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Nicoya Earthquake Rupture Anticipated by Geodetic Measurement of the Locked Plate Interface

Submitted to *Nature Geoscience*

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The Nicoya Peninsula of Costa Rica is one of the few places on earth where land exists directly over the seismically active subduction megathrust interface where large earthquakes occur. Nicoya suffers from magnitude 7+ earthquakes approximately every 50 years, and a new large earthquake was anticipated\textsuperscript{1,2}. The unique geography allowed recent land-based Global Positioning System (GPS) deformation\textsuperscript{3,4} and seismic studies\textsuperscript{5,6} to map out interseismic locking along the subduction interface that was accumulating elastic strain building for possible release in future earthquakes. On 05 September 2012 the long-anticipated Nicoya earthquake occurred in the heart of the previously identified locked patch. Here we use GPS and geomorphic observations of coseismic deformation along the peninsula to show that the moment magnitude ($M_W$) 7.6 Nicoya earthquake ruptured the lateral and downdip extent of the previously locked region. This study marks the first paired observation of the spatial extent of interseismic locking and subsequent coseismic rupture from a large megathrust earthquake. A previously locked region immediately offshore may not have slipped during the 2012 earthquake and may need more study to fully understand. The 2012 event highlights the utility of detailed near-field geodetic investigations for identifying future earthquake potential during the late interseismic period.

The interface between convergent plates produces most of the world’s largest earthquakes, threatening local inhabitants and global populations through destructive shaking and tsunami generation, as demonstrated by the recent 2011 $M_W$ 9.0 Tohoku-Oki and 2004 $M_W$ 9.15 Sumatra-Andaman earthquakes and tsunami. Because of the significant societal impacts, geoscientists endeavor to understand the driving and locking mechanisms controlling subduction zone seismicity. The shallow earthquake-generating portion of the subduction interface, hereafter
referred to as the megathrust, is difficult to characterize because it is relatively inaccessible, spans great lengths of continental margins, and requires detailed near-field observations primarily in the marine environment.

In the late-1990’s the Nicoya Peninsula of Costa Rica was recognized by the U.S. National Science Foundation MARGINS program as a focus area for seismogenic zone studies, in part because of the unique occurrence of land directly over the active subduction megathrust—normally, the megathrust seismogenic zone ends at or seaward of the coastline. The Cocos plate subducts beneath the Caribbean plate here at about 8.5 cm/yr according to recent plate motion models. Rapid plate convergence has generated magnitude 7+ earthquakes in 1853, 1900 and 1950 (Figure 1). Because a similar event was likely to occur geophysical characterization of the state of the megathrust environment during what we’ll refer to as the “late-interseismic” was a focus of a number of studies aimed at evaluating the temporal and spatial variations in seismicity, the controls on asperities, energy partitioning during rupture, and the nature of stress and strain through the seismic cycle.

Several recent studies developed detailed images of the geodetically locked interface from both GPS data, and microseismicity. These results using independent but complementary data types imaged a large, locked patch near the coastline of central Nicoya, roughly 60 km in length along-strike. At the periphery of this patch, studies identified a number of slow-slip events both down- and up-dip of the locked patch, and associated low- to very low-frequency earthquakes. A well-developed seismic lineation was originally thought to be the seismogenic updip limit, however geodetic locking was subsequently observed to exist both above and below this region, suggesting that the location of microseismicity alone cannot identify the shallow extent of significant locking. The most recent projects established the dense
network of broadband seismic and continuous GPS stations over the Nicoya Peninsula that recorded the 2012 earthquake in unprecedented detail.

The 2012 Nicoya earthquake occurred just after 08:42 am local time (14:42:05 UTC) on 5 September directly under the Nicoya Peninsula (Figure 1). The event was expected given recent studies that used geodetic and seismic means to illuminate plate coupling and build-up of elastic strain\textsuperscript{3,4,7,14,15}. In part due to recent efforts to raise awareness throughout the peninsula and develop and enforce building codes\textsuperscript{2} there were no confirmed human fatalities from this event even though local ground shaking was observed to be higher than 0.5 g on the peninsula, with a maximum value of almost 1.4 g near the epicenter\textsuperscript{16}. No substantial tsunami was observed from this earthquake, consistent with expectations of prior studies\textsuperscript{17}.

