Final Technical Report

Relationships Among Tremor Amplitude, Slow Slip and Megathrust Earthquakes

USGS Grant No. G12AP20033
January 1, 2012 – December 31, 2012

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Abstract
Along the northern Cascadia margin, GPS observations provide evidence of periodic, ~4-week-long movements of plate motion between the subducting slab and overriding continental crust [*Rogers and Dragert*, 2003]. These slip events coincide with an emergent, enduring, and low-frequency signal know as tectonic tremor. From a hazards perspective, slow slip events are important in assessing risk associated with the up-dip seismogenic zone in two ways. First, it is thought that slip relieves stress locally while increasing stress on the locked zone with the potential to trigger a megathrust earthquake [*Dragert et al.*, 2001]. Second, spatially resolving slow slip could help map the freely-slipping, transition, and locked segments of the subducting Juan de Fuca plate relative to the densely populated urban centers along the fault margin. The other aspect of this episodic tremor and slip (ETS) phenomenon, tectonic tremor, could prove very useful in monitoring slow slip and understanding the parameters controlling it. Geodetic observations offer good macroscopic views of slow slip events; however, GPS observations provide limited spatial and temporal resolution and require a large amount of moment release before slip can be detected. Thus, establishing a link between tectonic tremor and slow slip enables the possibility of using tremor activity as a proxy for slow slip in time and space. Tremor monitoring can provide more timely slip recognition, and a tremor catalog enables higher-resolution estimates of when and where this stress loading—and hence triggering potential—may occur. We focus our efforts on 1) evaluating the Cascadia-wide relationship between tremor and slow slip by comparing the tremor catalog with our new estimate of geodetically determined slow slip, 2) adding amplitude information to the tremor catalog, 3) examining the relationship between tremor amplitude and time/space variations in tidal stressing to show that the coefficient of friction on the fault is very low (μ<0.2), 4) examining the tremor amplitudes versus down-dip distance and ETS vs. inter-ETS tremor and 5) maintaining the near-real-time tremor catalog.

1) Cascadia-wide Relationship between Geodetic Slow Slip and Tremor

We use continuous GPS position time series and tectonic tremor locations to explore along strike variations in ETS (Figure 1). We use three-component GPS time series to estimate block rotations and locking between SSEs, slip from 16 SSEs and an earthquake between July 1, 2005 and January 1, 2011. Individual slow slip events are well fit in space and time. The 5.5 year cumulative slow slip is largest in Washington and northern California, and smallest in central and northern Oregon. Along-strike variation in cumulative tectonic tremor counts from August 2009 to January 2013 exhibit similar trends as the cumulative slow slip. Disperities in along strike quantities may be due to differing observation times. Tectonic tremor counts and slow slip are reduced between ~42-46N latitude, in a region with large gravity anomalies that outline the dense Siletz terrane, an accreted Eocene age basalt.

