The synchronous occurrence of shallow tremor and very low frequency earthquakes offshore of the Nicoya Peninsula, Costa Rica

Jacob I. Walter,[1,2] Susan Y. Schwartz,[1] Marino Protti,[3] and Victor Gonzalez[3]

Received 18 December 2012; revised 30 January 2013; accepted 31 January 2013; published 29 April 2013.

[1] The occurrence of transient, shallow slow slip at seismogenic zones has important implications for earthquake and tsunami hazards. Here we provide evidence that a tremor and slow slip event occurred at shallow depth offshore of the Nicoya Peninsula, Costa Rica, in August 2008. The temporal coincidence of offshore tremor, very low frequency earthquakes (VLFEs), motions consistent with slow slip on the plate interface on western coastal GPS stations, and a pressure transient in an IODP borehole all indicate slow slip occurring at shallow depths. Large ocean loading stresses on the shallow plate interface modulate tremor activity, with the peak Coulomb stress forced by semi-diurnal ocean tides correlating with tremor productivity. Based on beamforming data, we constrain that the VLFE activity occurs in the same region as the tremor and slow slip. The presence of slow slip at shallow depth has important implications for the up-dip extent of earthquake rupture. The proximity of the 5 September 2012, M_w 7.6 megathrust earthquake to slow slip, tremor, and VLFE activity in the 2008 event suggests abrupt frictional transitions from locked to conditionally stable behavior on the plate interface offshore of the Nicoya Peninsula.
Citation: Walter, J. I., S. Y. Schwartz, M. Protti, and V. Gonzalez (2013), The synchronous occurrence of shallow tremor and very low frequency earthquakes offshore of the Nicoya Peninsula, Costa Rica, *Geophys. Res. Lett., 40*, 1517–1522, doi:10.1002/grl.50213.

1. Introduction

[2] At a subduction zone, as the oceanic plate slides beneath the overriding plate, the motion is resisted by friction at their contact. This friction is overcome as elastic energy is released by earthquakes of all sizes, including some of the world's largest on record. The largest earthquakes nucleate and propagate at intermediate depths along the megathrust interface. Frictional conditions that control the accumulation of strain across the interface can vary along-dip and along-strike, due to increasing pressure and temperature, contact roughness, presence of soft sediments and fluids at the plate interface, and a number of other physical parameters. In order to characterize these interfaces, GPS has been used to record deformation associated with locked plate boundaries. The widespread use of continuous GPS in the last decade at subduction zones has led to the discovery of episodic slow slip at some of these margins [e.g., *Miller et al.*, 2002].

[3] Slow slip in Japan and Cascadia is typically accompanied by episodes of tectonic tremor [*Rogers and Dragert*, 2003; *Obara et al.*, 2004]. In the last decade, the number of observations of episodic tremor at different subduction zones and continental faults has increased significantly to include Mexico [e.g., *Payero et al.*, 2008], Alaska [e.g., *Peterson and Christensen*, 2009], New Zealand [*Kim et al.*, 2011; *Wech et al.*, 2012], the San Andreas fault [e.g., *Nadeau and Dolenc*, 2005], and Costa Rica [*Outerbridge et al.*, 2010; *Walter et al.*, 2011], in addition to Cascadia and Japan. Most of these observations include tremor occurring down-dip of the frictionally locked seismogenic zone in areas believed to be at the transition between stick-slip and stably sliding behavior. Costa Rica is the one subduction zone where both tremor and slow slip are documented to occur up-dip or within the seismogenic zone [*Walter et al.*, 2011].

[4] At the Nankai Trough in Japan, a new class of slow earthquakes, deficient in seismic energy above 0.05 Hz, called very low frequency earthquakes (VLFEs) was discovered [*Obara and Ito*, 2005]. The Nankai VLFEs occur in similar locations to deep tectonic tremor during episodic tremor and slow slip [*Ito et al.*, 2007] as well as at the accretionary prism, near the trench [*Ito and Obara*, 2006; *Ito et al.*, 2009; *Hirose et al.*, 2010]. Initial discovery of VLFEs located them within the accretionary prism sediments where the elastic rigidity and therefore accumulation of elastic strain are thought to be low. Close by recordings of these shallow VLFE made by ocean bottom seismometers indicates that they represent slow, yet seismic slip at the interface of accretionary prism sediments and the subducting oceanic crust [*Sugioka et al.*, 2012]. These events have both long source durations and radiate high-frequency energy, consistent with the simultaneous occurrence of fast and slow rupture mechanisms [*Sugioka et al.*, 2012]. Earthquakes can rupture to the trench and produce devastating tsunamis, as demonstrated by the 2011 Tohoku event [e.g., *Lay et al.*, 2011]. Thus, it is critical to understand the frictional behavior of the shallowest portions of subduction zone thrusts and determine if strain is released by earthquakes, stable sliding, slow slip, or hybrid processes akin to the Nankai VLFEs. Here we describe the behavior of the shallow plate interface offshore the Nicoya Peninsula, Costa Rica. In contrast to Nankai, this margin has little to no sediment entering the trench, but like Nankai, its shallow plate interface generates VLFEs and exhibits slow and fast rupture characteristics in close proximity.