The earthquake initiated immediately seaward of the central portion of the peninsula and ruptured down-dip with the most impulsive component occurring 3 seconds later\textsuperscript{18}. Centroid moment tensor solutions roughly align with the axis of the trench and locate down-dip of the initial hypocenter\textsuperscript{18,19} (Figure 1). In the 32 minutes prior to the mainshock, three local magnitude $M_L$ 2+ foreshocks occurred within 25 km of the Nicoya earthquake epicenter (Figure 1c). The largest and last foreshock ($M_L$ 2.9) occurred just 2 minutes before the mainshock. In the weeks before the earthquake slow-slip similar to prior events\textsuperscript{9,10} was not observed. Early aftershocks were observed in the first several days across the peninsula, but are dominantly in the region surrounding and down-dip of the earthquake hypocenter. Geomorphic coastal uplift observations, and both continuous and repeat survey GPS measurements obtained within the first 5 to 12 days after the event highlight large trench-ward horizontal displacements up to 68 cm and uplift up to 53 cm along the central coast, with deformation diminishing, and uplift transitioning to subsidence further inland (Figure 2). The GPS also revealed a clear “pivot-line” denoting the
inland transition between vertical uplift and subsidence marking the downdip extent of major slip (Figure 2) – a feature that occurs offshore in most large megathrust earthquakes, including the 2011 Tohoku-Oki event\textsuperscript{20}. Along the central coast uplift was over 0.5 m causing visible changes in the coastline, particularly along rocky tidal platforms and estuaries (Figure 3). This region also had the maximum late-interseismic subsidence of about 1.0 cm/yr, corresponding to almost 100\% recovery of vertical strain accumulation since the last major earthquake 62 years prior if interseismic deformation rate remained constant through the period.

The earthquake occurred in the immediate area defined by prior geodetic studies and was approximate to, but was somewhat smaller than, the expected $M_W$ 7.7-7.8 given the spatial extent of interseismic coupling assuming constant strain accumulation since the 1950 magnitude 7.7 earthquake\textsuperscript{4}. A smaller $M_W$ 6.9 earthquake occurred in central Nicoya in 1978, having about 0.7 m slip\textsuperscript{7}. Though relatively small, this event may have been sufficiently large to modestly postpone the most recent event as it accounts for approximately 16\% of the accumulated strain energy between 1950 and 2012\textsuperscript{4}. Details of the seismic, geodetic and geomorphic data and subsequent reduction methods are included in the electronic supplement.

Inversions of three-dimensional displacement vectors from 18 continuous and 21 campaign GPS sites (Figure 2) using the same model geometry as developed in the Feng study\textsuperscript{4} show that the earthquake ruptured the landward extent of the most recently defined locked patch along the central coast of Nicoya (Figure 4a). The locked patch, identified as the area creeping at less than 50\% of the convergence rate, has a rather complex geometry that corresponds to characteristics of the incoming plate, as identified by magnetic lineations\textsuperscript{21}. The coseismic slip distribution as determined from strong ground motion and teleseismic waveforms, and a sub-
network of 11 GPS stations, including 9 high-rate results, agrees well with that shown here from the static GPS.