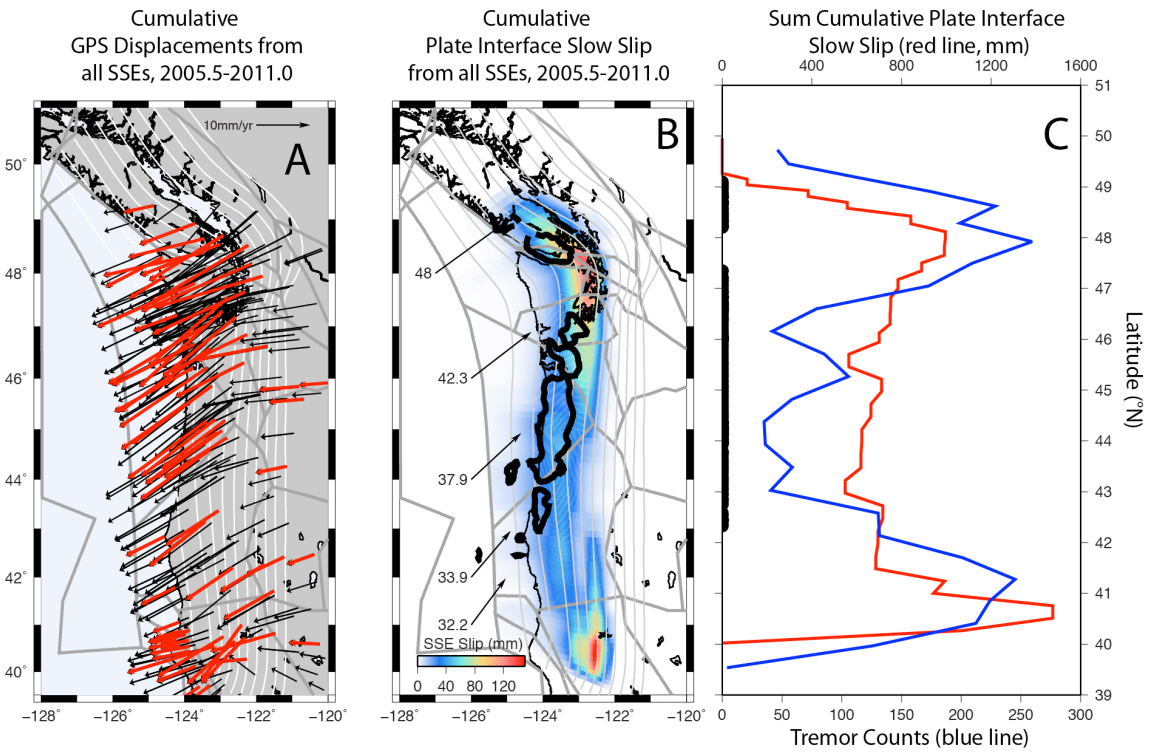

Figure 1. (A) Distribution of cumulative slow slip displacements detected by GPS from 2005.5-2011 (vectors). Red vectors indicate sites that were in operation for 90% or more of the time period studied. Light grey lines are depth contours from McCrory et al. [2004] and thick dark grey lines are modeled blocks. (B) Total plate interface slow slip from 2005.5-2011. Vectors are North America relative convergence rates and directions (pole from McCaffrey et al. (2007)). Solid black lines marks the 10 mgal gravity anomaly contours of Blakely et al. [2005]. (C) Summed cumulative node depth profile interface SSE slip from 2005.5-2011 (red line) and cumulative tremor counts (blue line) from 2009.8-2013. Thick black line represents latitudes with magnetic anomaly (B).

2) Tremor Catalog: detection, location and amplitudes

Using a previously developed autonomous method for detection and location of tectonic tremor [*Wech and Creager*, 2008], we have created a catalog of tremor activity across the Cascadia margin. Applying this technique to 9 overlapping networks from northern California to northern-Vancouver Island on past and real-time data, we monitor both ETS and inter-ETS tremor activity starting from 2006. The resulting epicenters augment previous monitoring efforts in northern Washington to provide an unprecedented map of the Cascadia tremor source region, a new ability to investigate the role of inter-ETS tremor, a basis for analyzing tremor amplitudes, and a basis for expanding real-time routine monitoring to the rest of the subduction zone.

Using this catalog, we define a new class of event that encompasses the larger ETS events by searching for tremor that clusters in space and in time and call these events "tremor swarms" [*Wech et al.*, 2010]. In northern Washington (where we have the most consistent catalog) ETS events repeat every 15±2 months [*Miller et al.*, 2002; *Rogers and Dragert*, 2003] and are remarkably similar in duration, area, and moment. For each of these events, the tremor pattern is in strong agreement with geodetic slip patterns [*Wech et al.*, 2009]. From 2006 through 2013, we find nearly 1000 distinct tremor swarms including major Northern Washington ETS events (durations exceeding 100 hours) in January 2007, May 2008, May 2009, August 2010, August 2011, September 2012, and September, 2013 as well as others under Vancouver Island, in central/northern Oregon and southern Oregon/northern California. Inter-ETS tremor swarms (duration less than 100 hours) were detected in nearly 100,000 5-minute time windows. The number of hours of tremor per inter-ETS swarm ranged from about 1 to 99, totaling 5840 hours. These smaller tremor swarms generally locate along the downdip side of the major ETS events, and account for 49% of the time that tremor has been detected. Only the largest events coincide with geodetically observed slip, meaning that current geodetic observations may be missing nearly half of the total slip. Like the major ETS tremor swarms, many of the smaller events are near-carbon copies in duration, spatial extent and propagation direction.

We have calculated amplitudes for 5-minute windows of located tremor in northern Washington using data from EarthScope Flexible Array experiments Array of Arrays and CAFE. Following Maeda and Obara [2010], the mean rate of band-limited (1.5-5.5 Hz) seismic energy radiated from the tremor source is proportional to the square of the root-mean-square particle velocity measured at each station corrected for geometric spreading and attenuation. We set up an inverse problem to invert rms velocity at each station in 5-minute windows for source amplitudes and station corrections.

3) Modulation of Tremor Amplitudes by Tidal Stresses in Cascadia

We recorded the 2010 and 2011 episodic tremor and slip events in Northern Cascadia on the Array of Arrays, a group of eight small-aperture seismic arrays on the northern Olympic Peninsula. In addition the 2007, 2008, 2009, 2010 and 2011 ETS events were also recorded on six stations from the CAFE experiment that were distributed along a 100 km N-S line just west of Hood Canal. We invert these data for amplitude at the tremor source and investigate the relationship between tremor amplitude and tidal stress, using a Cascadia-wide tidal loading model [Hawthorne and Rubin, 2010]. We find enhanced tremor amplitudes at times of high shear stress. The amplitude modulation is strongest at the 12.42 h period tide, but we also observe a modulation associated with the 12 h, 12.66 h and 23.9 h periods (Figure 4). Amplitudes are uncorrelated or anticorrelated with the larger-amplitude normal stress, which suggests low friction ($m<0.3$) at the plate interface (Figure 2) [e.g. Lambert et al., 2009; Thomas et al., 2009].

The timing of peak tremor amplitude is roughly concurrent with that of maximum slip rates and maximum numbers of tremor detections. We consistently find that peak tremor amplitude leads peak Coulomb tidal stress by 1.5 hours and lags peak Coulomb stress rate by 1.5 hours (Figure 3).

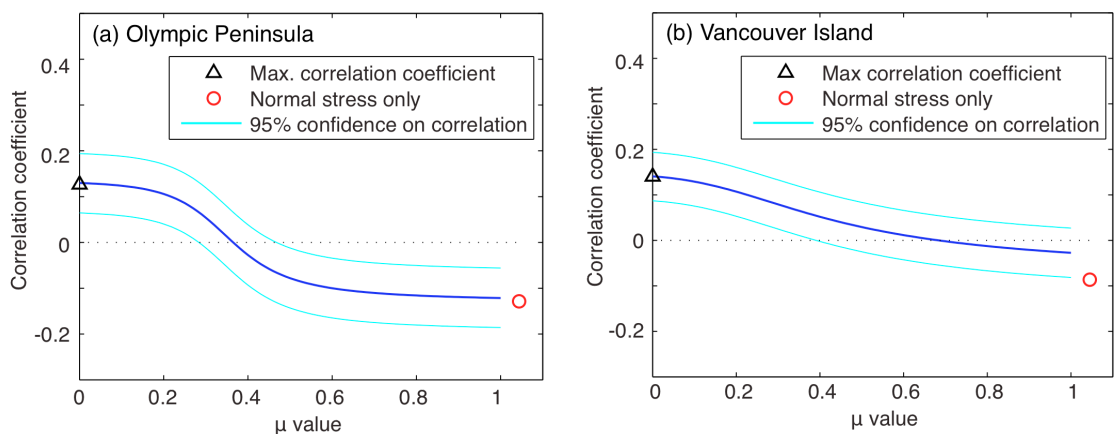

Figure 2. Correlation coefficient between tremor amplitudes (2010 and 2011 ETS events) and tidal Coulomb stress for tremor under the Olympic Peninsula (a) and under Vancouver Island (b), for values of friction, μ, ranging from 0 to 1. The bounding lines show the 95% confidence limits on the correlation coefficient. The red dot shows the correlation between tremor amplitudes and normal stress only.

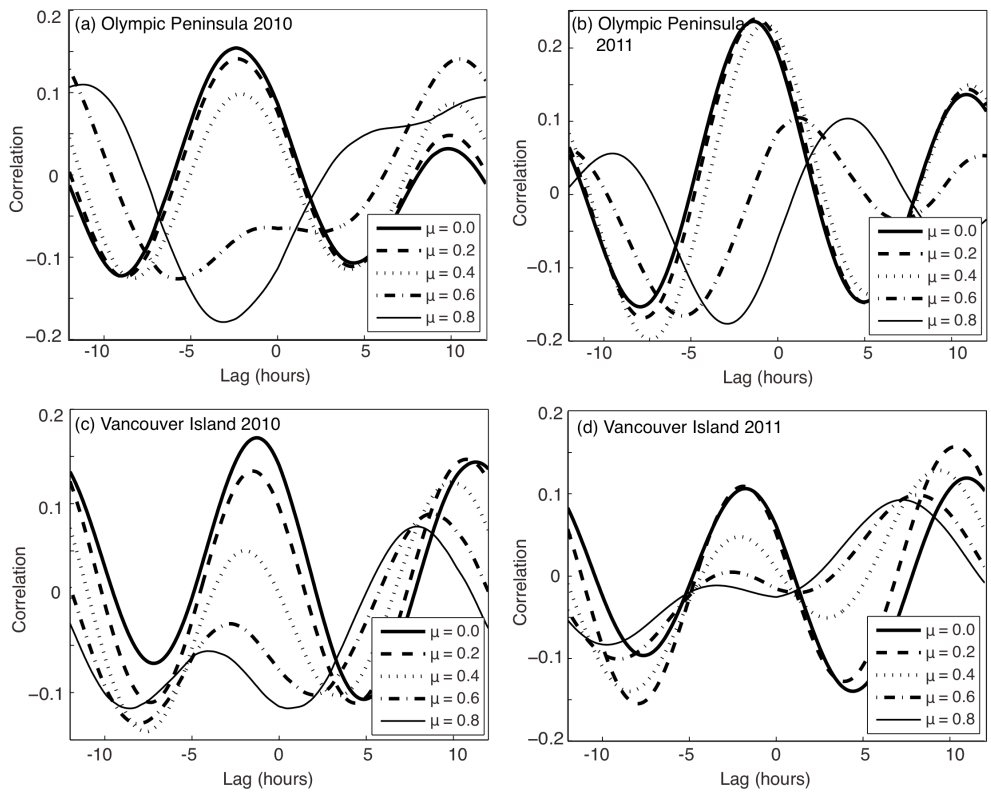

Figure 3. Cross correlation between tremor amplitude time series and tidal stress, for frictional coefficients ranging from 0 to 0.8, for the Olympic Peninsula (a-b) and Vancouver Island (c-d). For μ = 0, the lag time to maximum cross correlation is -1.75 hours(a), -1.5 hours(b) , -1.25 hours(c) , -1.75 hours(d) .

