GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L01307, doi:10.1029/2010GL045586, 2011

Persistent tremor within the northern Costa Rica seismogenic zone

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Received 24 September 2010; revised 1 November 2010; accepted 15 November 2010; published 13 January 2011.

[1] We identify tremor using a spectral detection method and characterize its occurrence over a period of four years (2006–2009) in the vicinity of the Nicoya Peninsula, Costa Rica. Although a few major tremor events accompanied by geodetic slow slip occur, much of the tremor record consists of minor episodes with short duration and no detectable geodetic slip. Its persistent occurrence suggests that some portion of the interface is experiencing slow slip nearly continuously driving small patches to fail in accelerated slip. Locations indicate that much of the tremor occurs at shallow depth, in freely slipping regions of the seismogenic zone. This result is significant in that locations of slow slip and tremor at other subduction zones are largely limited to the downdip frictional transition. Tremor locations may help to refine the heterogeneous distribution of locked and freely slipping patches within the Costa Rica seismogenic zone. **Citation:** Walter, J. I., S. Y. Schwartz, J. M. Protti, and V. Gonzalez (2011), Persistent tremor within the northern Costa Rica seismogenic zone, *Geophys. Res. Lett.*, *38*, L01307, doi:10.1029/2010GL045586.

1. Introduction

[2] Most of the largest recorded earthquakes occur along the plate boundary at convergent margins. The region of the plate interface capable of rupturing during large earthquakes, termed the seismogenic zone, exhibits frictional stick-slip behavior and is bounded by stably sliding portions both up- and downdip [*Scholz*, 2002]. Because slow slip and tremor are thought to occur at transitions in frictional stability, the shallowest occurrence of tremor has been used to demarcate the downdip edge of the seismogenic zone and thus the greatest depth to which earthquake rupture can occur [*Chapman and Melbourne*, 2009]. More recently, it is becoming clear that frictional transitions from stick-slip to stable sliding are not confined to the up- and downdip edges of the seismogenic zone, but also occur within it. Seismic and aseismic slip have been shown to occur in complementary regions within the seismogenic zone in northeast Japan [*Igarashi et al.*, 2003], Sumatra [*Chileh et al.*, 2008], Chile [*Moreno et al.*, 2010], and Central Peru [*Perfettini et al.*, 2010]. Just as the occurrence of tremor has been used to delineate the downdip extent of seismic rupture, its incidence at shallower depth may help to refine the distribution of asperities within the seismogenic zone. Here we report persistent observations of tremor at the northern Costa Rica margin that locate within the seismogenic zone, at boundaries between locked and more freely slipping regions.

[3] In the vicinity of the Nicoya Peninsula in northern Costa Rica the Cocos and Caribbean plates undergo convergence at a rate of ~90 mm/yr [*Norabuena et al.*, 2004]. This relatively fast rate likely contributes to the abundance and short recurrence interval of large earthquakes. The following five magnitude 7 or greater earthquakes occurred in or around this region during the last century: 1990 M_s 7.2, 1916 M_s 7.4, 1939 M_s 7.3, 1950 M_s 7.7, and 1978 M_s 7.0 [*Nishenko*, 1991]. The 1950 M_s 7.7 earthquake was the largest event in this time period and both aftershock relocations [*Guendel*, 1986] and surface deformation [*Marshall and Anderson*, 1995] suggest a significant portion of the plate interface below the Nicoya Peninsula ruptured during this event. The shallow portion of the inferred rupture zone of the 1950 earthquake corresponds to a locked patch determined by inversion of geodetic data [*Norabuena et al.*, 2004; *LaFemina et al.*, 2009; *Outerbridge*, 2010]. It is thus the likely location of maximum slip (asperity) during the next large earthquake. Given that the largest two earthquakes preceding the 1950 event occurred in 1853 and 1900 [*Protti et al.*, 2001], the Nicoya Peninsula segment of the plate boundary is late in its earthquake cycle.

[4] The prevalent regional microseismicity of the Nicoya region [*DeShon et al.*, 2006] requires a tremor detection algorithm capable of discriminating tremor from microearthquakes. We developed a spectral detection method and apply it, along with a tremor envelope cross-correlation location technique, to produce a four-year tremor catalog. This catalog displays four major tremor episodes, including: a May 2007 event accompanied by slow slip and studied by *Outerbridge et al.* [2010], an August 2008 event, and two events in 2009 that are all under study; this paper focuses on the temporal/spatial relationships of the nearly continuous tremor record.

