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MARINO PROTTI, Universidad Nacional de Costa Rica
SHAWN MORRISH, Cal Poly Pomona

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Research Advisor: Marino Protti

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ACTIVATION OF A SECONDARY OBLIQUE SLIP FAULT FOLLOWING THE M_W=7.6 SEPTEMBER 5, 2012, NICOYA, COSTA RICA, EARTHQUAKE

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Research Advisors: Terry Pavlis and Aaron Velasco

INTRODUCTION

The Nicoya peninsula on the Pacific coast of Coast Rica in Central America is located within 60 km of the Middle America Trench (MAT) above the seismogenic zone. On September 5th, 2012 the Mw=7.6 Nicoya, Costa Rica, Earthquake ruptured the megathrust. Yue et al. (2013), utilizing data collected from the continuous broadband Nicoya seismic network, high-rate GPS and strong motion data accurately located the 2012 Nicoya earthquake slip distribution. The earthquake ruptured a segment the plate interface recognized as a seismic gap (Nishenko, 1991; Protti et al, 1995), initiating offshore of the Nicoya peninsula. Following the main-shock, only 5 moderate size (Mw > 5) aftershocks have occurred. Given the relatively large magnitude of the event the low number of large aftershocks appears anomalous.

The Keck Network was deployed in the summer of 2013 to closely investigate the post-seismic behavior of rupture zone in the near-field. This paper focuses on the analysis of waveform data collected from the Keck Network to locate small (Mc from 0.0 to 3.6) aftershocks. A possible crustal fault in the vicinity the rupture zone of the 2012 Nicoya earthquake was also identified. Further analysis shows that the fault appears to be an oblique slip fault that was activated by the Nicoya 2010 earthquake and its aftershocks.

DATA

As a part of a Keck Geology Consortium summer research internship in Costa Rica, a dense temporary broadband seismic array (the Keck Network) was deployed directly over the rupture zone of the September 5th, 2013 Mw=7.6 earthquake. The network consists of five Nanometrics Trillium compact seismometers with Taurus digitizers. Station spacing ranged from 3 to 14 km. The Keck network operated from July 2nd to July 18th, 2013. On June 23rd, eight days prior to the deployment, a Mw=5.4 aftershock occurred beneath the area of the array; this was one of only 5 aftershocks of the Nicoya earthquake with magnitudes above 5. Other stations of the permanent Nicoya and OVSICORI broadband seismic networks were utilized in this study; data was collected in order to cover the gap in time between the June 23rd aftershock and the deployment and to complement our locations with the Keck Network. In addition, the extra data allows enough coverage to generate fault plane solutions for some events.

A manual search for local earthquake events was conducted for each hour of waveform data collected. First arrival phases were picked (*P*-wave and *S*-wave,) weighted, and *P*-wave first motion polarities were picked. A coda was marked for each event and Seisan software computes the location and calculates coda magnitude (Mc) automatically for each event. I identified 220 local events (Fig. 1) from June 23rd to July 18th 2013, and located events using the program Hypocenter [*Lienert et al*., 1986; *Lienert*, 1991; *Lienert and Havskov*, 1995] integrated into Seisan. Each event location has a residual rms less than or equal to 0.5. Events were catalogued, the magnitudes (Mc) of events range from Mc=3.6 to Mc=0.0. A catalogue of 86 constrained events was then generated excluding any events with an azimuthal gap greater than 180 degrees. The constrained catalogue was then converted to hypoDD format (a catalogue of p and s-wave phase data) to process, cross-correlate, and relocate events.