An interesting aspect of this earthquake is that the rupture was not obstructed by a well-documented transition in subduction crust origin and morphology. The northwestern segment of the incoming plate was generated at the East-Pacific Rise (EPR), while the southeastern segment was generated along the Cocos-Nazca Spreading center (CNS). While the plates are of similar age (20-24 Ma), differences exist in the orientation of the subducting crusts relative to their plate generation axes as identified by seafloor magnetic anomalies. Trench-parallel subduction of anomalies occurs along the EPR section, while trench-perpendicular subduction occurs along the CNS section. Along the subduction interface, the transition between subducted segments corresponds to differences previously noted in the depth of microseismicity, predicted thermal profiles, tomographically-defined slab morphology, and long-term net forearc uplift over multiple seismic cycles. Along with an estimated 35°C increase in temperature, an approximate 5 km upward shift in the depth of the megathrust interface occurs along the transition from EPR to CNS crust at seismogenic depths. Though not well understood, this transition corresponds to a change in the interseismic coupling immediately offshore, with a fully locked patch occurring along the EPR segment and significant creep to the south past the EPR-CNS transition. Landward of the coast, the interseismic coupling also transitions between EPR and CNS segments. Here, along the EPR subducted segment, there appears to be a creeping section that corresponds to ongoing microseismicity before becoming more coupled again immediately downdip. However, along the CNS segment, coupling remains high through the zone of microseismicity before hitting the downdip limit at about 30-35 km depth.
The earthquake, though initiating immediately offshore, ruptured primarily beneath land with up to 4.3 meters of thrust, and 1.1 m right-lateral motion. On average the large slip region includes 1.9 m of thrust and 0.3 m of right-lateral motion, as calculated by averaging the rake of the rupture area with slip $\geq 1$ m (Figure 4b), and similar to the rake of 102° CMT determined using local seismic data. The area of coseismic slip exceeding 2 meters covers the along-strike and downdip extent of interseismic locking. Updip and immediately offshore there appears to be no coseismic rupture, however some slip is required further offshore, but is mostly outside our area of resolution (Figure S3). The offshore locked segment does not appear to have ruptured (white contours in Figure 4b), and remains an area of possible concern.

The apparent remaining locked patch immediately offshore Nicoya is large enough to generate a substantial earthquake (up to $M_w$ 6.9), but decreasing resolution offshore prohibits an accurate assessment of the extent of this slip deficit. Such an event could slip as long-term postseismic afterslip, or occur as a single unusually large aftershock. Alternatively, this segment may remain locked and fail as part of a future large megathrust earthquake similar to the occurrence of the 2010 Mentawai earthquake following the 2007 Sumatran earthquake, or in one or multiple aseismic slow slip events, similar to those identified before the event. Along-strike to the northwest and southeast of the Nicoya earthquake, adjacent locked patches may also slip, in similar near-magnitude 7 events. Outside the area of resolution shown in Figure 4 little can be said about the near-term earthquake potential, and the possibility of a near-trench rupturing tsunami earthquake occurring offshore, similar to the 1992 Nicaraguan event immediately to the northwest, cannot be excluded. To constrain the potential for strain accumulation continued geodetic observations in the area, and along the seafloor are necessary.
Given the early establishment of seismic and geodetic networks, this event constitutes a success for international scientific efforts to illuminate subduction megathrust behavior prior to large earthquakes. In Nicoya, nearly 20 years of seismic, geodetic, and geomorphic data were collected in the late-interseismic period, and now unprecedented data are available to study coseismic rupture and postseismic processes. Many questions remain about the overall earthquake efficiency of subduction zones, particularly in Central America where earthquakes are estimated to account for less than 25% of the geodetically determined plate convergence rates. By evaluating ongoing deformation and earthquakes in the region, Nicoya becomes an opportunity to establish a unique “seismic cycle” observatory.

As the result of two decades of locally focused scientific discovery and infrastructural development, the location and approximate magnitude of the 2012 Nicoya earthquake were anticipated. The event ruptured the on-land extent of the previously locked section along the central Nicoya peninsula bounded by recently observed episodic slow slip events. An area of unrecovered strain accumulation may remain offshore, with the potential for a future large aftershock. The results from this study show the utility of detailed near-field geodetic observations and modeling for identifying major earthquake potential along interplate regions. For most other subduction environments similar near-field measurements would require substantial seafloor geodetic observations.

**Methods Summary:**

Details of the earthquake location method, GPS and geomorphic data reduction and inversion methods are included in an electronic supplement, and are only briefly summarized here.
**Earthquake locations:** Local earthquakes recorded by the UC Santa Cruz and Georgia Tech seismic networks were located within a local three-dimensional velocity model\(^2\) (Figure 1).

**GPS displacements and slip solutions:** Coseismic displacements of the Nicoya earthquake were determined by examining differential daily solutions of processed campaign and coseismic sites and are reported in Table S1. Most continuous GPS data reported the day after the earthquake, while campaign GPS data was used between 4 and 14 days after the event, with the shortest delays for sites above and near the main slip patch. For data where a large pre-seismic gap exists, the interseismic velocity field was used to correct for pre-event conditions. Using the GPS displacement fields a linear inversion scheme that trade-off roughness between individual slip patches was performed using the same model geometry as in the Feng study\(^4\). The optimal solution was chosen as one where a reasonable trade-off between increased solution misfit and increased model smoothness is obtained.