2. Data and Methods: Tremor Identification and Location

[5] The Nicoya seismic network (Figure 1a) was deployed in stages between 2006 and 2009. During this time instrumentation varied from an initial network consisting of 5 broadband (deployed in ~1.5 m deep vaults) and 3 short-period stations to a configuration of 10 broadband (4 in 5 m deep vaults) and 6 short-period stations, with 4 of these located in 100 m boreholes. Sampling rates also varied between 40 and 100 Hz depending on instrument type. To detect non-volcanic tremor (NVT) we developed a spectral method (see Text S1 of the auxiliary material), which discriminates tremor energy from prevalent regional microseismicity and cultural noise.[1] This method computes daily

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0094-8276/11/2010GL045586

[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL045586.

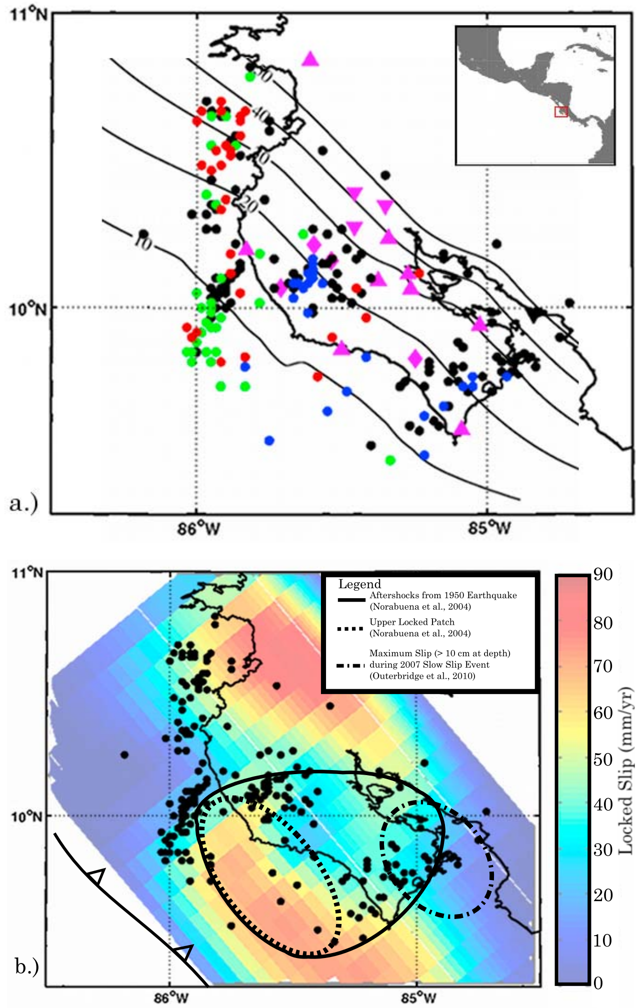

Figure 1. (a) Map of tremor locations color coded to correspond to the temporal record of tremor activity from Figure 3a, including major (blue-May 2007, green-August 2008, and red-April 2009) and minor (black) tremor events. Seismic stations are indicated by the magenta symbols with inverted triangles and diamonds representing borehole and deep vault sites, respectively. The black inverted triangle indicates the location of Puntarenas. (b) Contours of locked slip on the plate interface from *Outerbridge* [2010] with all tremor locations in black. The plate rate approaches ~90 mm/yr [*Norabuena et al.*, 2004]. The aftershock area of the 1950 Nicoya Peninsula Earthquake (Ms 7.7), the shallow locked patch determined by episodic GPS measurements [*Norabuena et al.*, 2004], and the region of maximum slip at depth (greater than 10 cm) during the 2007 Slow Slip Event [*Outerbridge et al.*, 2010] are also indicated.