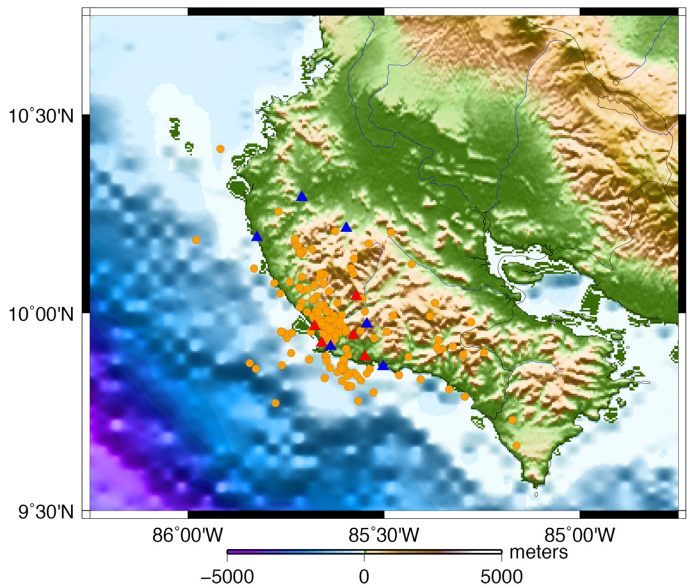

Figure 1. Seismicity located in this study. Orange dots are a total 220 events from June 23, 2012 to July 18, 2013. Red Triangles represent station locations of the Keck Network. Blue triangles represent station locations of Nicoya network that were utilized in this project

METHODS

A catalogue of 86 constrained events was processed through the program ph2dt in preparation for input into hypoDD. Ph2dt searches catalog P- and S-phase data using travel time information at common stations to cross-correlate and create event pairs [*Waldhauser & Ellsworth*, 2000] the catalogue data in preparation for input into hypoDD. A script is prepared integrating the 1-D velocity model developed by *DeShon et al.*, 2006 specific to the Nicoya Peninsula, and a table (Table 1) with *P*-wave phase weighting scheme for input in hypoDD. The cataloged cross-correlated event data were input into hypoDD to analyze and relocate events. The differential travel time of events was then used to determine double-difference hypocenter locations. Several iterations were carried out and assessed, after a series of 12 iterations using several different weighting schemes. Event relocations were plotted and compared side-by-side, locations remained consistent. All iterations yielded highly similar results, inferring a stable relocation solution. The final relocations were chosen on the basis of the lowest residual rms for all events.

NITER	WTCCP	WTCCS	WRCC	WDCC	WTCTP	WTCTS
5	-9	-9	-9	-9	1	-9
5	-9	-9	-9	-9	1	-9
5	-9	-9	-9	-9	1	-9
5	-9	-9	-9	-9	2	-9
5	-9	-9	-9	-9	2	-9
5	-9	-9	-9	-9	2	-9
5	-9	-9	-9	-9	2	-9

Table 1. HypoDD input Data weighting and reweighting values. NIETR: last iteration to use the following weights. WTCCP, WTCCS: Weight for cross-correlated P-wave, S-wave data. –9 = data not used. WTCTP, WTCTS: Weight for catalog P-wave, S-wave data. –9 = data not used. WRCC, WRCT: residual threshold in sec for cross-correlated, catalog data. WDCC, WDCT: max distance in km between cross-correlated, catalog linked pairs. [Waldhauser, 2001]

RESULTS

A comparison of initial event locations and final relocations (Fig. 2), reveals a distinct tight cluster of events (in the region). The tight cluster of relocated events arrange in a linear manner, consistent with a source along a single fault. Cross-sections were generated across the seismicity and along strike of the linear cluster (Fig. 3) (using a Matlab script provide by *Waldhauser*, 2001 with hypoDD) to further investigate the geometry. The cross-sections focus on the linear cluster and have been angled in accordance to its apparent geometry, striking ~165 degrees, ~45 degrees off the orientation Middle American Trench in the region. The fault correlates to a bounding edge of the 2012 Nicoya earthquake, indicating strain may be transferring from the plate interface into the fault in overriding Caribbean plate.

