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A GEOBIOLOGICAL APPROACH TO UNDERSTANDING DOLOMITE FORMATION AT DEEP SPRINGS LAKE, CA
Faculty: *DAVID JONES*, Amherst College, *JASON TOR*, Hampshire College,
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POTENTIAL EFFECTS OF WATER-LEVEL CHANGES ON ON ISLAND ECOSYSTEMS: A GIS SPATIOTEMPORAL ANALYSIS OF SHORELINE CONFIGURATION
Faculty**:** *KIM DIVER*, Wesleyan Univ.
Students: *RYAN EDGLEY*, California State Polytecnical University-Pomona, *EMILIE SINKLER*, Wesleyan University

PĀHOEHOE LAVA ON MARS AND THE EARTH: A COMPARATIVE STUDY OF INFLATED AND DISRUPTED FLOWS
Faculty: *ANDREW DE WET*, Franklin & Marshall College, *CHRIS HAMILTON*. Univ. Maryland, *JACOB BLEACHER*, NASA, GSFC, *BRENT GARRY*, NASA-GSFC
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THE GEOMORPHIC FOOTPRINT OF MEGATHRUST EARTHQUAKES: A FIELD INVESTIGATION OF CONVERGENT MARGIN MORPHOTECTONICS, NICOYA PENINSULA, COSTA RICA
Faculty: *JEFF MARSHALL*, Cal Poly Pomona, *TOM GARDNER*, Trinity University, *MARINO PROTTI, OVSICORI-UNA, SHAWN MORRISH*, Cal Poly Pomona
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HOLOCENE AND MODERN CLIMATE CHANGE IN THE HIGH ARCTIC, SVALBARD NORWAY
Faculty: *AL WERNER*, Mt. Holyoke College, *STEVE ROOF,* Hampshire College, *MIKE RETELLE*, Bates College
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Keck Geology Consortium: Projects 2013-2014
Short Contributions— Earthquake Geomorphology, Costa Rica Project

THE GEOMORPHIC FOOTPRINT OF MEGATHRUST EARTHQUAKES: MORPHOTECTONICS OF THE 2012 MW 7.6 NICOYA EARTHQUAKE, COSTA RICA
Faculty: JEFF MARSHALL, Cal Poly Pomona
TOM GARDNER, Trinity University
MARINO PROTTI, Universidad Nacional de Costa Rica
SHAWN MORRISH, Cal Poly Pomona

ACTIVATION OF A SECONDARY OBLIQUE SLIP FAULT FOLLOWING THE MW=7.6 SEPTEMBER 5, 2012, NICOYA,
COSTA RICA, EARTHQUAKE
RICHARD ALFARO-DIAZ, University of Texas at El Paso
Research Advisors: Terry Pavlis and Aaron Velasco

EARTHQUAKE RELOCATION AND FOCAL MECHANISM ANALYSIS IN THE AREA OF RUPTURE FOLLOWING THE MW=7.6 NICOYA EARTHQUAKE, COSTA RICA
GREGORY BRENN, Union College
Research Advisor: Dr. Matthew Manon

MODELING COSEISMIC SLIP OF THE 2012 NICOYA PENINSULA EARTHQUAKE, COSTA RICA: ROLES OF MEGATHRUST GEOMETRY AND SURFACE DISPLACEMENT
PAULA BURGI, Smith College
Research Advisor: Jack Loveless

HOLOCENE BEACHROCK FORMATION ON THE NICOYA PENINSULA, PACIFIC COAST, COSTA RICA
CLAYTON FREIMUTH, Trinity University
Research Advisor: Thomas Gardner

ANALYSIS OF AFTERSHOCKS FOLLOWING THE SEPTEMBER 5, 2012 NICOYA, COSTA RICA MW 7.6 EARTHQUAKE
SHANNON FASOLA, St. Norbert College
Research Advisor: Nelson Ham