network stacked spectrograms and identifies time windows where power exceeds a defined threshold in a tremor (2–7 Hz) and/or earthquake/noise (7–15 Hz) band. An example of this technique applied to a single day of seismic data (2008 JD 215) is presented in Figure 2. While many tremor detections are identified throughout (Figure 2a), the second half of this day contains a lot of energy above 5 Hz. This time period corresponds to 06:00 to 18:00 local time in Costa Rica and the energetic high frequencies are believed to reflect cultural noise. Abundant noise during daylight hours is typical of our entire data set. Although our method can detect tremor during daylight hours, tremor is surely obscured by the high level of noise during this time period. As opposed to noise with peak energy above 5 Hz, local earthquakes possess significant energy across the entire 2–15 Hz band (a few examples of local earthquakes are indicated by arrows in Figure 2c). These are always detected, categorized as both tremor (Figure 2a) and earthquake/noise (Figure 2b) and eliminated from our record of tremor counts (Figure 2d). Applying the detection method described, we obtain the tremor timeseries for 2006–2009 shown in Figure 3a. The relatively low number of tremor events prior to mid-2007 likely reflects fewer stations included in our analysis. Data from 3 additional short-period and 5 broadband stations became available in mid-2007 and mid-2008, respectively. For each detection in the tremor catalog, we employ an envelope cross-correlation method to locate tremor events (see auxiliary material). Locations of events with computed horizontal errors less than 5 km (true errors are expected to be much larger due to the simple velocity model and large uncertainties inherent to the envelope cross-correlation location method used) are shown on Figure 1. Applying this error criterion eliminates 70% of the events, so that only the better-located tremor events are retained.

3. Results and Discussion

3.1. Temporal Behavior of Tremor

[6] The four-year (2006–2009) tremor time series for the Nicoya Peninsula, Costa Rica (Figure 3a) reveals four major tremor episodes in May 2007, August 2008, January 2009, and June/July 2009. Geodetically detectable slow slip accompanied the May 2007 [*Outerbridge et al.*, 2010], August 2008, and 2009 tremor activity with details of the later two events currently under investigation. These four episodes account for only 22% of the tremor record with the remaining activity distributed nearly continuously in time. This is a fairly novel observation, since most accounts of tremor activity at other subduction zones emphasize its temporal clustering. The continuous nature of tremor activity may not be a unique property of the Costa Rica margin, due instead to enhanced tremor detection facilitated by the proximity of the network to shallow tremor sources. Although temporal clustering of tremor is generally emphasized, careful examination of tremor time series from Cascadia [*Wech and Creager*, 2008], Japan [*Suda et al.*, 2009] and Mexico [*Husker et al.*, 2010] reveals incessant low-level tremor activity between major tremor episodes. In all regions, only major tremor episodes are accompanied by geodetically recorded slow slip, but most studies still suggest that transient slip is what causes tremor. If tremor is driven by slow slip, its nearly continuous occurrence in northern Costa Rica suggests that transient slip is almost always occurring somewhere, along the ~100 km strike of the plate interface.

[7] Figure 3a appears to indicate a crude recurrence interval of 12–14 months for the more major tremor events, although this estimation is hardly robust given the relatively short monitoring period. Considering all tremor activity, a shorter period cyclic behavior emerges. Ocean loading has been shown to influence tremor activity in Cascadia [*Rubinstein et al.*, 2008; *Lambert et al.*, 2009] and Japan [*Nakata et al.*, 2008]. In order to assess ocean tidal influence on tremor in Costa Rica, we compute spectra for our tremor time series