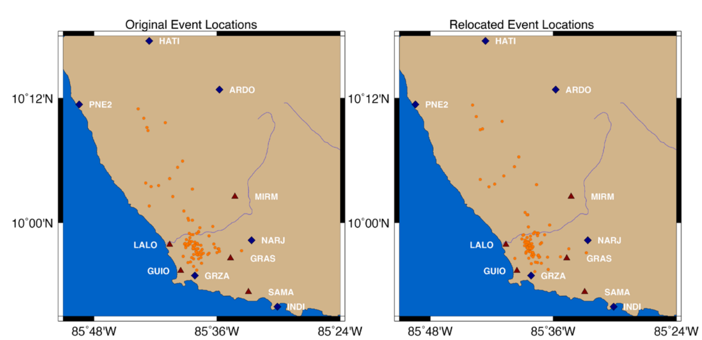

Figure 2. The left represents a map of the original locations of seismicity. The right represents a map of relocations of seismicity. Red triangles represent station locations of the Keck Network. Blue diamonds represent station locations of Nicoya Network that utilized in this project. White labels indicate station names.

To examine the motion of the fault in further detail, a composite focal mechanism was generated using the software HASH (*Hardebeck & Shearer,* 2002, 2003). Only events within the linear cluster of the fault (68 of a total of 86 events) were used to generate a fault plane solution. The solution only considers *P*-wave first motion polarities. Several composite solutions are generated using HASH and compared to fault plane solutions generated by the software FOCMEC [*Snoke et al*., 1984]. All iterations remain consistent indicating the generation of a stable fault plane solution. There are two preferred focal mechanism's (Fig. 3) produced by HASH both have similar steep dipping fault planes, and a geometry consistent with the direction of convergent plate motion, and a very low residual error.

DISCUSSION

After analysis of aftershocks we recorded of the Nicoya 2012 earthquake, it appears strain has transferred from the plate interface to the upper plate activating a fault in the overriding Caribbean plate. The fault exhibits oblique slip motion consistent with the oblique convergence of the Cocos plate; that is, both alternative composite focal mechanisms (Fig. 4) show a dextral slip component for a high-angle fault parallel to the aftershock zone. This fault occurs at the transition from the EPR crust to CNS-1 crust. This suggests that the fault is related to differences in structure, thermal structure, morphologic, thickness, and fluid influences at the transition. The fault's orientation lies about ~45 degrees off of

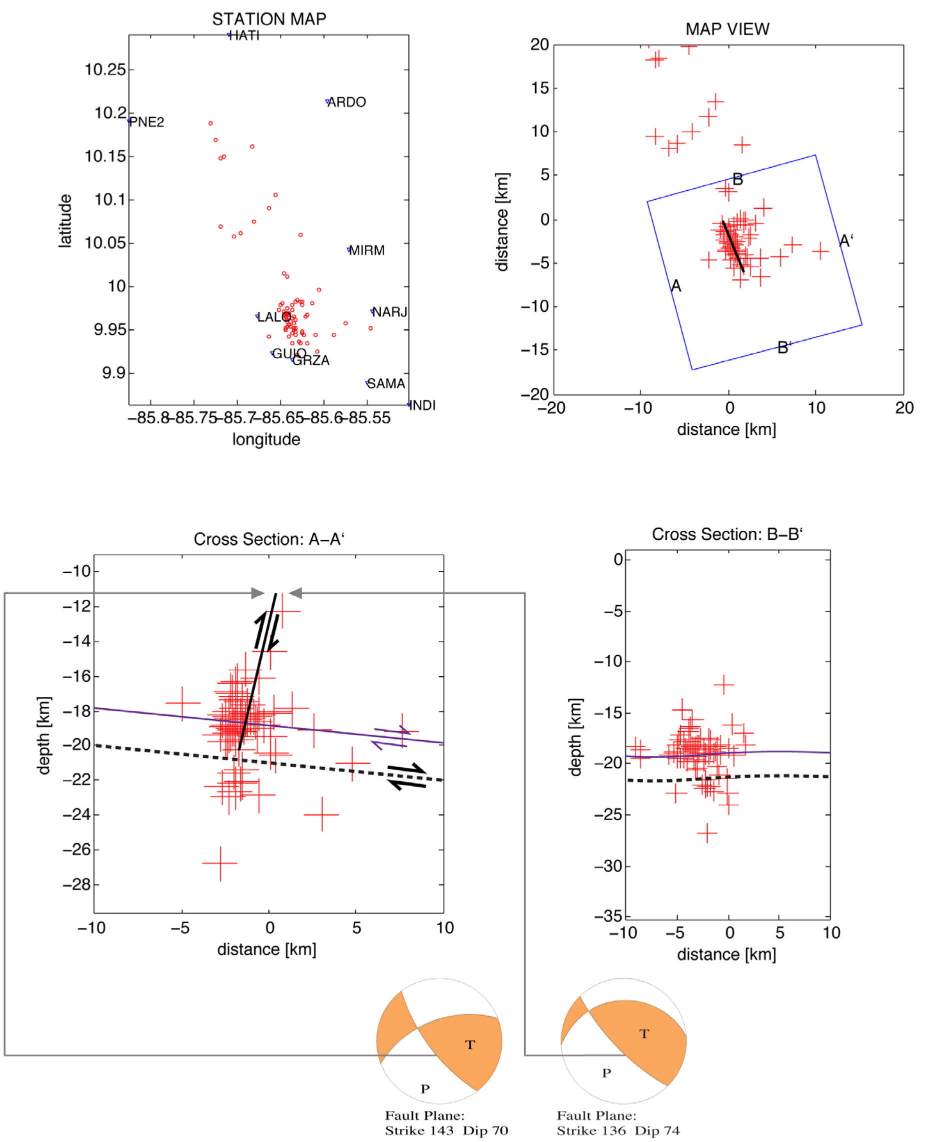

Figure 3. Red cross indicate relocated earthquake events, length of crosses indicate approximate range of error in locations. Dashed black line indicates the approximate depth of the plate interface according to [Audet & Schwartz, 2013]. Solid black line indicates approximate fault orientation. Purple lines indicate approximate uncertainty of the depth of the plate interface [Marino Protti, personal communication 2014] indicating seismicity may come from the plate interface. Two preferred composite fault plane solutions generated using HASH (Hardebeck & Shearer, 2002, 2003) are plotted below cross sections. Earthquake events within the linear cluster of the fault (68 of a total of 86 events) were used to generate the fault plane solutions. T refers to the tension axis. P refers to the pressure axis (P). Possible fault planes are indicated and correlated to Cross Section: A-A' by grey lines.

the orientation of the MAT offshore of the Nicoya Peninsula. The fault plane solution (GCMT) for the Nicoya 2012 earthquake indicates purely thrust motion, thus, the oblique (strike-slip) component of convergence must also be accommodated. Slip partitioning could accommodate the strike-slip component, and the fault determined in this study can be inferred to accommodate that strike slip component of motion. (Fig. 4)

The fault is interpreted to have partially accommodated the strain released by the 2012 Nicoya earthquake. The fault lies directly on the edge of the 2012 rupture zone, determined by *Yue et al.,* 2013 (Fig. 4). The rupture zone does not propagate past the fault. This suggests fault motion accommodated for the energy release in this localized area. The fault also locates in the central area between two patches of ~100% locking along the plate interface recognized by *Feng et al*., 2012. The fault motion may have in fact dispersed energy of the 2012 earthquake, preventing slip from propagating towards the un-ruptured region that displaying 80% and 100% slip deficit [*Feng et al*., 2012] (Fig. 4). The fact that this fault forms a bounding edge of the rupture zone of the 2012 Nicoya earthquake indicates the importance of the fault as a secondary feature.

It is important to mention the true velocity structure of the Nicoya peninsula remains unknown and 3-5 km of error in depths may be common even with local seismic networks. Different depths have been published for the plate interface beneath the Nicoya peninsula and can easily range ~3km above or below published depths. [Marino Protti, personal communication 2014]. The relocated seismicity shows strong clustering and as an alternative interpretation of relocated events could be as occurring along the plate interface (Fig 3.).

CONCLUSION

This study highlights the advantages of a dense relatively small seismic network. Using the Keck Network, a dense broadband temporary array of seismometers, invaluable data were collected, and provided insight into anomalous behavior of the September 5th 2012 Nicoya Earthquake rupture zone. An active oblique slip fault is proposed to have activated near a bounding edge of the rupture zone of the 2012 Nicoya earthquake. The fault activated as a secondary feature of the 2012 earthquake and is interpreted as due to variations in thermal structure, morphology, thickness, and frictional properties at the transition from EPR to CNS-1 crust. The fault locates directly on the edge of the 2012 rupture zone,

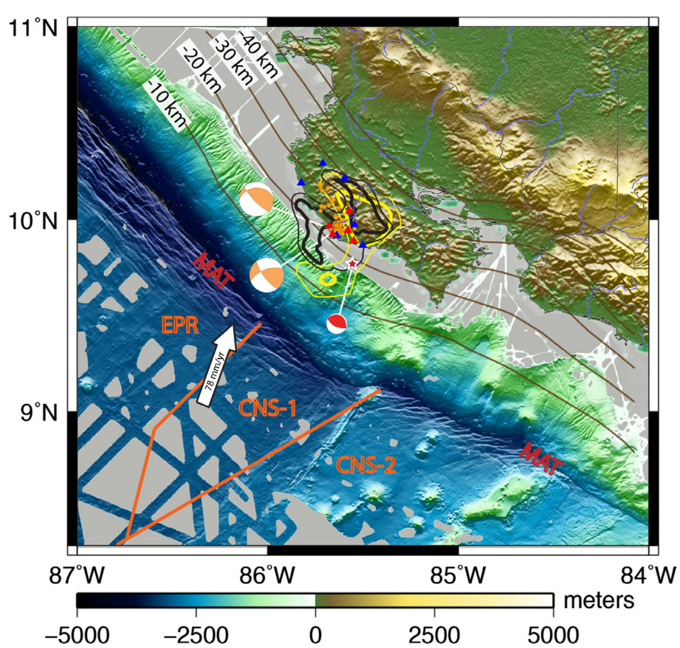

Figure 4. Summary map, orange circles: aftershocks of the 2012 Nicoya, Costa Rica earthquakes from June 23, 2013 to July 18, 2013. Red triangles: Keck Network station locations, blue triangles: Nicoya Network station locations utilized for event locations. Red star: epicenter of the September 5th 2012 Nicoya, Costa Rica Earthquake. Red focal mechanism: fault plane solution for 2012 Nicoya earthquake [Yue et al., 2013]. Yellow outlined area indicates the rupture zone of 2012 Nicoya Earthquake, regions of coseismic slip > 1.2 m outlined in thin yellow and slip > 2.0 m outlined with thick yellow [Yue et al., 2013]. The interseismic locked region is outlined in thick/thin black counters for > 80% and 100% slip deficit [Feng et al., 2012]. Orange focal mechanisms: the two preferred composite fault plane solutions for the fault implied to have been activated by the 2012 Nicoya Earthquake the fault forms at the bounding edge of the 2012 rupture zone. Dark brown lines: depth to slab contour in km [Audet & Schwartz, 2013]. MAT refers to the Middle America Trench and indicates it position. Acronyms EPR, CNS-1, and CNS-2 refers to the spreading center where the oceanic crust originates, Orange lines: boundaries between EPR, CNS-1 and CNS-2. The relative plate motion direction and convergence rate of the Cocos plate is indicated by the white arrow.

determined by *Yue et al.,* 2013 (Fig. 4), co-seismic slip does not propagate passed the fault. The fault also locates within the area of 80% slip deficit and a central region the between two large patches of 100% locking of the plate interface recognized by *Feng et al*., 2012 (prior to the 2012 Nicoya Earthquake). This indicates that the fault motion of the fault may have dissipated localized energy of the 2012 earthquake preventing slip/rupture from affecting the un-ruptured region which displays 80% and 100% slip deficit [*Feng et al*., 2012] (Fig. 4). This suggests the fault may have accommodated slip motion in this localized area. The fault plane solution (GCMT) for the Nicoya 2012 earthquake indicates a purely thrust mechanism. The activation of the right lateral oblique slip fault in the overriding Caribbean crust indicates slip partitioning of oblique convergence at the MAT. The fault accommodates for the strike slip component of motion and may further imply the development of a future forearc sliver.

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