**Geomorphic uplift:** Uplift measurements were made at a total of 22 coastal sites between 5 and 16 days following the earthquake. Depending on the conditions of the site, one or any combination of six methods were used to determine relative ground-level changes. Offset measurements were corrected for tidal differences, differential wave run-up, and post-seismic deformation as observed by near-field GPS sites.
References:


All correspondence, and informational requests should be made to AVN.

**Acknowledgements:**

We thank the field team including S. Polster, J. Richardson, D. Voytenko, G. Barcheck, S. Morrish, E. Menjivar, and E. Hernandez. We thank the now finished NSF MARGINS program for providing regional focus for studying seismogenic zone processes in Costa Rica. Support to
SYS and THD was provided by NSF #0847382 and 1140261, support to JSM was provided by NSF #0948312, and support to AVN was provided by NSF #1262267 and #0847382.

Author contributions:

MP and VG provided original insight of Nicoya earthquake vulnerability, and long-term dedication and support to field research in Nicoya, including the post-earthquake campaign. AVN obtained NSF funds, managed the post-earthquake field campaign, and coordinated efforts on this manuscript. SYS and THD established and maintain much of the Nicoya seismic network, and the continuous GPS network, respectively. JSM performed pre and post-earthquake field geomorphic studies and provided final geomorphic results. Each AVN, SYS, THD, MP, and JSM provided individuals for the field campaign. JIW performed early aftershock analysis and provided Figure 1. SEO provided initial rapid GPS solutions for rapid field assessment. RM provided final GPS solutions. LF provided rapid and final inversion models for coseismic slip and Figures 4, S2 and S3. AVN wrote the paper with all authors adding contributions to the final version and supplementary text.

Competing financial interests:

The authors have no competing financial interests in this work.

Figures:

Figure 1: Past large earthquakes, prior microseismicity and aftershocks. [a] 05 September 2012 Nicoya Earthquake, foreshocks (bordered in white) and early aftershocks (colored by time of occurrence) are shown with past microseismicity (7) (open circles) and large earthquakes
(large colored regions). The global Centroid Moment Tensor focal mechanism (beach ball) shows almost complete thrust. Large earthquakes occurred immediately to the southeast and northwest of Nicoya in 1990 and 1992. The Nicoya seismic network is shown (black triangles).

[b] Hourly binned histogram of seismicity shows the timing of early aftershocks. [c] Events in the 1-hour bin during the mainshock include 3 foreshocks.

**Figure 2: Observed and modeled coseismic deformation of the 2012 Nicoya earthquake.**
The horizontal (left) and vertical (right) coseismic displacements were observed by campaign (orange circles) and continuous (yellow circles) GPS and geomorphic observations (blue circles). The “pivot-line” (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 geomorphic change highlighted in Figure 3. Also shown are the predicted displacements from the preferred coseismic slip model shown in Figure 4. GPS and geomorphic displacements are detailed in supplementary tables S1, and S2.

**Figure 3: Observations of earthquake-induced changes in a coastal estuary.** Pre and post-earthquake photographs of high tide at Playa Carrillo estuary (location shown in Figure 2), showing the effects of coseismic uplift directly inland of epicenter: [a] 5 July 2012, 3:50 pm (+3.0 m tide), [b] 13 September 2012, 12:30 pm, (+2.4m tide). The tide pictured at left was the highest 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. After correcting for predicted tidal differences (0.6 m) the coseismic uplift was determined to be 0.7±0.2 m.

**Figure 4: Comparison of late-interseismic coupling and coseismic displacement.** [a] Interseismic coupling (4) and [b] the preferred coseismic slip model for the 2012 Nicoya
earthquake (color contours and vectors) are shown in the area of maximum resolution (see Figure S3). Depth to interface is shown as vertical dashed contours (km). Downgoing lithosphere is generated by the East Pacific Rise (EPR) to the NW and Cocos-Nazca Spreading center (CNS) to the SW. The central 50% coupling area from (a) is shown is repeated in (b). A strongly coupled region immediately offshore did not appear to rupture during the 2012 earthquake (white contours).
Figure 1:
Figure 2:
Figure 4: