Final Technical Report

Improved detection, location and characterization of Cascadia Tremor

USGS Grant No. G10AP00033
January 1, 2010 – December 31, 2010

PI Kenneth C. Creager
Department of Earth and Space Sciences
University of Washington
Seattle, WA 98195-1310
206-685-2803
206-543-0498 (FAX)
kcc@ess.washington.edu

Abstract
Along the northern Cascadia margin, GPS observations provide evidence of periodic, 2-week-long movements of plate motion between the subducting slab and overriding continental crust [*Rogers and Dragert*, 2003]. This slip event coincides with an emergent, enduring, and low-frequency signal know as tremor. From a hazards perspective, slow slip events are important in assessing risk associated with the updip 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 dense urban centers along the fault margin. The other aspect of this episodic tremor and slip (ETS) phenomenon, 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 detection of slip often occurs late in or after the event with limited spatial and temporal resolution. Thus, establishing a link between tremor and 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.

Tremor Catalog

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 7 overlapping networks from northern California to mid-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 2011, we find 586 distinct tremor swarms including the Northern Washington ETS events (durations exceeding 100 hours) in January 2007, May 2008, May 2009, August 2010 and August 2011, as well as two others under Vancouver Island, three in central/northern Oregon and four in southern Oregon/northern California. Inter-ETS tremor swarms (duration less than 100 hours) were detected in 48000 5-minute time windows. The number of hours of tremor per inter-ETS swarm ranged from about 1 to 68, totaling 2941 hours. These smaller tremor swarms generally locate along the downdip side of the major ETS events, and account for approximately 45% 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.

A continuum of stress, strength and slip in the Cascadia subduction zone

As oceanic lithosphere descends beneath continents in subduction zones worldwide, the contact between the two plates undergoes a transformation in response to a variety of physical parameters that vary with increasing depth. The result of this transformation is a transition in fault coupling from fully locked on the shallow, updip side to stable sliding downdip where the oceanic plate descends into the mantle. But how this transition zone works is not entirely understood. Updip of tremor, the fault yields no displacement for hundreds of years, constantly accumulating stress before breaking in the form of a megathrust earthquake. On the downdip side, the plates are thought to stably slide past each other at a constant rate without increasing stress. By accumulating stress for months to years between discrete episodes of stable moment release, episodic tremor and slip (ETS) provides an intermediate mechanism for accommodating plate convergence between the locked and stable sliding end members in relatively young, warm subduction zones.

Using automatically detected tectonic tremor as a slow slip indicator in northern Cascadia, we observe a depth dependence to the amount of slip and to the

periodicity of slip events. Large tremor events migrate updip from the deeper zone of frequent small slip to progressively less frequent, higher-slip zones. Our observations fill in the transition zone spectrum with a continuum of slow slip behavior that reflects the fault strength. This behavior is explained by a fractal-like stress transfer model controlled by friction, which provides a new and intuitive understanding of subduction zone dynamics (Figures 1 and 2; [*Wech and Creager*, 2011]).

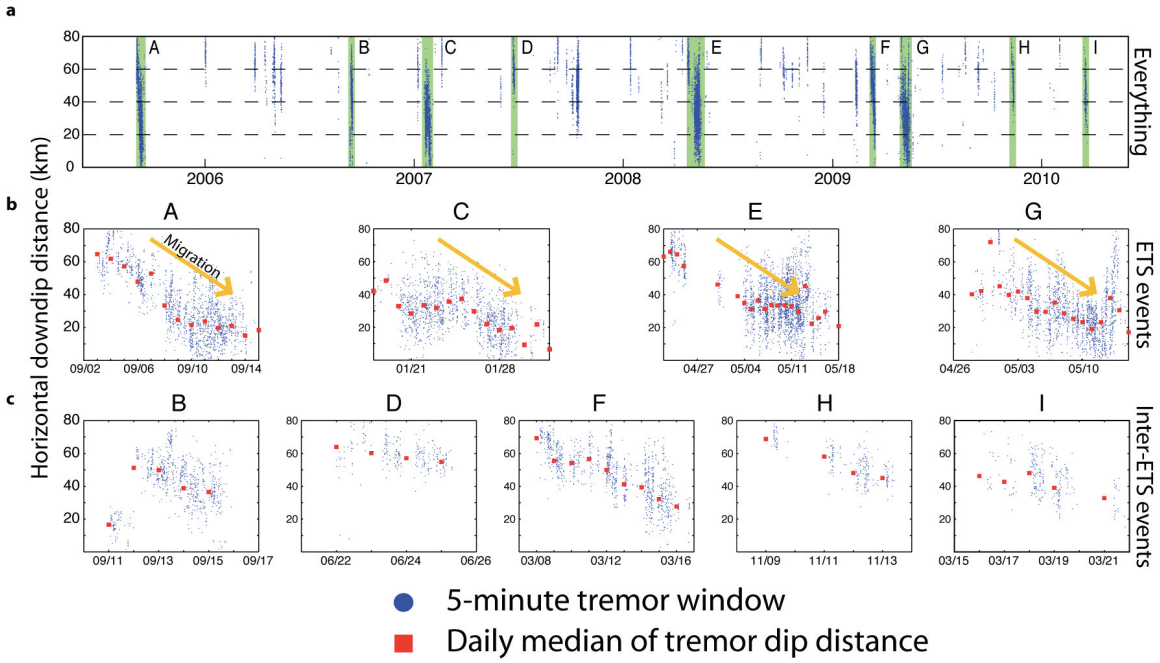

Figure 1. Updip tremor migration. (a) Horizontal downdip tremor distance versus time of northern Washington catalog showing many small swarms downdip and larger swarms initiating deep and migrating updip. (b) Migration for the past 4 ETS episodes. Blue dots represent tremor epicenters and red squares show median daily downdip distance. (c) Example migration of 5 small and large inter-ETS tremor swarms.