All Supporting Information may be found in the online version of this article.

[1]Department of Earth and Planetary Sciences, University of California, Santa Cruz, Santa Cruz, California, USA.
[2]Now at School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia, USA.
[3]Observatorio Vulcanológico y Sismológico de Costa Rica, Universidad Nacional, Heredia, Costa Rica.

Corresponding author: J. I. Walter, School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA, USA. (jwalter@gatech.edu)

0094-8276/13/10.1002/grl.50213

[5] At the Nicoya Peninsula, the Cocos plate converges with the Caribbean plate at a rate of 78 mm/yr [*Protti et al.*, 2012]. This fast rate likely contributes to the frequent magnitude 7 or greater earthquakes that occurred on or near the Nicoya Peninsula within the last century: an M_w 7.6 event on 5 September 2012, an M_s 7.7 event in 1950, and two magnitude 7 events in 1978 and 1990 [*Protti et al.*, 2001]. University of South Florida, University of California Santa Cruz, and OVSICORI-UNA, in collaboration with the Georgia Institute of Technology, operate a network of high precision, continuously recording GPS receivers and broadband seismometers on the Nicoya Peninsula (Figure 1). This network has been used to identify at least five slow slip and tremor episodes in the last decade in this region [*Outerbridge et al.*, 2010; *Walter et al.*, 2011; *Jiang et al.*, 2012], including the 2008 event. This paper strengthens and builds on results from previous work [*Walter et al.*, 2011] demonstrating that Nicoya slow slip and tremor occurs at the up-dip, shallow limit of the seismogenic zone, is tidally modulated, and that the slow slip activity is also accompanied by VLFEs.

2. Observations

2.1. Tremor Semi-diurnal Periodicity

[6] Early August 2008 was the most energetic period of Costa Rica tremor, identified in a previous study [*Walter et al.*, 2011]. The occurrence of this tremor at shallow depth, directly below the ocean in a region that experiences a large range in ocean tides, suggests that tidally induced stresses may influence tremor behavior. In order to determine the nature of the tidal forcing, we used the tidal program SPOTL [*Agnew*, 1996] to compute the ocean tide heights near the tremor locations. Perturbations of stress are determined via plane stress transformations [*Wilcock*, 2009] on a shallow dipping fault with a rake of 90° (reverse fault). The total stress promoting failure is called the Coulomb stress [*Scholz*, 2002], and relative changes can be calculated as follows:

$$\Delta\sigma_c = \Delta\tau - \mu_f \Delta\sigma_n \tag{1}$$

where $\Delta\sigma_c$ is a change in the Coulomb stress, $\Delta\tau$ is a change in the shear stress, μ_f is the coefficient of friction, and $\Delta\sigma_n$ is a change in normal stress, where compressional stresses are positive. We use a value of 0.6 for the coefficient of friction. Figure 2 shows relative changes in shear, normal, and Coulomb stresses due to ocean loading on the fault plane plotted with hourly-binned tremor counts from *Walter et al.* [2011]. The phases of positive shear and Coulomb stress qualitatively correlate well with tremor counts. The tremor activity occurs primarily during 02:00 and 14:00 UTC, which corresponds to 20:00 and 08:00 local time, respectively. Therefore, observations of tremor do not appear to be biased towards occurring only during periods of time when cultural noise is expected to be low.

[7] Tremor in Cascadia [*Rubinstein et al.*, 2008] and Japan [*Nakata et al.*, 2008] is modulated at semi-diurnal and diurnal periods during slow slip events by ocean and solid-earth tides. In those studies, stresses were estimated at 40 km depth and were an order of magnitude smaller [*Nakata et al.*, 2008] or a similar order of magnitude (when only ocean tide forcing was considered [*Rubinstein et al.*, 2008]) to the stresses we estimate. In Costa Rica, because the tremor locates at shallow depths, we calculate the effect of ocean loading at the seafloor due to the predicted tide change (Figure 2), with a correction for a shallow dipping fault plane [*Wilcock*, 2009]. The stresses we calculate are an order of magnitude larger than horizontal stresses predicted from solid earth tides. Therefore, we ignore the horizontal solid earth tides, as they do not alter the predicted stresses significantly. Previous results suggest that tremor is modulated over ~180 day period, corresponding to the equinox tide [*Walter et al.*, 2011]. During this particular event in 2008, the tremor appears to be strongly modulated by the Coulomb stress changes due to ocean tides at tidal (semidiurnal) periods. The strong tidal periodicity of tremor at Costa Rica suggests that during the tremor and slow slip event, the plate interface is at a critical threshold, such that the small Coulomb stress changes promote slip and its accompanying tremor activity.

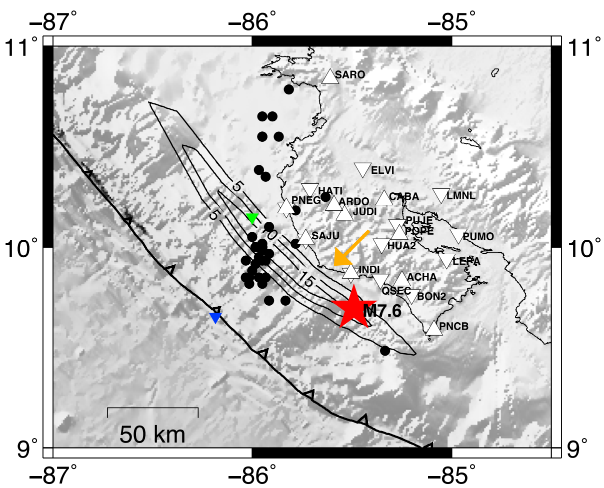

Figure 1. Map of the seismic network at the Nicoya Peninsula, Costa Rica, and evidence of shallow tremor and a slow slip event in August 2008. Contours are modeled displacement during the slow slip event [*Jiang*, 2012], where the contour interval is 5 mm. White filled triangles indicate seismic stations, and white inverted triangles indicate continuous GPS stations operating during the 2008 event. Black filled circles are locations of tremor events occurring in August 2008, the red star indicates the epicenter of the 5 September 2012 M_w 7.6 earthquake, and a blue inverted triangle marks the position of the pressure observation in IODP Borehole 1255. The green inverted triangle indicates the location of the ocean tide prediction. The orange arrow indicates azimuth of the VLFE activity during VLFE event number 35 (Figure 5), where the arrow's origin is the center of the array.

2.2. VLFE Presence and Source Constraints

[8] Very low frequency earthquakes (VLFE) embedded within tremor are detected during the 2008 slow slip event (2008 JD 210–230) by band-passing the east component daylong seismograms between 0.02 and 0.05 Hz and identifying periods of coherent energy across multiple stations. The VLFEs appear to lack body waves, making the determination of their location and origin time difficult. Fifty-four events are detected, which all occur during periods of tremor. An example set of seismograms during an active period of VLFEs is shown in Figure 3. The VLFE catalog is included as a

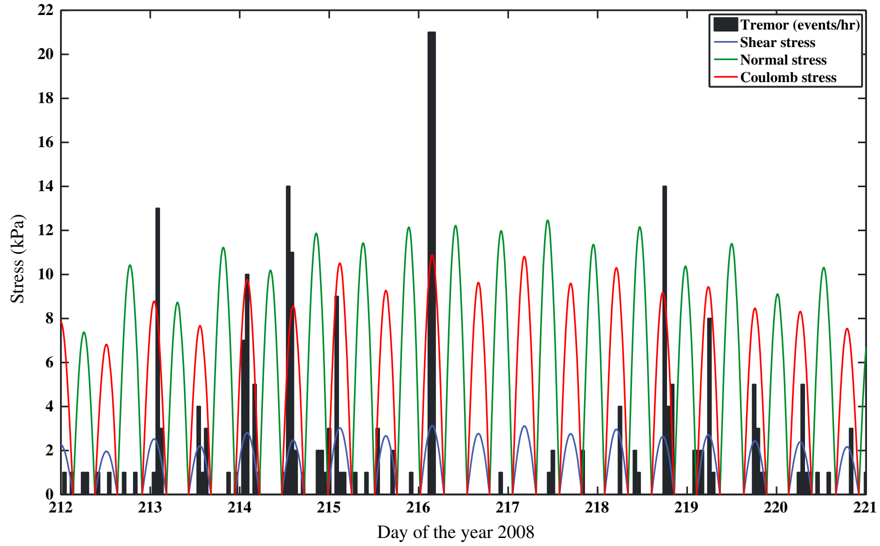

Figure 2. Ocean loading stresses oriented with respect to a shallow (20°) dip on the subduction interface from predicted tides near the offshore tremor locations. Blue, green, and red lines indicate estimated shear, normal, and Coulomb stresses, respectively. Black bar graph indicates number of tremor counts binned hourly.

