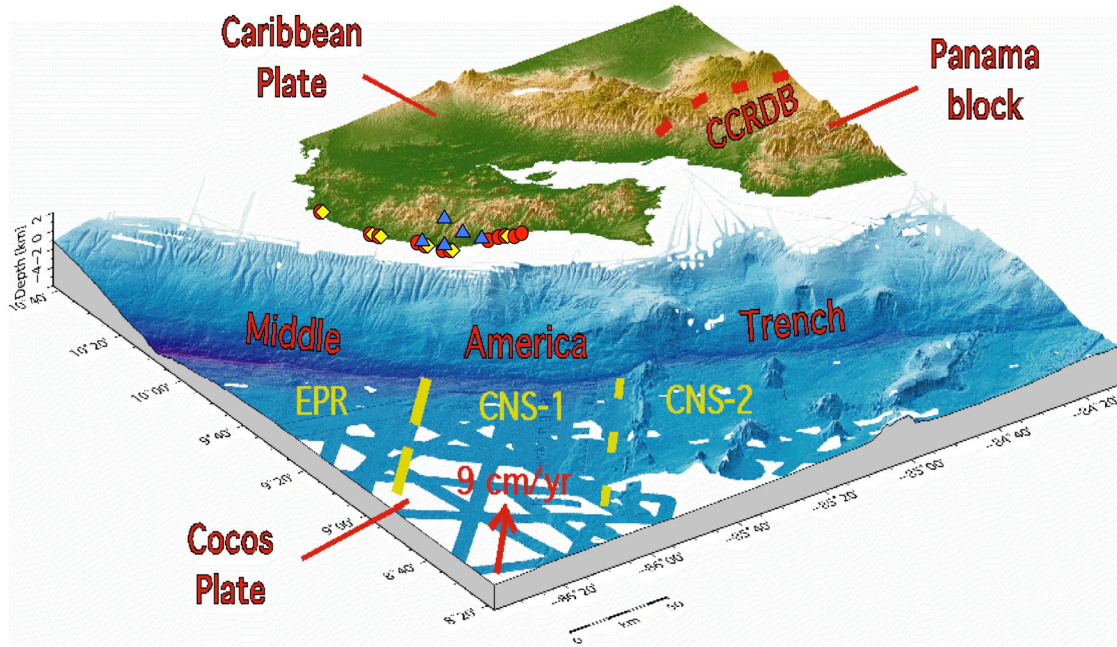


Figure 1. Morphotectonic setting of the Nicoya Peninsula along the northern Costa Rica convergent margin. Keck Project study sites are indicated for each of the three field teams: Coastal Uplift (red circles), Beachrock (yellow diamonds), and Geophysics (blue triangles). Three contrasting domains of subducting Cocos Plate seafloor intersect the margin offshore of the Nicoya Peninsula: 1) smooth, older crust (≥ 23 Ma) formed at the East Pacific Rise (EPR), 2) smooth, younger crust (23–19 Ma) formed at the Cocos-Nazca spreading center (CNS-1), and 3) rough, hotspot-thickened crust (≤ 19 Ma) formed at the Galapagos Hotspot (CNS-2). DEM data from IFM-GEOMAR and NASA-SRTM.

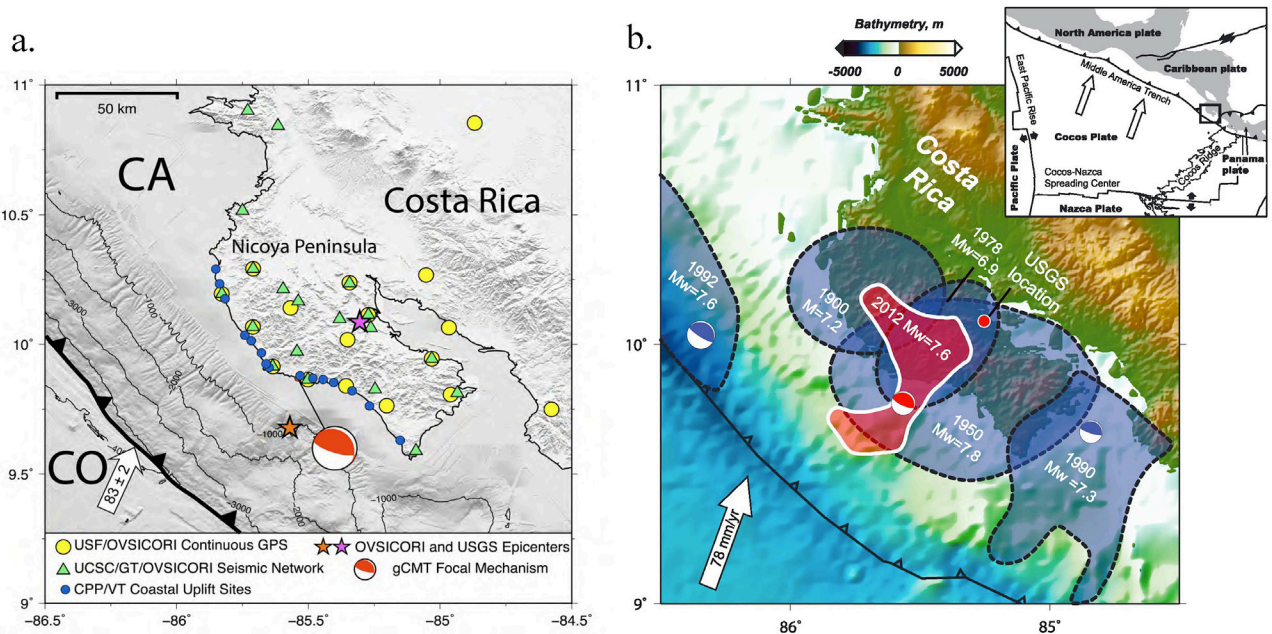


Figure 2. a) Map of the Nicoya Peninsula (from Dixon et al., 2012) showing three locations for the 2012 M_w 7.6 Nicoya Earthquake determined by USGS (purple star), OVSICORI-UNA (orange star), and Lamont-Doherty Global CMT Project (red circle and focal mechanism). Additional symbols show geodetic monitoring networks and geomorphic study sites: 1) continuous GPS stations (yellow circles; OVSICORI-UNA, University of South Florida), 2) seismic stations (green triangles; OVSICORI-UNA, University of California, Santa Cruz, Georgia Tech), and 3) geomorphic and paleoseismic field sites (blue dots; Cal Poly Pomona, Virginia Tech). b) Map of the Nicoya Peninsula (from Yue et al., 2013) showing primary rupture zone (>1.2 m slip) of 2012 M_w 7.6 Nicoya Earthquake (red patch) and aftershock regions of prior historic events (blue patches). Global CMT solutions are shown for 2012 (red), 1990 (blue), and 1992 (blue) earthquakes. Inset map shows regional tectonic setting.

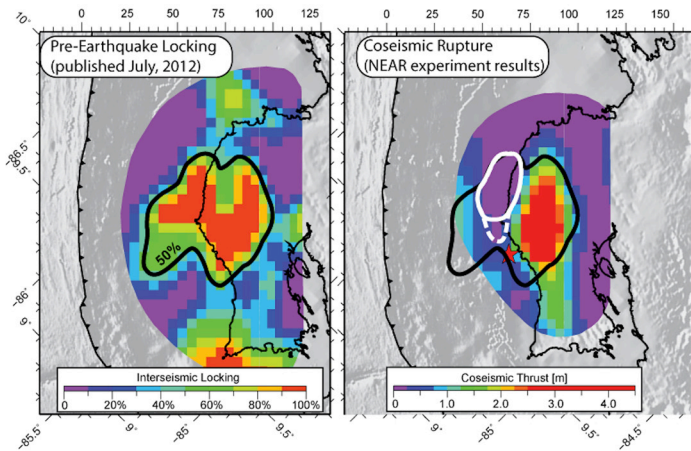


Figure 3. Comparative areas of pre-event locking and coseismic slip for the 2012 M_w 7.6 Nicoya Earthquake (after Protti et al., 2014). The model for late-interseismic coupling (left) was determined from continuous and campaign GPS data collected from 1996–2010 (Feng et al., 2012). The 2012 coseismic slip model (right) was determined from GPS data recorded during and immediately after the earthquake (Protti et al., 2014). Central area of 50% pre-event locking (thick black line) is shown in both figures to emphasize similarity. A strongly coupled patch offshore (thick white line) did not rupture during the 2012 earthquake.

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 hypothesized that the magnitude and pattern of seismic cycle deformation is related to the earthquake rupture geometry and slip distribution, which are in turn controlled by subduction zone characteristics such as convergence rate, obliquity, slab dip, plate roughness, heat flow, and fluid flux.