COASTAL UPLIFT AND MORTALITY OF INTERTIDAL ORGANISMS FROM A MAGNITUDE 7.6 EARTHQUAKE, NICOYA PENINSULA, COSTA RICA
CLAIRE MARTINI, Whitman College
Research Advisors: Kevin Pogue and Bob Carson

ASSESSMENT OF CURRENT RADIOMETRIC DATING TECHNIQUES OF BEACHROCK ON THE NICOYA PENINSULA, COSTA RICA
ELIZABETH OLSON, Washington and Lee University
Research Advisor: David Harbor

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RELATIONSHIP BETWEEN BEACH MORPHOLOGY AND COSEISMIC COASTAL UPLIFT, NICOYA PENINSULA, COSTA RICA
CAROLYN PRESCOTT, Macalester College
Research Advisor: Kelly MacGregor

STRATIGRAPHIC ARCHITECTURE OF AN ANOMALOUS HOLOCENE BEACHROCK OUTCROP, PLAYA GARZA, NICOYA PENINSULA, COSTA RICA
DUSTIN STEWART, Cal Poly Pomona
Research Advisor: Jeff Marshall

PREMONITORY SEISMICITY BEFORE THE SEPTEMBER 5, 2012, MW 7.6 NICOYA EARTHQUAKE, COSTA RICA: RELATIONSHIP WITH MAINSHOCK RUPTURE AND AFTERSHOCK ZONE
ANTHONY MURILLO GUTIÉRREZ, Universidad Nacional de Costa Rica (UNA)
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GREGORY BRENN, Union College
Research Advisor: Dr. Matthew Manon

INTRODUCTION

The Nicoya peninsula, Costa Rica represents an ideal location to study earthquake seismicity in a subduction zone environment, since this peninsula lies directly above the seismically active plate interface with its coastline ~60 km east of the Middle America Trench. Due to the Nicoya peninsula's proximity to the trench and the rapid convergence rate of the Cocos plate of 82.3 ± 2.2 mm/yr subducting beneath the Caribbean plate, four megathrust earthquakes with magnitude 7+ have been recorded in the last ~150 yr, in 1853, 1900, 1950, and 2012, following an approximate 50 year earthquake cycle (Feng et al., 2012). The September 5, 2012 earthquake (M_w=7.6), a large shallow-dipping thrust event, partially ruptured the plate interface beneath the Nicoya peninsula, Costa Rica, with its hypocenter relocated to ~10 km offshore and 13 km deep along this megathrust boundary (Yue et al., 2013). Before the September 5, 2012 earthquake, two fully coupled plate interface zones, one zone centered offshore at ~15 km depth and the other located more inland, centered at ~24 km depth, were identified as areas of high seismic hazard with the potential to generate a M_w > 7.5 earthquake (Feng et al., 2012). Land-based GPS and seismic measurements revealed that the Nicoya earthquake ruptured the previously identified locked patch in central portion of the Nicoya Peninsula (Protti et al., 2013).

Following the determination of the ruptured patch of the plate interface, a five-station temporary seismic network was installed directly above the rupture zone to record aftershock seismicity related to the September 5, 2012 earthquake. Previous seismic studies such as the collaborative Costa Rica Seismogenic Zone Experiment (CRSEIZE), a seismic network that consisted of 20 land and 14 ocean-bottom seismometers, recorded small magnitude local earthquakes on the Nicoya Peninsula from 1999 to 2001 (Deshon et al., 2006). The main objective of this study is to use data from the Keck network to perform earthquake relocation, focal mechanism determination, along with seismic waveform correlation, to better understand subduction zone earthquake processes following a significant megathrust earthquake event, within the area of rupture beneath the Nicoya peninsula.

METHODS

When deploying seismic stations, choosing the location of the station is important for limiting the amount of noise recorded by the seismogram. At each deployment site, a Trillium compact seismometer was buried underneath 0.5-1 m of soil to protect against above-ground disturbances. Fences were built around the stations prone to cattle or human interference. A Taurus digitizer, which records the data onto 2- or 4- Gb hard drives, along with a battery, sits inside a protective case, which rests above ground with a solar panel charging the battery.

