Final Technical Report

Relationships Among Tremor Amplitude, Slow Slip and Megathrust Earthquakes

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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. 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. On the other hand, observations of tectonic tremor reveal that bursts of tremor occur throughout the year with durations ranging from hours, presumably during slow slip events below the GPS detection threshold, to weeks, during large episodic tremor and slip (ETS) events. Tremor monitoring provides more timely slip recognition, and a tremor catalog enables higher-resolution estimates of when and where stress loading from slow slip—and hence triggering potential—may occur. 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. We focus our efforts on 1) evaluating the Cascadia-wide relationship between tremor and slow slip by comparing the tremor catalog with estimates of geodetically determined slow slip, 2) adding amplitude information to the tremor catalog, 3) examining the tremor amplitudes versus down-dip distance and ETS vs. inter-ETS tremor, 4) investigating the initiation of large ETS events, 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) [Schmalzle et al., 2014]. 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. While disparities in along-strike quantities may be influenced by differing observation times, these patterns can be seen in subsets of the data and are

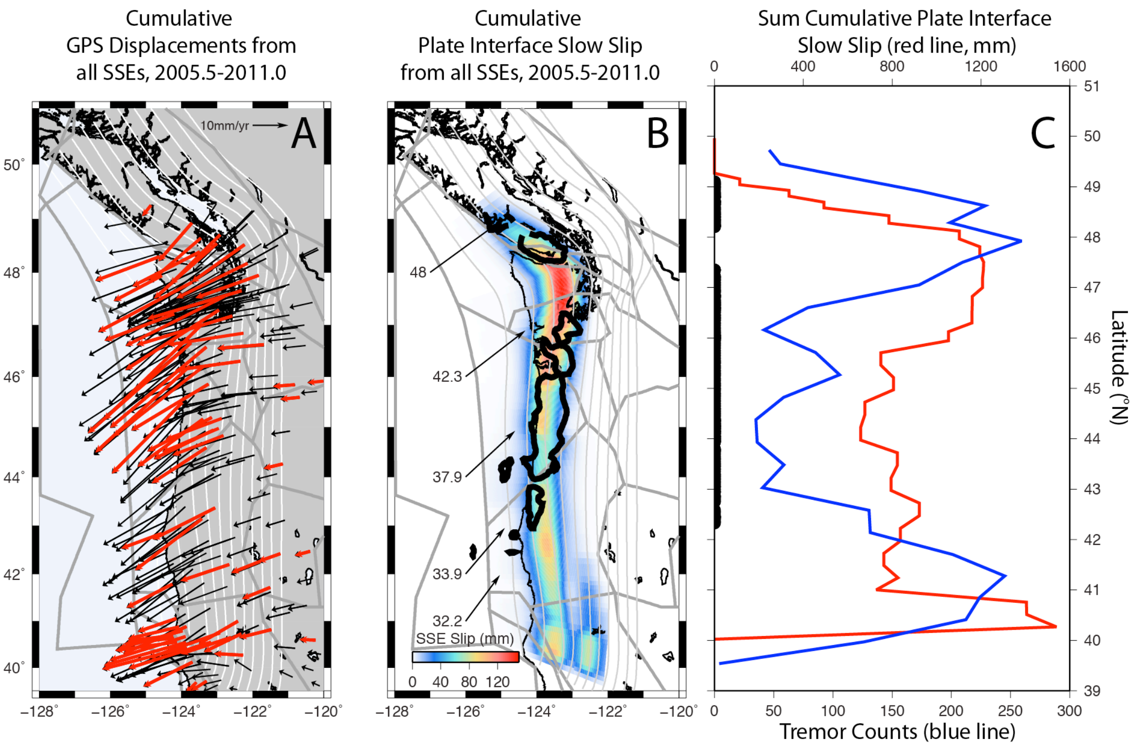

Figure 1. (A) Distribution of cumulative slow-slip displacements detected by continuous GPS from 2005.5 to 2011.0 (black vectors). Red vectors mark sites that were operating for 90% or more of the study time period. Near-vertical light gray lines are 10 km depth contours from McCrory et al. [2004] and dark gray lines are modeled blocks. (b) Summed plate interface slow-slip from 2005.5 to 2011. Black vectors are North America relative convergence rates and directions. Thick, solid black lines mark the 10 mgal gravity anomaly contour of Blakely et al. [2005]. (c) Cumulative node depth profile interface slow-slip from 2005.5 to 2011 (red line) and 50 km binned cumulative tremor counts from 2009.8 to 2013.0 acquired from the PNSN tremor catalog (blue line). Thick black line represents latitudes with high gravity anomalies. From Schmalzle et al., [2014].

robust. Tectonic tremor counts and slow slip are reduced between ~42-46N latitude, in a region with large gravity anomalies that outline the dense Siletz terrain, an accreted Eocene age basalt.

2) Updip Limit of Tremor and Slip

Houston [2012] concluded that that geodetically-observed slip occurred updip of tectonic tremor during the August 2010 ETS event. The displacement vectors from 71 stations in the Pacific Northwest Geodetic Array (PANGA) are analyzed for both the 2010 and 2012 ETS events in northern Cascadia [*Hall and Houston*, 2014]. These data are inverted for slip on the fault surface using the Okada [1992] formulation of buried rectangular faults in a halfspace with a grid of 8x8 km subfaults based on the McCrory [2012] slab model. Two different inversions are compared for each event: (1) slip occurs on a broad regional grid and, (2) a tremor-restricted inversion (TRI) where slip is restricted to the grid points where tremor was detected. In the TRI inversion, slip on the updip edge of the grid reached >6 cm during each of the 2010 (Figure 2) and 2012 events. Given that the Cascadia convergence rate is ~4 cm/year and that the repose interval between northern Cascadia ETS events is 12-15 months, this is physically implausible, so slip must occur updip of the region where tremor is observed. Supporting this conclusion, the regional inversions for both events show significant slip updip of the tremor region.

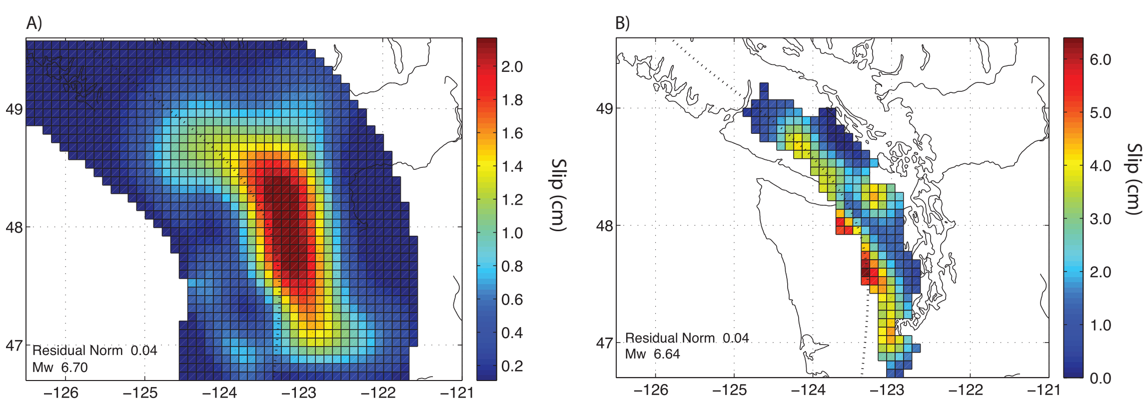

Figure 2. Slip distributions of the 2010 ETS event from the regional (A) and tremor-restricted (B) inversions. The dashed line represents the 35 km plate interface contour. The tremor-restricted inversion shows large amounts of slip (>6 cm), exceeding plate convergence rates. Additionally, the large amount of slip is forced to the updip edge of the allowed slip region, suggesting that slip is preferred updip.

3) Tremor Catalog: detection, location and amplitudes

Using a previously developed autonomous method for detection and location of tectonic tremor [*Wech and Creager*, 2008], we continue to create a catalog of tremor activity, in near-real-time, across the Cascadia margin. This technique has been applied to northern Washington since 2006. Continuously since in 2009, it has been applied to near-realtime data for 7 overlapping station networks covering about 80% of Cascadia. In 2012, we added two more regions in Canada and California producing 9 overlapping regions that cover all of Cascadia from northern California to northern-Vancouver Island. Tremor is detected and located daily and 250,000 5-minute windows of tremor are all available for download or analysis at pnsn.org/tremor. The resulting epicenters provide an unprecedented map of the Cascadia tremor source region, an ability to investigate the role of inter-ETS tremor, and a basis for analyzing tremor amplitudes.

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 14±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 2015, we find 1400 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, September, 2013 and November, 2014, 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 150,000 5-minute time windows. The number of hours of tremor per inter-ETS swarm ranged from about 1 to 99, totaling 8700 hours. These smaller tremor swarms generally locate along the downdip side of the major ETS events [*Wech and Creager*, 2011], and account for 48% 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.