2012 NICOYA EARTHQUAKE

On 5 September 2012, a M_w 7.6 earthquake ruptured the subduction megathrust beneath the Nicoya Peninsula (Dixon et al., 2012; Yue et al., 2013; Protti et al., 2014). The rupture initiated 10 km offshore at a depth of 13 km (Fig. 2) and propagated downward beneath the central peninsula (Yue et al., 2013). The principal slip zone (> 1 m) extended 70 km along strike and 30 km down dip, corresponding to an area of pre-earthquake locking (Fig. 3) identified by GPS modeling (Feng et al., 2012; Protti et al., 2014). More than 1700 aftershocks were recorded within the first

five days, however only five events of $M \geq 5.0$ occurred during the first year after the mainshock. This low rate of moderate magnitude aftershocks suggests an incomplete rupture, consistent with geodetic models that show a remaining locked patch offshore (Fig. 3).

The last major earthquake in this area (M_w 7.8) occurred in 1950 (Protti et al., 2001), causing widespread damage and casualties, and producing landslides, liquefaction, and pronounced coseismic uplift along the Nicoya coast (Marshall and Anderson, 1995). Since then, seismologic, geodetic, and geomorphic studies had recognized the Nicoya Peninsula as a mature seismic gap, with a high probability of rupturing in the near future (e.g., Protti et al., 1995 and 2001; Marshall and Anderson, 1995; Norabuena et al., 2004; Feng et al., 2012). In 1989, the USGS gave a 93% probability of a large earthquake occurring here before 2009, listing Nicoya as fourth among the top seismic gaps of the Pacific Rim (Nishenko, 1989). To monitor precursory seismicity and the build-up of crustal strain, the Observatorio Volcanológico y Sismológico

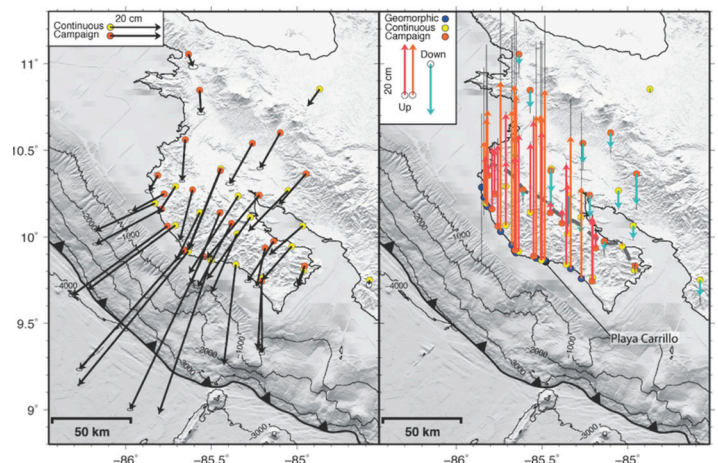


Figure 4. Horizontal and vertical coseismic deformation produced by the 2012 M_w 7.6 Nicoya Earthquake (after Protti et al., 2014). The horizontal (left) and vertical (right) coseismic displacements were measured by campaign (orange circles) and continuous (yellow circles) GPS, and by geomorphic observations (blue circles). The “pivot-line” (dark gray dashed line) marks the transition between uplift and subsidence. Errors are shown at 95% and 65% confidence for GPS and geomorphic data, respectively. Playa Carrillo is the site of maximum observed geomorphic uplift (0.7 m) along the coast (Marshall et al., 2013).

de Costa Rica (OVSICORI-UNA), working with international collaborators, developed a dense network of seismometers, GPS stations, and coastal survey sites across the Nicoya Peninsula (Fig. 2). In 2012, the anticipated Nicoya Earthquake released 62 years of accumulated strain, generating a wealth of geophysical data (Dixon et al., 2012; Yue et al., 2012; Protti et al., 2014), and providing an unprecedented opportunity for geologists to capture the near-field pattern of coseismic deformation produced by a major megathrust earthquake.

In the wake of the 2012 Nicoya Earthquake, an NSF Rapid Response Team collected geomorphic and geodetic field data to constrain patterns of coseismic deformation across the peninsula (Newman et al., 2013). Geomorphic spot measurements at more than a dozen field sites (Fig. 4) indicate that the earthquake produced up to 0.7 m of coseismic uplift along the central Nicoya coast (Marshall et al., 2013). GPS data from the OVSICORI geodetic network yielded consistent results (Fig. 4), showing maximum uplift along the coastline and inland subsidence along the Nicoya Gulf (Protti et al., 2014).

Similar earthquake cycle deformation has been observed along convergent margin coastlines worldwide, including 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. Along the Nicoya Peninsula's seaward-facing coastline, 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, 2008, 2009, 2012a; Sak et al., 2009). Along the peninsula's landward-facing gulf coast, net subsidence results in drowned rivers and broad mangrove estuaries (Marshall, 2007). Ongoing geomorphic, paleo-geodetic, and paleoseismic studies (e.g., Marshall et al., 2008 and 2012a; Spotila et al., 2010; Marshall and Spotila, 2011) 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 (Marshall et al., 2012a). Results 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. 1), designated EPR, CNS-1, and CNS-2 (Barckhausen et al., 2001), each originated at distinct oceanic spreading ridges and exhibit contrasts in age, crustal thickness, surface roughness, heat flow, and fluid flux (e.g., von Huene et al., 2000). Such contrasts may exert important controls on seismogenic zone geometry, seismic coupling, and earthquake rupture behavior (e.g., Newman et al., 2002; DeShon et al., 2006; Schwartz and DeShon, 2007).

STUDENT RESEARCH

Ten students, three faculty mentors, and one graduate teaching assistant conducted fieldwork along the Nicoya Peninsula coastline from June 23 to July 20, 2013 (Fig. 5). Their work expanded on geomorphic, geodetic, and seismologic studies of the fault rupture and coseismic deformation produced by the 2012 M_w 7.6 Nicoya Earthquake (Dixon et al., 2012; Newman et al., 2013; Marshall et al., 2013; Yue et al., 2013; Protti et al., 2014). The students worked in three



Figure 5. Photographs of 2013 Keck Geology Consortium Costa Rica Research Project. a) Student researchers (L to R): Dustin Stewart (Cal Poly Pomona), Richard Alfaro-Díaz (University of Texas, El Paso), Clayton Freimuth (Trinity University), Anthony Murillo (Universidad Nacional, Costa Rica), Greg Brenn (Union College), Paula Burgi (Smith College), Claire Martini (Whitman College), Shannon Fasola (St. Norbert College), Carolyn Prescott (Macalester College), Liz Olsen (Washington & Lee University), b) Claire and Paula surveying with laser range finder, c) Coastal Uplift Team (Paula, Claire, Carolyn) surveying uplifted tidal platform, d) Geophysics Team (Greg, Anthony, Shannon, Richard (not pictured) calibrating equipment with Dr. Marino Protti, e) Beachrock Team (Dustin, Clayton, Liz) surveying beachrock study site, f) Project Director Dr. Jeff Marshall (seen through laser range finder) surveying intertidal zone mortality.

collaborative field teams, *Coastal Uplift*, *Beachrock*, and *Geophysics*, to collect data for individual research projects. Together, they learned research techniques of tectonic geomorphology, coastal geology, stratigraphy, geochronology, seismology, and GPS geodesy.

Coseismic Coastal Uplift

Students working on the *Coastal Uplift Team* investigated earthquake generated uplift along the Nicoya coastline through detailed site investigations, collecting geomorphic field data, and surveying coastal landforms. Research tools included laser range finders, survey levels, stadia rods, tape measures, and hand held GPS to survey topographic profiles and measure uplift. The students studied the impact of coseismic uplift on beaches and rocky

shorelines by measuring geomorphic changes, including modification of beach profiles, stream incision, shifts in tidal levels, changes in wave erosion, and the displacement and mortality of intertidal organisms.

Carolyn Prescott (Macalester College) examined the impact of coseismic uplift on beach face geomorphology. She focused on morphologic changes in the high-tide zone and identified several characteristic indicators of uplift, including formation of a new lower beach berm (resulting in “double-berm” morphology), a downward shift in the high-tide debris line, and expansion of dune vegetation down the beach face. **Claire Martini** (Whitman College) studied the uplift-induced die-off of sessile intertidal organisms. She conducted mortality counts and measured the vertical extent of mortality (VEM)

of ribbed barnacles, jewel-box clams, and crustose algae. She found that the pattern of coseismic uplift determined by VEM data, was consistent with that recorded by prior GPS and geomorphic studies (Protti et al., 2014). **Paula Burgi** (Smith College) evaluated post-seismic deformation by reoccupying pre-earthquake and co-seismic earthquake survey lines (Marshall et al., 2013), but found that the post-seismic signal was too small to detect within the range of survey uncertainty. She shifted her focus to numerical dislocation modeling to investigate the relationship between published fault slip models (Yue et al., 2013) and the measured geodetic and geomorphic deformation field (Protti et al., 2014). Paula developed a new 3-D fault model (“Geometry S”) and found that it provides a better fit to local slip variations revealed by dense geomorphic measurements, than the smoother pattern resulting from more widely spaced geodetic data.

Uplifted Carbonate Beachrock Deposits

Students working on the **Beachrock Team** examined Holocene-age carbonate beachrock deposits, a common feature of the Nicoya Peninsula coastline (Marshall et al., 2012b). These tabular horizons of lithified beach sediment form by precipitation of carbonate cement within intergranular pore spaces in the groundwater excursion zone between high and low tide. As earthquakes elevate the coastline, beachrock horizons are moved upward on the beach face, and thus can be used as indicators of tectonic uplift. Students surveyed beachrock outcrops using laser range finders, hand held GPS, stadia rods, and reflectors. Sites were mapped, surveyed, and described in detail, and samples collected for radiocarbon dating and thin section analysis.

Clayton Freimuth (Trinity University) investigated mechanisms of beachrock formation by characterizing deposits at outcrop, hand specimen, and microscopic scales. He analyzed samples using petrographic and SEM microscopes, and studied beach sedimentology and groundwater flow, concluding that Nicoya beachrocks form principally by the mixing of meteoric and marine water within the tidal zone. **Elizabeth Olson** (Washington and Lee University) evaluated strategies for beachrock age dating. She collected samples at multiple field sites, examined matrix and

cement composition using petrographic and SEM microscopes, and conducted comparative radiocarbon dating of whole-rock and crushed samples sieved to different grain sizes. She concluded that the finest size fraction, representing the carbonate cement, yields the most accurate age of beachrock formation.

Dustin Stewart (Cal Poly Pomona) studied an anomalous beachrock outcrop that in prior studies yielded unusually old whole-rock ages (Marshall et al., 2012b). He found that the outcrop consists of a complex stratigraphy of five distinct lithologic units, including calc-arenite bedrock, fossiliferous lithic breccias, and typical carbonate beachrock. He concluded that prior whole-rock ages were skewed by incorporation of older biogenic material and/or carbonate-rich lithic clasts.

Fault Rupture, Aftershocks, and Crustal Deformation

Students working on the *Geophysics Team* constructed a temporary local network of seismic and geodetic stations (KECK Network) that operated throughout the length of the project. To study the processes of fault rupture, aftershocks, and crustal deformation, the students combined their local network data with that from the permanent Nicoya Network operated by OVSICORI-UNA. The students learned to install and maintain seismometers and GPS receivers, and to download and process data to interpret seismotectonic deformation related to the 2012 Nicoya Earthquake.

Anthony Murillo (Universidad Nacional de Costa Rica) investigated the distribution of small earthquakes prior to the 2012 mainshock and evaluated their spatial relationship with the main event rupture and aftershock zone. He concluded that the precursory seismicity was typical of normal background activity up until 30 minutes prior to the mainshock, when a cluster of small events occurred near the mainshock hypocenter. **Greg Brenn** (Union College) examined aftershocks of the 2012 Nicoya Earthquake recorded by the KECK seismic network. He generated composite focal mechanisms to evaluate deformation kinematics and observed varying patterns of fault slip including plate-interface thrusting, and strike-slip and normal faulting within the upper and lower plate. **Shannon Fasola** (St. Norbert College) also studied aftershocks, plotting their spatial distribution and relationship to tectonic

variations along the margin. She found that most aftershocks occurred within the observed area of pre-event locking (Feng et al., 2012) and that aftershock depths were consistent with along-strike changes in the up-dip limit of seismicity observed in prior studies (Newman et al., 2002). **Richard Alfaro-Díaz** (University of Texas, El Paso) analyzed waveform data collected by the KECK Network to locate small aftershocks. He identified a cluster of shallow events along a linear trend and produced a composite focal mechanism that indicated activation of an upper-plate oblique-slip fault.

CONCLUSIONS

This research project addressed key geoscience questions about how earthquake-generated uplift impacts coastal geomorphology, and how seismic cycle motions contribute to net deformation and topographic growth. Specific conclusions are presented in the student project contributions that follow. The project results add to several decades of prior research on the seismotectonics and geomorphology of the Nicoya Peninsula, and provide an important contribution to the growing body of scientific knowledge on convergent margin morphotectonics.

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