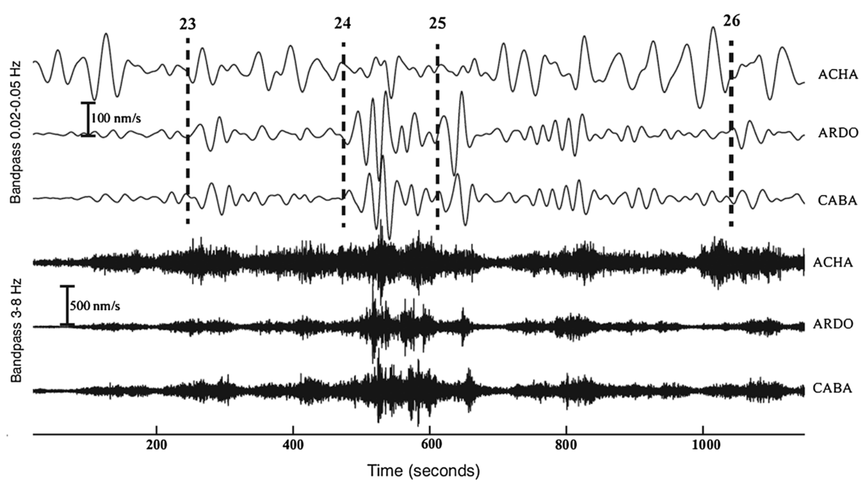

Figure 3. Example of presence of VLFEs during increased tremor activity. All stations are the horizontal east component of the ground velocity, the top three seismograms are band-passed from 0.02 to 0.05 Hz, and the bottom three are band-passed from 3 to 8 Hz for the same stations. Vertical dashed lines indicate identification of VLFEs and their corresponding event number (See supplementary table). Each subset of three seismograms shares the same vertical scale.

supplemental table, and a histogram of the VLFE activity is shown with tremor in Figure 4a.

[9] We cannot definitively demonstrate that the tremor and VLFEs originate at the same location; however, we can approximate VLFE locations for comparison with our tremor catalog. We use delay-and-sum beamforming [e.g., *Rost and Thomas*, 2002] on band-passed vertical component seismograms to determine the azimuth and speed of the VLFE long period energy (auxiliary material). Beamforming results for VLFE 35 on Day 216 are shown on the polar plot in Figure 5a. The highest amplitude stack is at an azimuth of ~225° from the center of the seismic array and wave speed of 3000–4000 m/s, which is also the approximate azimuth of the offshore tremor (Figure 1). The value of 3000–4000 m/s is consistent with surface wave velocities for this region [*DeShon et al*., 2006].

[10] In order to expand this analysis to other events, we perform the beamforming technique on all three components for all the events. We beamform each event and each component, as described previously, and record the azimuth with the maximum amplitude beam. We average the preferred azimuth of the three components for each of the events, and those data are shown in Figure 5b, in addition to error bars defined by the 1σ standard deviation. We only show azimuths for those events where the standard deviation is less than 80°, leaving 26 of the 54 detected events (Figure 5b).

2.3. Coastal and Seafloor Evidence of Slow Slip

[11] In addition to the tremor locations and the inferences of co-located VLFEs, GPS data also indicate that slow slip occurred offshore of the Nicoya Peninsula over a period of

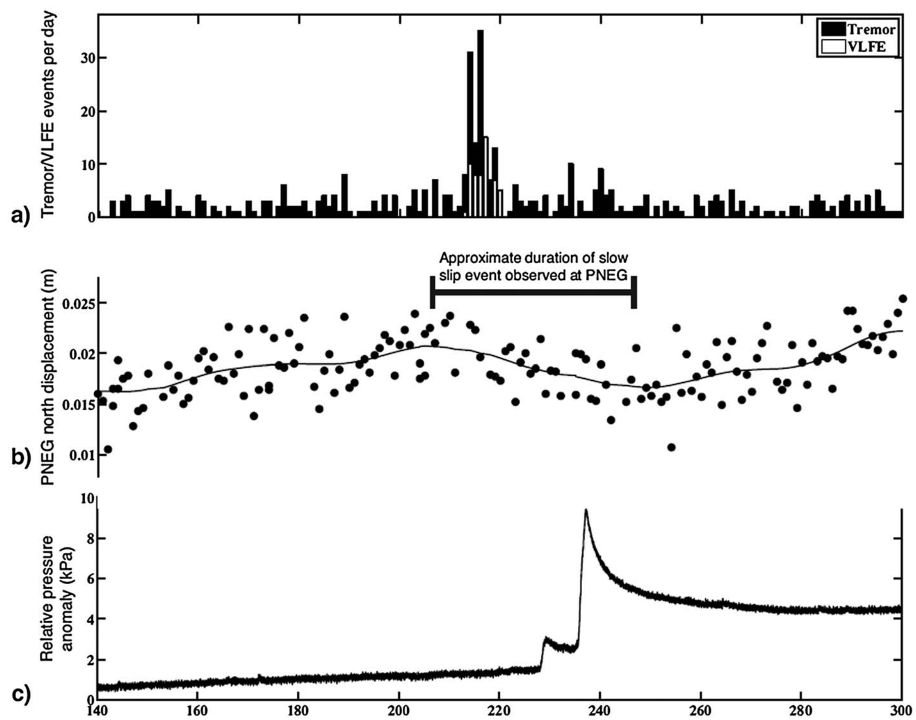

Figure 4. Evidence for synchronous offshore slow slip and tremor. (a) Tremor histogram of events per day, (b) GPS displacement at coastal station PNEG, and (c) pressure transient observed at IODP Site 1255. The peak pressure changes occur ~15–25 days following the peak in tremor activity.

approximately 20 days between 28 July and 17 August 2008 [*Jiang et al.*, 2012]. Daily displacement estimates for station PNEG relative to Managua, Nicaragua, are shown in Figure 4b, including a 30 day running average. Only GPS stations in the western coastal regions of the Nicoya Peninsula recorded the slow slip event, and inversion of surface displacements at these stations reveals a maximum slip of nearly 2 cm between 12 and 18 km depth on the plate interface [*Jiang*, 2012] (Figure 1), equivalent to a M_w 6.1 earthquake. The geodetic slow slip is approximately temporally (Figure 4) and spatially (Figure 1) coincident with the peak in tremor activity. The slow slip event appears to begin ~7 days before and continue for ~20 days following the peak in tremor activity; however, the temporal resolution of this transient slip event is very poorly constrained.

[12] Another line of evidence for offshore upper-plate deformation includes pressure transients observed in the IODP Site 1255 borehole [*Davis et al.*, 2011]. The site is located 400 m arc-ward of the trench and drilled through the overlying sediment. The location of the offshore borehole appears on Figure 1 as a blue square. Figure 4c shows a pair of pressure transients that occurred approximately 15–25 days following peaks in tremor activity. The positive sign of the anomaly likely represents contraction in the prism sediments [*Davis et al.*, 2011], consistent with the interpretation that slip occurred on the plate interface. Similarly, previous measurements of seafloor fluid flow in this area have been attributed to seafloor deformation during inferred aseismic slip [*Brown et al.*, 2005]. The temporal delay of 15–25 days for the observation of pressure transients following the peak in tremor activity may indicate migration of the slow slip event towards the trench [*Davis et al.*, 2011].

3. Discussion

[13] In Japan, VLFEs occur near the trench [*Ito and Obara*, 2006], as well as down-dip of the seismogenic zone [*Ito et al.*, 2007; *Ito et al.*, 2009]. In addition, during a single slow slip event in the Bungo Channel, tremor and VLFE activity spanned the seismogenic zone, occurring simultaneously up-dip (VLFE) and down-dip (tremor), providing evidence that slow slip occurred in the intervening region within the seismogenic zone and continued to shallow depth [*Hirose et al.*, 2010]. The first analysis on the near-trench Japan VLFEs concluded that they occurred on splay faults within the accretionary prism in response to dynamic deformation of the prism during slow slip events [*Ito and Obara*, 2006]. A subsequent study that utilized ocean bottom seismometers found that shallow VLFEs occurred on the slipping interface [*Sugioka et al.*, 2012]. Thus, it is becoming clear that the Nicoya Peninsula is not unique in experiencing slow slip within a range of depths on the plate interface including down-dip [*Brown et al.*, 2009], up-dip, and within the seismogenic zone [*Walter et al.*, 2011]. Slow slip straddling the seismogenic zone may amplify the seismic hazard compared with down-dip slip alone by increasing the strain on the locked interface.

[14] The epicenter of the 5 September 2012 M_w 7.6 Nicoya earthquake adjacent to the 2008 slow slip and tremor activity (Figure 1) suggests a rather abrupt transition from a locked [*Feng et al.*, 2012] to a conditionally stable plate interface offshore the Nicoya Peninsula. There is evidence for another abrupt transition northwest of the Peninsula. Slow slip occurring here is suggested by some of the VLFE beamforming locations as well as the occurrence of the 1992 Nicaragua tsunami earthquake [*Ide et al.*, 1993].

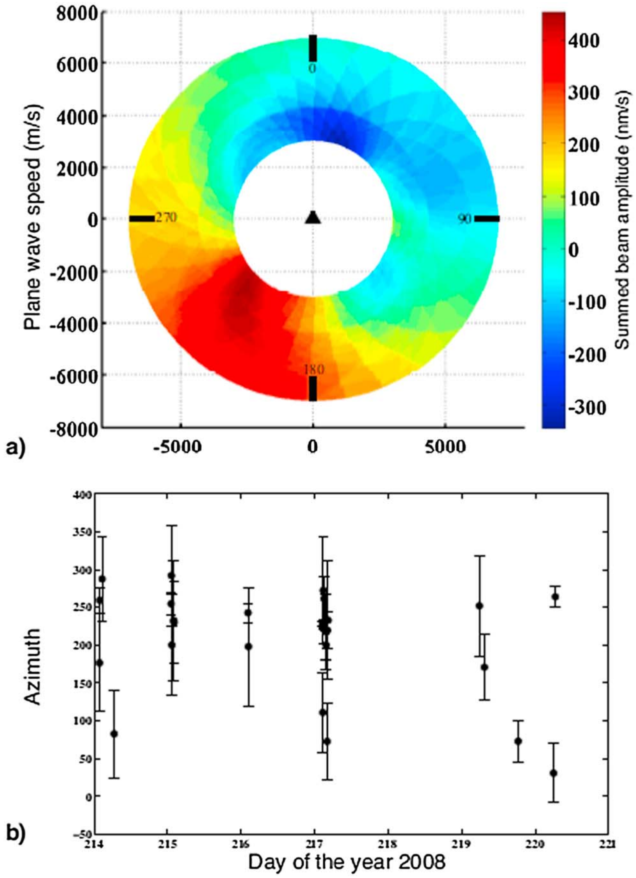

Figure 5. Beamforming of VLFE activity. (a) Example for event 35, indicating azimuth and plane wave speed of highest amplitude beam. Colorbar indicates beam amplitude. (b) Average azimuth for the three components, where error bars indicate standard deviation. Note that Figure 5b includes 26 of 54 identified events, as we do not show events where the standard deviation is greater than 80°.

Tremor and possibly VLFEs may concentrate at these frictional transitions [*Walter et al.*, 2011].

[15] The dense instrumentation in Japan and proximity of the Nicoya Peninsula to the trench has led to the identification of VLFEs thus far at only these two margins. Recent evidence suggests VLFE activity at an erosional margin like Nicoya, in north Japan [*Asano et al.*, 2008]. However, the occurrence of VLFEs at subduction zones with very different near-trench structure, erosional at the Nicoya Peninsula versus accretionary at Nankai, suggests that shallow VLFE and slow slip events may be ubiquitous phenomena. Recent efforts to install broadband ocean bottom seismometers at the Cascadia margin may confirm such a hypothesis.

4. Conclusions

[16] We provide evidence that a shallow slow slip event occurred offshore of the northwest portion of the Nicoya Peninsula adjacent to the 2012 Nicoya earthquake. The tremor during this time period locates offshore and has a semi-diurnal periodicity. In addition, coastal GPS and pressure transients in a borehole observatory near the trench provide evidence of shallow slip on the plate interface. Further evidence is the presence of VLFEs which, when beamformed, seem to originate in a similar source region. Since 2008, we have augmented the number of broadband instruments in the Nicoya network, which will improve future detailed analysis of VLFE events.

[17] The compilation of all the data outlined in this paper suggests that a slow slip event occurred offshore and possibly at the shallowest limit of the plate interface. Typical conceptual models for earthquake nucleation at subduction zones suggest that frictional coupling does not occur near the trench, though the presence of tremor and VLFEs suggests that the plate interface sometimes becomes locked near the shallow limit. Frictional coupling processes at this upper limit are especially relevant for predicting hazards from tsunamis produced by megathrust earthquakes. Finally, identifying the diverse behavior of subduction zones may improve our understanding of the spatial and temporal dimensions of the earthquake cycle. For example, the tremor activity presented in this paper occurs in an area between slow slip and a recent large earthquake, suggesting that it occurs at the frictional transition from stick-slip to steady sliding.

[18] **Acknowledgments.** We thank two anonymous reviewers for careful reviews that greatly improved the manuscript. This work was supported by a NASA Earth and Space Science Fellowship to J.I.W. and NSF grants EAR 0842338 and OCE 0841061 to S.Y.S. GPS network equipment services and field support provided by the UNAVCO Facility with support from the National Science Foundation (NSF) and National Aeronautics and Space Administration (NASA) under NSF Cooperative Agreement No. EAR-0735156. 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. Seismic and CGPS networks in and around the Nicoya Peninsula are operated by SISMOGENICO (Sistema de Monitoreo Geodinamico de Nicoya) project of OVSICORI-UNA. Figure 1 was constructed using GMT [*Wessel and Smith*, 1998]. We thank Dan Sampson for his continued technical assistance maintaining the seismic network. We also thank Emily Brodsky, Slawek Tulaczyk, and Thorne Lay for comments on an earlier version of this manuscript.

References

Agnew, D. C. (1996), SPOTL: Some Programs for Ocean-Tide Loading, SIO Ref. Ser. 96–8, 35 pp., Scripps Institution of Oceanography, La Jolla, CA.

Asano, Y., K. Obara, and Y. Ito (2008), Spatiotemporal distribution of very-low frequency earthquakes in Tokachi-oki near the junction of the Kuril and Japan trenches revealed by using array signal processing, *Earth Planets Space*, *60*, 871–875.

Brown, K. M., M. D. Tryon, H. R. DeShon, L. M. Dorman, and S. Y. Schwartz (2005), Correlated transient fluid pulsing and seismic tremor in the Costa Rican subduction zone, *Earth Planet. Sci. Lett.*, *238*, 189–203.

Brown, J. R., G. C. Beroza, S. Ide, K. Ohta, D. R. Shelly, S. Y. Schwartz, W. Rabbel, M. Thorwart, and H. Kao (2009), Deep low-frequency earthquakes in tremor localize to the plate interface in multiple subduction zones, *Geophys. Res. Lett.*, *36*, L19306, doi:10.1029/2009GL040027.

Davis, E., et al. (2011), Evidence for episodic aseismic slip across the subduction seismogenic zone off Costa Rica: CORK borehole pressure observations at the subduction prism toe, *Earth Planet. Sci. Lett.*, *306*(3–4), 299–305, doi:10.1016/j.epsl.2011.04.017.

DeShon, H. R., S. Y. Schwartz, A. V. Newman, V. Gonzalez, J. M. Protti, L. M. Dorman, T. Dixon, E. Norabuena, and E. Flueh (2006), Seismogenic zone structure beneath the Nicoya Peninsula, Costa Rica, from 3D local earthquake P and S wave tomography, *Geophys. J. Int.*, *164*, 109–124, doi:10.1111/j.1365-246X.2005.02809.x.

Feng, L., A. V. Newman, M. Protti, V. González, Y. Jiang, and T. H. Dixon (2012), Active deformation near the Nicoya Peninsula, northwestern Costa Rica, between 1996 and 2010: Interseismic megathrust coupling, *J. Geophys. Res.*, *117*, B06407, doi:10.1029/2012JB009230.

Hirose, H., Y. Asano, K. Obara, T. Kimura, T. Matsuzawa, S. Tanaka, and T. Maeda (2010), Slow earthquakes linked along dip in the Nankai subduction zone, *Science*, *330*, 1502, doi:10.1126/science.1197102.

Ide, S., F. Imamura, Y. Yoshida, and K. Abe (1993), The characteristics of the Nicaraguan tsunami earthquake of September 2, 1992, *Geophys. Res. Lett.*, *20*(9), 863–866.

Ito, Y., and K. Obara (2006), Dynamic deformation of the accretionary prism excites very low frequency earthquakes, *Geophys. Res. Lett.*, *33*, L02311, doi:10.1029/2005GL025270.
Ito, Y., K. Obara, K. Shiomi, S. Sekine, and H. Hirose (2007), Slow earthquakes coincident with episodic tremors and slow slip events, *Science*, *315*, 503–506.
Ito, Y., Y. Asano, and K. Obara (2009), Very low frequency earthquakes indicate a transpressional stress regime in the Nankai accretionary prism, *Geophys. Res. Lett.*, L20309, doi:10.1029/2009GL039332.
Jiang, Y., S. Wdowinski, T. H. Dixon, M. Hackl, M. Protti, and V. Gonzalez (2012), Slow slip events in Costa Rica detected by continuous GPS observations, 2002–2011, *Geochem. Geophys. Geosyst.*, *13*, Q04006, doi:10.1029/2012GC004058.
Jiang, Y. (2012), Detection of nonlinear crustal movements using Global Positioning System, PhD Thesis, University of Miami, Open Access Dissertations, Paper 844.
Kim, M. J., S. Y. Schwartz, and S. Bannister (2011), Non-volcanic tremor associated with the March 2010 Gisborne slow slip event at the Hikurangi subduction margin, New Zealand, *Geophys. Res. Lett.*, *38*, L14301, doi:10.1029/2011GL048400.
Lay, T., C. J. Ammon, H. Kanamori, L. Xue, and M. J. Kim (2011), Possible large near-trench slip during the 2011 Mw 9.0 off the Pacific coast of Tohoku Earthquake, *Earth Planets Space*, *63*, 687–692, doi:10.5047/eps.2011.5005.5033.
Miller, M., T. Melbourne, D. Johnson, and W. Q. Sumner (2002), Periodic slow earthquakes from the Cascadia subduction zone, *Science*, *295*, 2423, doi:10.1126/science.1071193.
Nadeau, R. M., and D. Dolenc (2005), Nonvolcanic tremors deep beneath the San Andreas fault, *Science*, *307*, 5708, doi:10.1126/science.1107142.
Nakata, R., N. Suda, and H. Tsuruoka (2008), Non-volcanic tremor resulting from the combined effect of Earth tides and slow slip events, *Nature Geosci.*, *1*, 676–678.
Obara, K., and Y. Ito (2005), Very low frequency earthquakes exited by the 2004 off the Kii peninsula earthquakes: A dynamic deformation process in the large accreationary prism, *Earth Planets Space*, *57*, 321–326.
Obara, K., H. Hirose, F. Yamamizu, and K. Kasahara (2004), Episodic slow slip events accompanied with non-volcanic tremors in southwest Japan subduction zone, *Geophys. Res. Lett.*, *31*, L23602, doi:10.1029/2004GL020848.
Outerbridge, K. C., T. H. Dixon, S. Y. Schwartz, J. I. Walter, M. Protti, V. Gonzalez, J. Biggs, M. Thorwart, and W. Rabbel (2010), A tremor and slip event on the Cocos-Caribbean subduction zone as measured by a GPS and seismic Network on the Nicoya Peninsula, Costa Rica, *J. Geophys. Res.*, *115*, B10408, doi:10.1029/2009JB006845.
Payero, J. S., V. Kostoglodov, N. Shapiro, T. Mikumo, A. Iglesias, X. Pérez-Campos, and R. W. Clayton (2008), Nonvolcanic tremor observed in the Mexican subduction zone, *Geophys. Res. Lett.*, *35*, L07305, doi:10.1029/2007GL032877.
Peterson, C. L., and D. H. Christensen (2009), Possible relationship between nonvolcanic tremor and the 1998–2001 slow slip event, south central Alaska, *J. Geophys. Res.*, *114*, B06302, doi:10.1029/2008JB006096.
Protti, M., V. González, J. Freymueller, and S. Doelger (2012), Isla del Coco, on Cocos Plate, converges with Isla de San Andrés, on the Caribbean Plate, at 78 mm/yr, *Rev. Biol. Trop.*, *60*(Suppl. 3), 33–41.
Protti, M., M. F. Güendel, and E. Malavassi (2001), Evaluación del Potencial Sísmico de la Península de Nicoya, 1st ed., 144 pp., Editorial Fundación Universidad Nacional, Heredia, Costa Rica.
Rogers, G., and H. Dragert (2003), Episodic tremor and slip on the Cascadia subduction zone: the chatter of silent slip, *Science*, *300*, 1942–1943.
Rost, S., and C. Thomas (2002), Array seismology: Methods and applications, *Rev. Geophys.*, *40*, 3, doi:10.1029/2000RG000100.
Rubinstein, J. L., M. La Rocca, J. E. Vidale, K. C. Creager, and A. G. Wech (2008), Tidal modulation of non-volcanic tremor, *Science*, *319*, 186–189.
Scholz, C. H. (2002), The Mechanics of Earthquakes and Faulting, 2nd ed., Cambridge University Press, Cambridge, United Kingdom.
Sugioka, H., T. Okamato, T. Nakamura, Y. Ishihara, A. Ito, K. Obana, M. Kinoshita, K. Nakahigashi, M. Shinohara, and Y. Fukao (2012), Tsunamigenic potential of the shallow subduction plate boundary inferred from slow seismic slip, *Nat. Geosci.*, *5*, 414–418, doi:10.1038/ngeo1466.
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.
Wech, A. G., C. M. Boese, T. A. Stern, and J. Townend (2012), Tectonic tremor and deep slow slip on the Alpine Fault, *Geophys. Res. Lett.*, *39*, L10303, doi:10.1029/2012GL051751.
Wessel, P., and W. H. F. Smith (1998), New, improved version of the generic mapping tools released, *Eos Trans. AGU*, *79*, 579, doi:10.1029/98EO00426.
Wilcock, W. S. D. (2009), Tidal triggering of earthquakes in the northeast Pacific Ocean, *Geophys. J. Int.*, *179*(2), 1055–1070.