4) ETS tremor is louder than inter-ETS tremor

We define the “up-dip limit” of tremor as a smooth curve 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 3) 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.

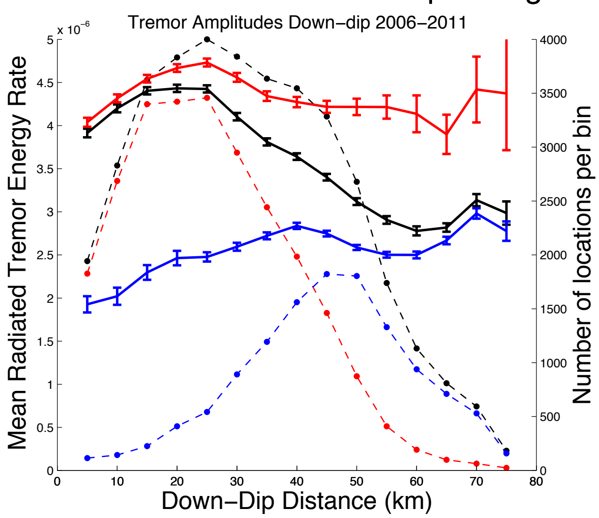

Figure 3. Mean and standard error in the mean of square root of band-limited seismic radiated energy (solid lines with error bars) for each 5-km bin down-dip of the up-dip tremor limit and total number of locations (dashed line) for ETS events (red), inter-ETS events (blue), and all tremor events (black) between 2006-2011.

5) **Initiation of ETS Events**

Northern Cascadia ETS events appear to have distinct initiation and propagation phases [*Ulberg and Creager*, 2013]. We find that there is a roughly linear increase in tremor amplitude over the first 5-8 days of each ETS event, corresponding to a linear increase in the areal distribution of tremor (Figure 4). These episodes typically initiate down dip, and after approximately 5-8 days have organized and migrated to fill the up-dip/down-dip width of the tremorgenic zone. After this time, tremor amplitudes vary wildly, modulated by tidal stresses, as the tremor propagates along strike in one or both directions at roughly 7-12 km/day, continuing for 2-3 weeks.

The linear increase in tremor area during ETS initiation could be due to stress diffusion in the two-dimensional fault plane, while the along-strike propagation rate is controlled more by the downdip width of the tremoring zone and the static stress buildup from already-slipped regions.

Alternatively, the growth of the tremor front could all be due to the same process, with the seemingly different behaviors arising from the geometry of the plate interface. A quasi-linear increase in tremor area during the first few days of an ETS event could be related to the direction of tremor propagation. It appears tremor fronts move more quickly in a direction parallel to strike as opposed to moving up or down parallel to the dip direction.

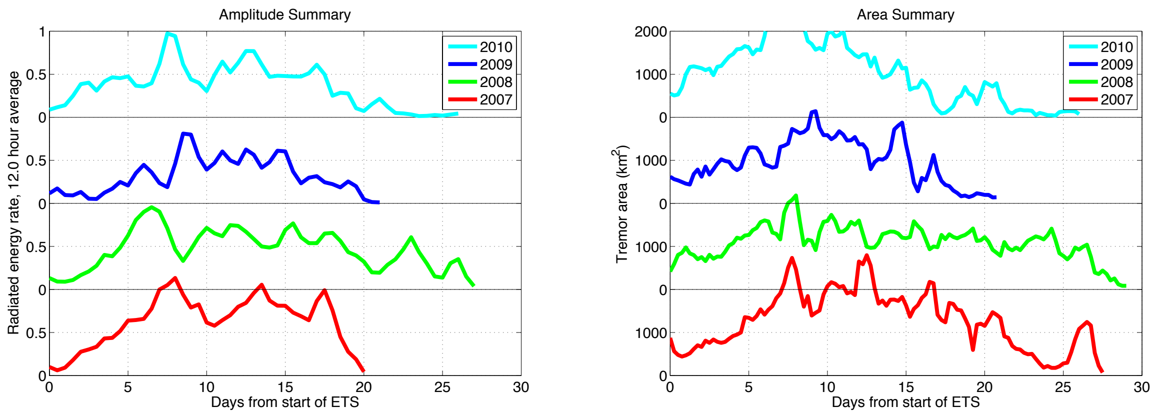

Figure 4. Normalized tremor source amplitude (left) and tremor source area (right) for the 4 ETS events for which we have calculated tremor amplitudes.

6) 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 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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