Earthquake events were identified using SeisAn Earthquake Analysis Software (Haskov and Ottemöller, 1999), a set of processing programs developed to display and analyze seismic data. Waveforms were collected from five stations deployed by the Keck Geophysics Team (Keck network). We also used data from June 23 to July 2, 2013, collected the permanent Nicoya and OVSICORI networks across the Nicoya peninsula. After converting the seismic data into the SEISAN waveform format and merging station data in hourly intervals, P and S-wave arrival times, and codas, were picked for each recorded event. To calculate an accurate location, depth, and magnitude of each event, at least three different stations were used to make picks. More stations allowed for more accurate determination of earthquake parameters. P-wave and S-wave picks were avoided for stations that exhibited a high signal-to-noise ratio, due to the likelihood of choosing an incorrect arrival.

To reduce the root-mean-squared (rms) travel time residual for each event, the Vp/Vs ratio and the velocity model were adjusted to obtain the lowest average rms value of the identified earthquakes. Initially, a global model velocity model (IASPEI91, Kennett & Engdahl, 1991) was used to locate the earthquakes. A velocity model that better correlates with the regional geology on the Nicoya Peninsula (Deshon et al., 2006), was used to improve the fit of the observed earthquake arrival times.

Fault plane solutions were created using two focal mechanism programs in Seisan, FPFIT which use the first motion polarities of the P-waves that exhibited high signal-to-noise ratios. Because manual polarity picking is not be the most accurate technique to pick P-wave polarities, especially for events with fewer impulsive P-wave arrivals, to create more reliable focal mechanisms only events that contained at least 4 clear, impetus arrivals were used for focal mechanism analysis. To create more accurate focal mechanisms with the use of more stations, earthquake clusters with nearly identical waveforms were identified to create a composite fault plane solution. This approach, which has been previously performed on the Nicoya peninsula (Hansen et al., 2006), allows focal mechanisms to be determined for events that occurred after July 2 when polarity readings could be taken from only the 5 stations of the Keck network. Since the Keck network did not cover a wide area, most focal mechanisms were created only events within the network, as the accuracy of earthquake location decreases outside of the small but dense Keck network.

RESULTS

From June 23 to July 18, a total of 256 events were located using the IASP91 velocity model. After preliminary locations with this model, the updated 1D P-wave velocity model obtained by Deshon et al, (2006) was used to relocate the earthquake events. This model uses velocities in the upper 30-40 km that are consistent with previously published refraction data. While only slight differences in epicenter locations can be identified, such as a different clustering of events specifically within the Keck Network, the average rms values exhibited differences. The average rms of the travel time residuals for the events located using the IASP91 model within the latitudinal boundaries of 10.11ºN and 9.78ºN and the longitudinal boundaries of -85.79ºW and -85.49ºW was 0.13 ± 0.22. The average RMS of the travel time residuals for events located using the Nicoya peninsula-specific model within the same latitudinal and longitudinal boundaries was 0.123 ±