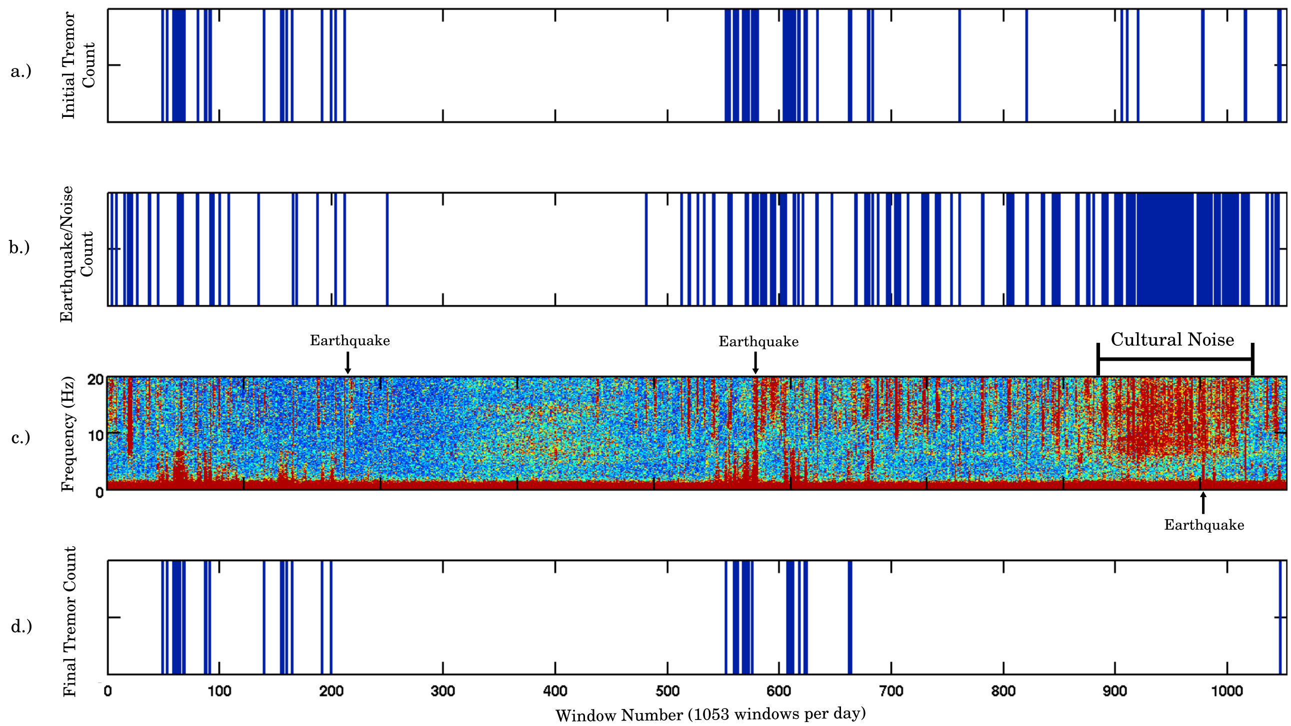

Figure 2. Illustration of the spectral detection method for one day (2008 JD 215) showing (a) initial tremor detections, (b) earthquake and cultural noise detections, (c) the daily stacked network-wide spectrogram with the color axis saturated at the detection threshold (red), and (d) final tremor detections determined by subtracting Figure 2b from Figure 2a. The high level of cultural noise and several earthquakes are indicated on the spectrogram.

and an equivalent four-year record of tide heights calculated for Puntarenas, Costa Rica (~15 km east of the Nicoya Peninsula). Predominant peaks in both datasets occur at approximately 180 days (Figure 3b), corresponding to the equinox period, where tides are enhanced due to earth's proximity to the sun. Although we recognize that the tremor catalog is woefully incomplete being far more likely to be missing detections during daytime hours and in the first 12–18 months of network operation, there is no indication of preferential seasonal detection that would bias the 180 day periodicity. Examination of the temporal tremor and tidal record for a single year of data in 2006, when seismic station coverage was sparse yet uniform, also shows the 180 day periodicity (Figure 3b). The qualitative correlation between spectra peaks at ~180 days suggests that tremor activity in northern Costa Rica is modulated by the ocean tide. As has been suggested in other regions where tides appear to modulate tremor, the areas of the plate interface where tremor occurs are inherently weak (having very low effective frictional stress) or critically stressed such that small perturbation to stress produce failure.