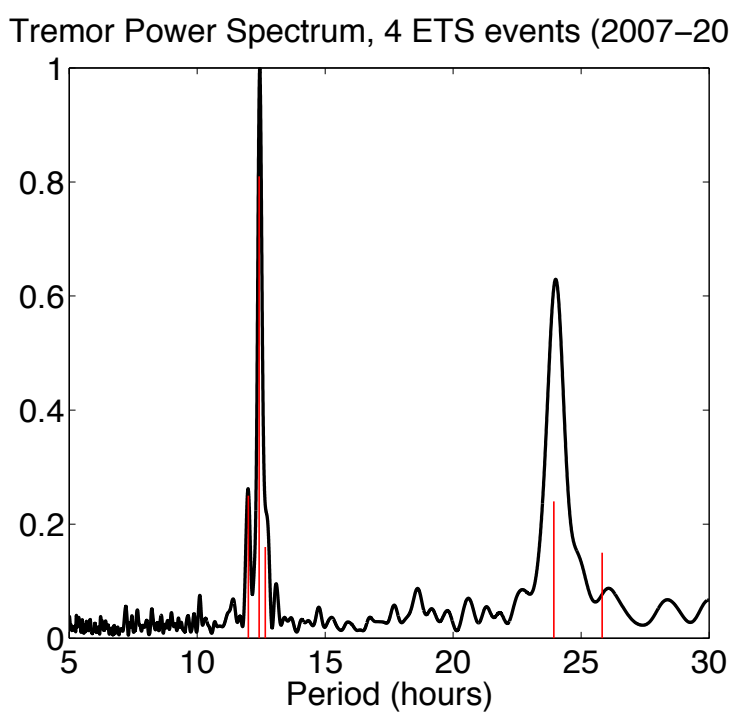

Figure 4. Tremor amplitude power spectrum for the January 2007, May 2008, May 2009 and August 2010 ETS events showing clear peaks at the dominant tidal frequencies (vertical lines).

4) ETS tremor is louder than inter-ETS tremor

We define the "up-dip limit" of tremor as smooth curved such that 95% of the tremor locations lie down dip (east) of this line [Wech and Creager, 2011]. The down-dip distance of each tremor source is the horizontal distance to this line. We calculate the mean amplitude of tremor in each 5-km down-dip distance bin. This is done separately for ETS and inter-ETS tremor. On average the ETS tremor is nearly twice the amplitude of inter-ETS tremor (Figure 5) regardless of down-dip distance. However, the inter-ETS tremor is generally down-dip of the ETS tremor, so the mean amplitude of down-dip tremor is less that that of up-dip tremor. The lack of systematic variation in amplitude during ETS events suggests that tremor duration may be a good proxy for slip. However, the systematically lower amplitudes during inter-ETS events suggest that the duration should overestimate the amount of slip during inter-ETS events.

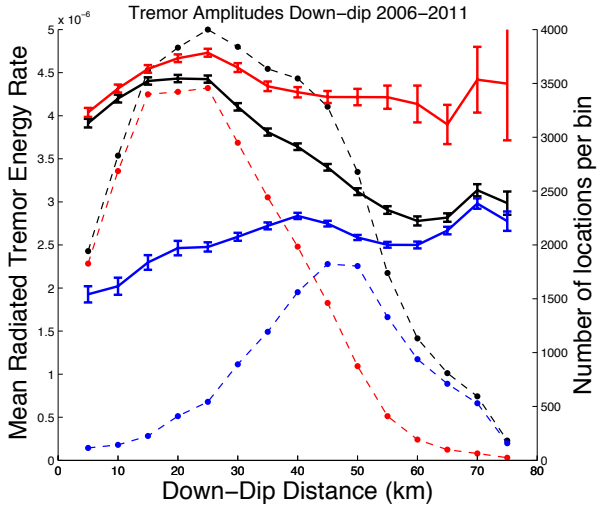

Figure 5. Mean and standard error in the mean of square root of band-limited seismic radiated energy (solid lines with error bars) for each 5-km bin down-dip of the up-dip tremor limit and total number of locations (dashed line) for ETS events (red), inter-ETS events (blue), and all tremor events (black) between 2006-2011.

5) Tremor Monitor web page:

Finally, we continue to maintain our system to automatically detect, locate and report tremor activity Cascadia wide in near-real-time on an interactive webpage (http://www.pnsn.org/tremor) [Wech, 2010]. Data from the several seismic networks stream into the Pacific Northwest Seismology Network's Seismology Lab. At the end of each GMT day, data from a preselected subset of ~100 of these incoming streams are broken into 9 overlapping regional sub-networks

spanning from northern California to northern Vancouver Island. If any activity occurred along the margin, the system will also dispatch email alerts and text messages detailing tremor results for each active region. Once online, the results are manipulated using dynamic hypertext markup language to give the user full control to customize and view locations and time series, customize time ranges, customize regions, animate tremor activity, view seismic station geometry, and view data.

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