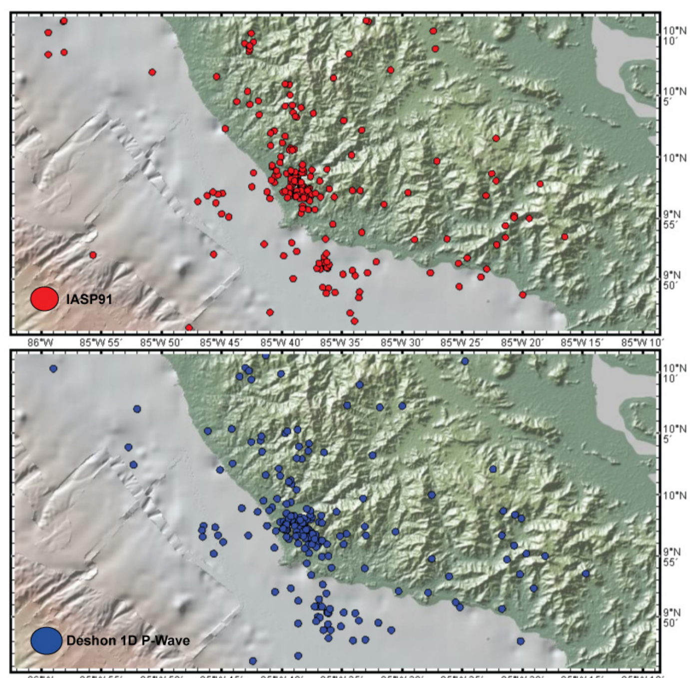

Figure 1. Comparison of earthquake locations using two velocity models, the IASP91 velocity model and the Deshon 1D P-Wave velocity model (Deshon et al., 2006). The IASP91 velocity model uses global traveltimes to calculate the P-wave and S-wave velocities, and the Deshon 1D P-wave velocity model uses refraction data taken for the upper 30-40 km and background seismicity beneath the Nicoya peninsula to determine the velocity structure specific to Nicoya Peninsula. Notice slight differences in the cluster of events just onshore, as well as the difference in epicentral locations for the offshore cluster.

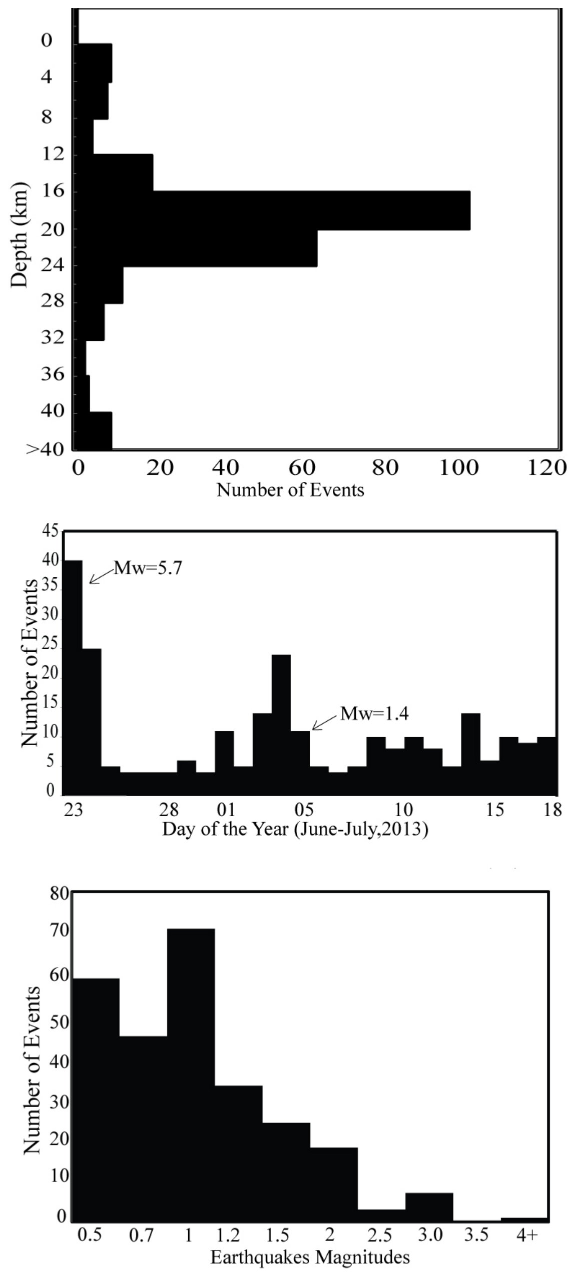

Figure 2: Histograms composed of earthquakes within the area of rupture of the September 5, 2012 earthquake. Notice the depths of most of these events are between 16-24 km, consistent with the depth of the plate interface in this area. Aftershocks following the June 23rd earthquake represent the increase in number of events on June 23-24. The magnitudes of these earthquakes are predominantly less than 2, and a significant number of earthquakes have a magnitude of ~1.0.

0.21. While the RMS values were not significantly lower with Deshon's 1D P-wave velocity model, using the Nicoya-specific model is more appropriate for the final earthquake locations.

On June 23, 2013 UTC one of the only 5 aftershocks of the 2012 mainshock with magnitude Mw above

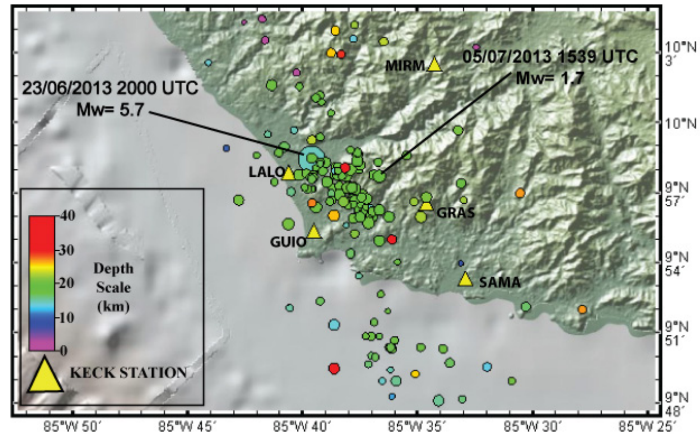

Figure 3: Zoomed in earthquake location map around the Keck network stations (indicated by the yellow triangles), with the earthquakes scaled by magnitude and colored by depth. Notice most of the event within the Keck network are at ~20 kmwith some variation for specific events. The cluster offshore of the Nicoya peninsula are at ~17-18 km depth.

5.0 was located 5 km northwest of Playa Garza, Guanacaste at 9°58'26.4"N, 85°39'35.9"W, (Mw=5.7) at ~15 km depth and located within 5 km of the LALO Keck Station and <10 km from the GUIO Keck Station. Four foreshocks of magnitude 0.9 to 1.6 were recorded on June 23, and 35 aftershocks were recorded the very same day following the Mw=5.7 event. The number of events decreased to 25 aftershocks on June 24, and then went back to background aftershock seismicity (4-5 earthquakes) for the rest of June with magnitudes ranging from ~0.6 to 1.3. The number of earthquakes increased to 25 on July 4, with the largest event having a magnitude of 2.6 (Fig. 2); however, this event was located outside of the Keck network.

Locally around and within the Keck network, 30 earthquakes recorded magnitudes greater than 1. The largest magnitude earthquake within the network following the June 23 event occurred on July 5, 1317 UTC at 9°57'43.1994"N and 85°36'39.6"W with a magnitude of 1.4. Of the 155 earthquakes located within the above area, 106 recorded depths of ~20 km. These events also recorded magnitudes of ~0.3-1.2. The cluster of events off the coast of the Nicoya Peninsula recorded slightly shallower depths compared to the cluster of events within the Keck network area, at ~17-18 km (Fig. 3).