3.2. Spatial Behavior of Tremor

[8] Figure 1a shows the location of all tremor events with horizontal errors less than 5 km, color-coded for time of occurrence as indicated on Figure 3a. Superimposed on Figure 1b is the strain accumulation pattern determined from inversion of continuous GPS data collected on the Nicoya Peninsula between 2006–2009 [*Outerbridge*, 2010]. Both *LaFemina et al.* [2009] and *Norabuena et al.* [2004] used episodic GPS measurements with a similar network configuration to define the interseismic surface velocity field, and inverted these data for the locking pattern on the plate interface under the Nicoya Peninsula. These episodic measurements lack the temporal resolution to recognize slow slip events, biasing the picture of interseismic locking. The model of *Outerbridge* [2010] corrects surface displacements for offsets produced by the well-documented May 2007 slow slip event and inverts interseismic velocities that are about 30% higher than previous studies. This produces a strain accumulation pattern that consists of two fully locked patches, rather than patches locked at only 50–65% of the plate convergence rate obtained by previous studies. Although improved, we still consider this model to be provisional; inversion of longer, less noisy time series that include the vertical component of velocity are required to significantly improve both the resolution and uniqueness of the model. Given this caveat, a comparison of this strain accumulation model to the location of tremor events reveals that they are anticorrelated. Nearly all of the tremor events locate within the freely slipping regions or at the boundaries between freely slipping and locked regions within the seismogenic zone (Figure 1b).

[9] The up-dip limit of the seismogenic zone is well-defined by the shallowest extent of geodetic locking and the

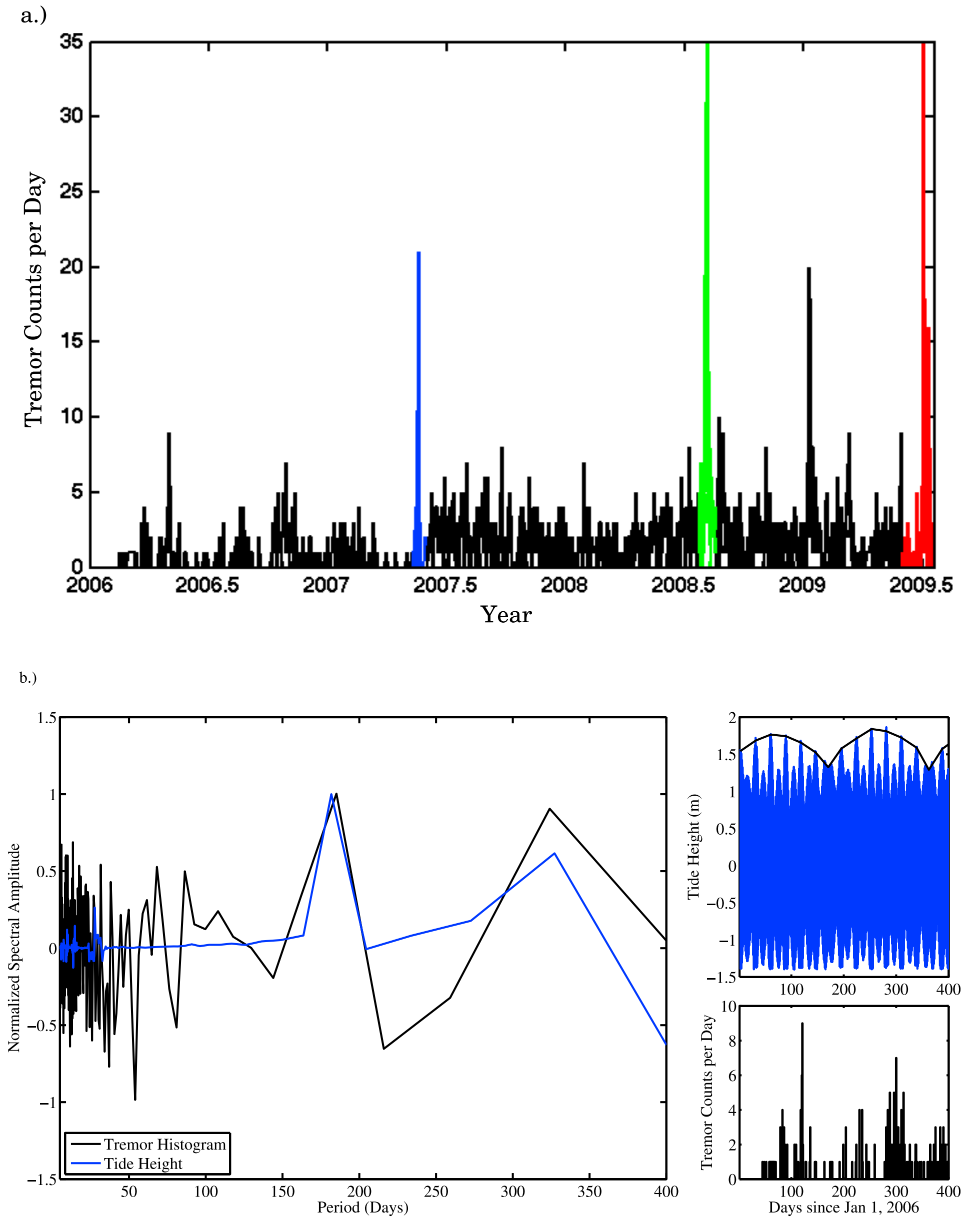

Figure 3. (a) Tremor histogram of daily events from 2006 through mid-2009. Three of the major tremor episodes are color-coded and event locations indicated in Figure 1 (blue for May 2007, green for August 2008, and red for April 2009). (b) (left) Spectra computed for the 2006–2009 tremor and tide height records calculated for Puntarenas, Costa Rica. (right) The 2006 tremor and tide height data to highlight the 180 day periodicity.

rupture of the 1950 Nicoya (M_S 7.7) earthquake [*Schwartz and DeShon*, 2007]. The downdip extent has been more difficult to determine given poorer GPS resolution above this transition that results in models of strain accumulation [*Norabuena et al.*, 2004; *LaFemina et al.*, 2009; *Outerbridge*, 2010] that differ significantly in this region. The deepest interplate seismicity occurs at about 30 km [*DeShon et al.*, 2006], which provides a minimum downdip limit to the seismogenic zone. Given these constraints, it is clear that tremor is distributed throughout the seismogenic zone, rather than at the downdip edge as reported in most other environments. If the occurrence of slow slip and tremor requires a transition in frictional properties from velocity weakening to strengthening, then tremor locations may be used to indicate where these frictional transitions occur within the seismogenic zone and thus the likely locations of maximum slip in future earthquakes.

4. Conclusions

[10] We developed a spectral method that can successfully detect tremor in the presence of prevalent microseismicity and cultural noise. We applied it to four years of seismic data (2006–2009) collected on the Nicoya Peninsula, Costa Rica and identified a few major tremor episodes with nearly continuous minor tremor activity in the intervening periods. In contrast to most other regions, Costa Rica tremor occurs at shallow depth, within the seismogenic zone. The tremor occurs within freely slipping regions, adjacent to patches that are presently accumulating strain [*Norabuena et al.*, 2004;

Outerbridge, 2010]. Although only the major tremor episodes are accompanied by geodetically detected slow slip, we believe that the copious minor tremor activity is also driven by episodic aseismic deformation that occurs more frequently than previously assumed. Variations in the quantity of tremor in time (major vs. minor episodes) may reflect the magnitude of slow slip deformation, as has been suggested by the linear scaling between tremor duration and geodetic moment in Cascadia [*Aguiar et al.*, 2009]. Both the major and minor tremor episodes tend to occur in similar localities assumed to be conditionally stable regions of the plate interface [e.g. *Scholz*, 2002]. These regions seem to be driven to failure in slow slip by very small stress perturbations caused by ocean loading. Therefore, the locations of tremor events are providing important information about the frictional properties and thus mechanical behavior of the plate interface.

[11] **Acknowledgments.** Thorough reviews by Hugo Perfettini and an anonymous reviewer considerably improved this paper. This work was supported by NSF awards OCE-0841061 and EAR-0842338 to S.Y.S. and a NASA Earth and Space Science Fellowship to J.I.W. We thank Dan Sampson, Andy Newman, Kim Outerbridge, Jaime Convers, Martin Thorwart, and Waldo Taylor for their invaluable assistance during installation and maintenance of the seismic network. Tidal data for Puntarenas, Costa Rica, was obtained using the freely available JTides program (http://www.arachnoid.com/JTides/). Some of the instruments used in the field program were provided by Andy Newman and Zhigang Peng at Georgia Tech and the PASSCAL facility of the Incorporated Research Institutions for Seismology (IRIS) through the PASSCAL Instrument Center at New Mexico Tech. Data collected during this experiment will be available through the IRIS Data Management Center. The facilities of the IRIS Consortium are supported by the National Science Foundation under cooperative agreement EAR-0552316 and by the Department of Energy National Nuclear Security Administration.

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