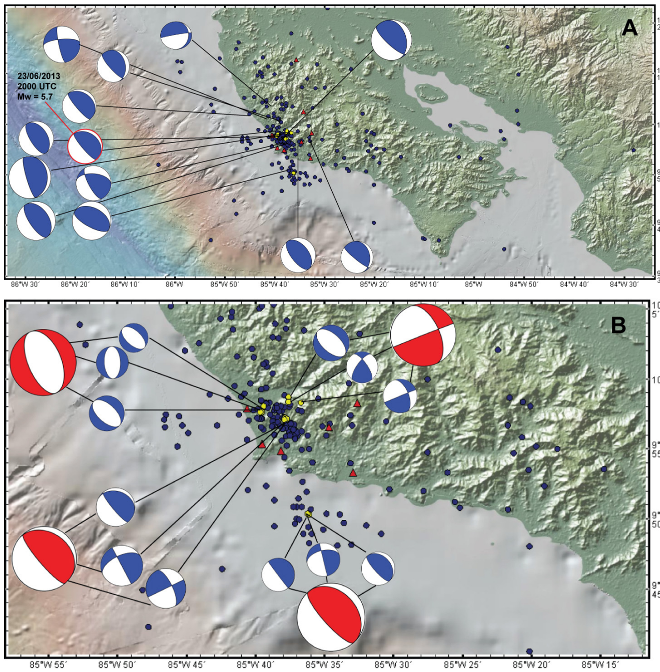

Figure 4, (a): Single –event focal mechanisms computed for events within the area of rupture of the September 5, 2012 earthquake. Dominantly thrust focal mechanisms were created for 14 events. (b) Correlated waveforms exhibiting similar seismic signatures were combined to create composite focal mechanisms (Red) with the single-event focal mechanisms in blue. Notice the normal faulting focal mechanism to the north of the network, which may have been caused by extension due to bending of the downgoing slab during subduction.

First motion polarities of P-wave onsets for 13 events were manually chosen, and focal mechanisms were obtained with these first motions using the FPFIT software package written by Reasenberg and Oppenheimer (1985). Because error in first-motion picks can occur when there exists a low signal-to-noise ratio, stations that recorded impulsive, or sharp, P-wave motions on multiple stations were chosen. Additionally, because the Keck network covers a relatively small area, most events were chosen from within the network so that the compression or dilatation at each station is spatially, better distributed on the stereonet projection. The foreshock that preceded the June 23 2000 UTC event exhibited a thrust mechanism, with a strike of 274º, dipping 41º and a rake of 41º. The June 23^{rd} aftershock also exhibited a thrust mechanism with a strike of 306º, dipping 16º, and a rake of 77º. An immediate aftershock at 2050 UTC was also calculated to have the same strike, dip, and rake as the 2000 UTC event. Fault plane solutions calculated for single events within the network also showed dominant thrusting mechanisms but with strikes differing by more than 100º and dips greater than 30º. Depths of the thrust-mechanism events are all between 18 and 22 km, corresponding to the depth of the plate interface under the Keck network.

After performing manual waveform correlation, 4 event clusters were identified (Fig. 4). Two of these clusters exhibited dominant composite thrust mechanisms. One composite thrust mechanism, located directly inside the Keck Network, is a composite of three single fault plane solutions with depths at ~20 km. The other composite thrust mechanism is within the cluster of events offshore, which was created from three events at ~17.5 km depth. One cluster exhibited dominant normal faulting just north of the network, consisting of events at ~18.5-20 km depth, and the final cluster exhibited thrusting strike-slip motion consisting of three single events at ~20 km depth.

DISCUSSION

The June 23^{rd} M_w= 5.7 earthquake represents an aftershock of the September 5, 2012, magnitude 7.6 Nicoya earthquake that ruptured the onland section of the locked region of the plate interface between the subducting Cocos plate and the overriding Caribbean plate (Protti et al., 2013). The increase in frequency of earthquakes that occurred on June 23 and June 24 suggests the magnitude 5.7 earthquake generated its own aftershocks. These smaller aftershocks represent many of the earthquakes in the large cluster of events within the Keck network, with hypocenter depths around 20 km (Fig. 3).

The cluster of earthquakes just south and offshore of the Keck Network, correspond with the increase in events from July 3 to July 5. This offshore cluster, with hypocenter depths around 17-18 km, may be due to the change in subducting oceanic crust from the Cocos-Nazca spreading center (CNS) to the north, and the East Pacific Rise (EPR) crust to the south. A similar trend in the change of earthquake depths from north to south has previously been analyzed by Newman et al., (2002), who noticed the seismogenic updip limit shallows south of the ‘elbow’ of the Nicoya Peninsula, which represents the location at

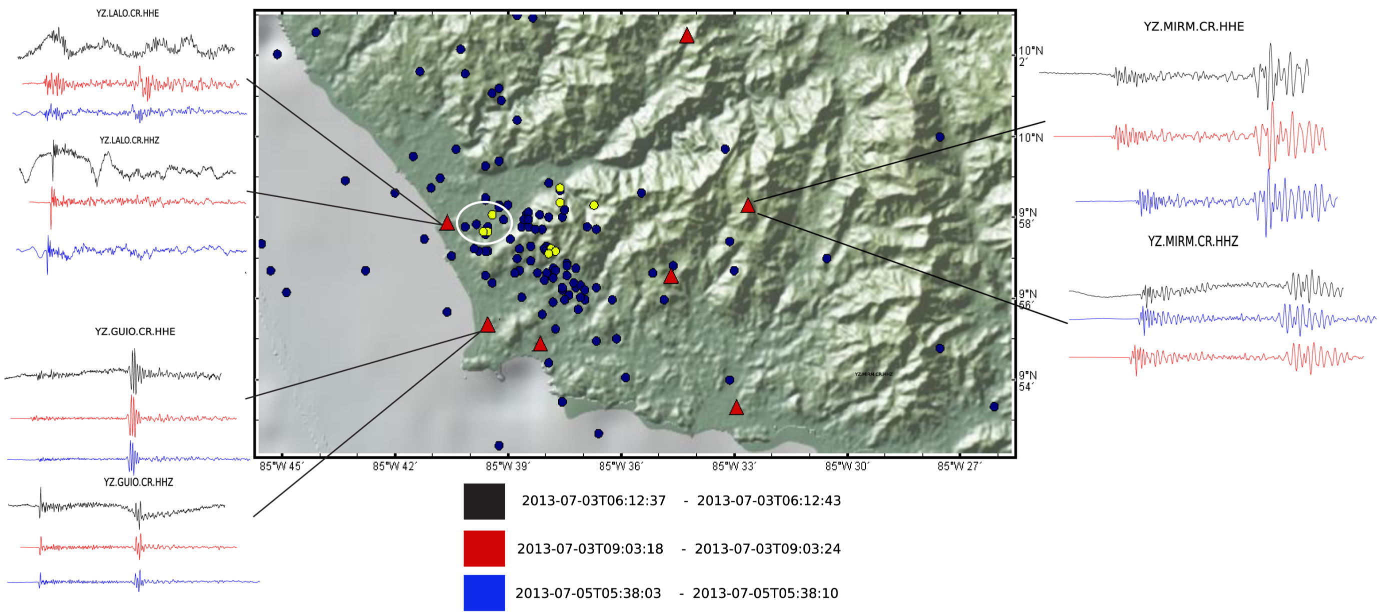

Figure 5. Waveform correlation of three events that correspond with the circled earthquake cluster. The black, red, and blue waveforms each represent a different event, but notice at each station, these three events exhibit identical waveforms. These earthquakes, which correspond with the normal-motion focal mechanisms identified in Figure 4b, must have radiated along almost identical paths and originated from the same source.

which the warmer EPR crust changes to colder CNS crust (Newman et al., 2002).

Single-event and composite focal mechanism analysis for events within the Keck network which show thrust faulting along a northeasterly, shallow-dipping nodal plane, indicates that these events, which are located at depths consistent with the plate interface depth, are due to underthrusting. The composite normal-motion focal mechanism was confidently chosen as an accurate fault plane solution from three different events that have identical waveforms. Each station exhibited the same compressional and dilatational first motions, representing an anomaly amongst the dominantly thrust focal mechanisms in this region. These normal fault- generated earthquakes, with depths at ~18.5-20 km, have hypocenters located below the plate interface. Previous studies suggest that the subduction of the Fischer seamount group, which is a northeast-trending seamount group that affects the bathymetry of the subducting oceanic crust, has contributed to normal fault-generated earthquakes (Fischer et al., 1998). However, the rough bathymetry of the subducting seafloor is predominantly located near the tip of the Nicoya Peninsula, with the smooth, EPR crust subducting beneath the Keck network. A plausible hypothesis for this normal-faulting event could be due to extension on the downgoing slab, which can create normal faulting events. These events, known as outer-rise events, caused by the bending of the Cocos plate, could extend all the way down below the seismogenic zone of underthrusting events. Further analysis and seismic monitoring along this subduction zone interface is needed to determine if there exists other normal-motion events constrained to hypocenter depths similar to what was identified with the Keck Network.

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