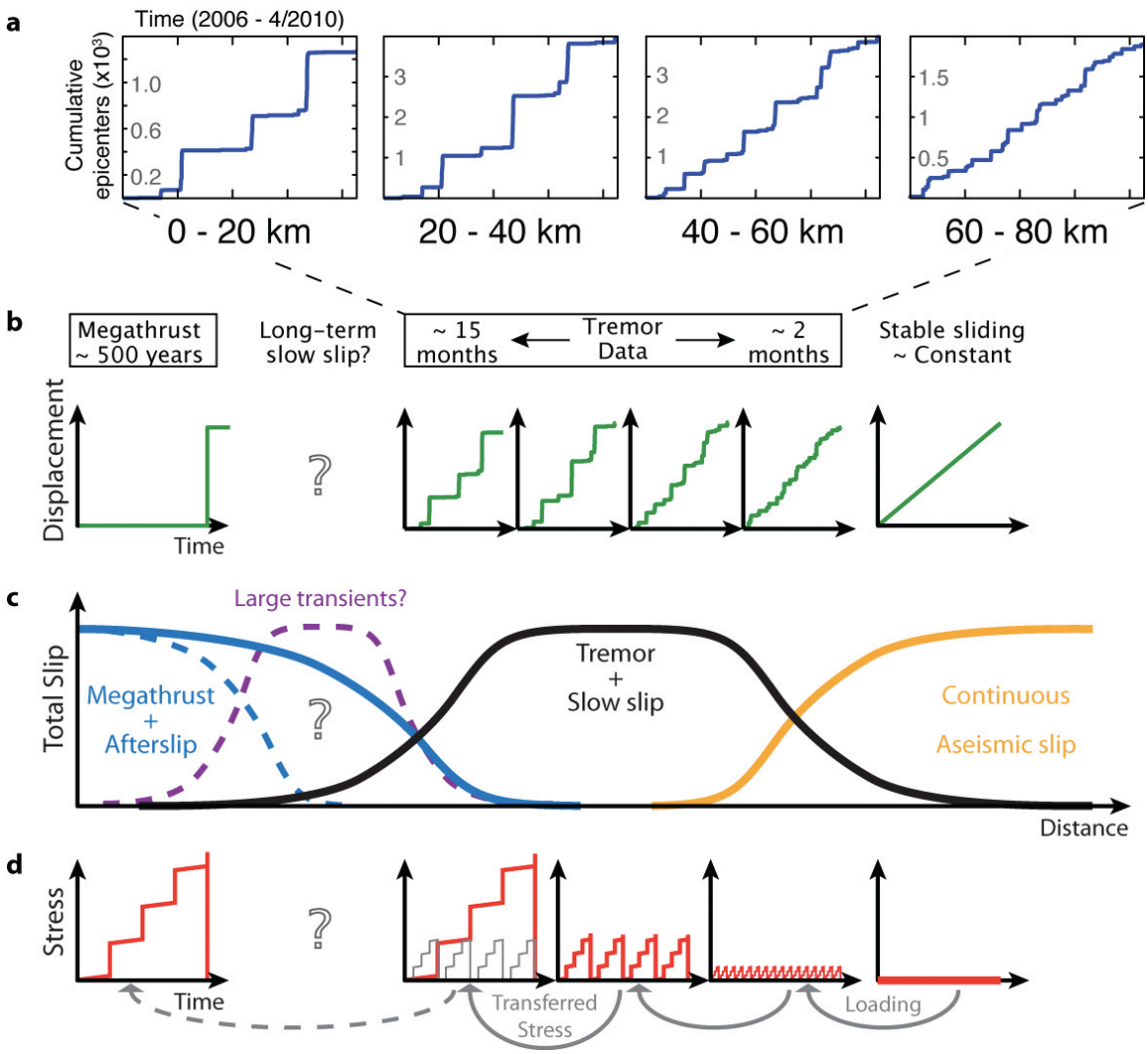

Figure 2. Displacement history profiles and transition zone model. (a) Cumulative tremor profiles in each strike-perpendicular bin showing a transition from small, frequent slip downdip to larger, less frequent slip updip. (b) Profiles of displacement timelines from the locked zone to stable sliding with results from a inserted in the transition zone. (c) Profile schematic showing how the different regions accommodate plate convergence. Our results may predict long-term slow slip updip (purple dashed line), which would shift the downdip limit of the megathrust (blue dashed line) updip. (d) Schematic profile of stress timelines illustrating our stress transfer model. Stable sliding loads the downdip tremor region, which is weakly coupled and slips easily. Each slip relieves stress locally and transfers stress updip to a stronger portion of the fault with a higher stress threshold. This is a fractal-like process where the local stress is the integrated effect of downdip slip.

Tidal Modulation of Tremor Amplitude

We have also begun working on an analysis of tremor amplitudes. This effort has several goals. One is to add information about amplitudes to our tremor catalogs, which currently only specify where tremor is at any given time. A first step has been to define and calculate amplitudes. First, the instrument response is deconvolved, seismograms are band-pass filtered at 1.5-5.5 Hz, and envelopes are made in 5-minute windows. An inverse problem compensates for site corrections, attenuation and geometric spreding to produce, for each five-minute window, a single amplitude measurement at the source. Source locations are the same as those described above, and are determined using an envelope cross-correlation method. This method has been applied to data from the Array of Arrays experiment. The time period used covers the 2010 and 2011 ETS events as well as several inter-ETS events in 2010.

A further goal is to study the relationship between tremor amplitudes and tidal stresses, using the Cascadia-wide tidal stress model of Hawthorne and Rubin [2010]. There is a strong signal in the amplitude data at tidal frequencies, especially the 12.4 hour lunar tide (Figure 3). Some of the long-period components of the data can be fit fairly well by a combination of sinusoids at the five primary tidal frequencies included in the model. The most critical tidal periods for fitting the data are the 12.4 hour and 23.9 hour periods. Although the importance of the 23.9 hour period suggests the influence of day-night differences in noise, the remoteness of many of the stations, the high signal-to-noise ratio of the tremor during this event, and the fact that the tremor amplitudes do not decrease over weekends all suggest that this is in fact a tidal signal and not merely noise. We have also found that the amplitude data correlates best with the Coulomb tidal stress for low values of μ, in keeping with other authors' suggestions that tremor may be possible because of very low friction at the plate interface caused by high pore pressures [e.g. *Lambert et al.*, 2009; *Thomas et al.*, 2009].

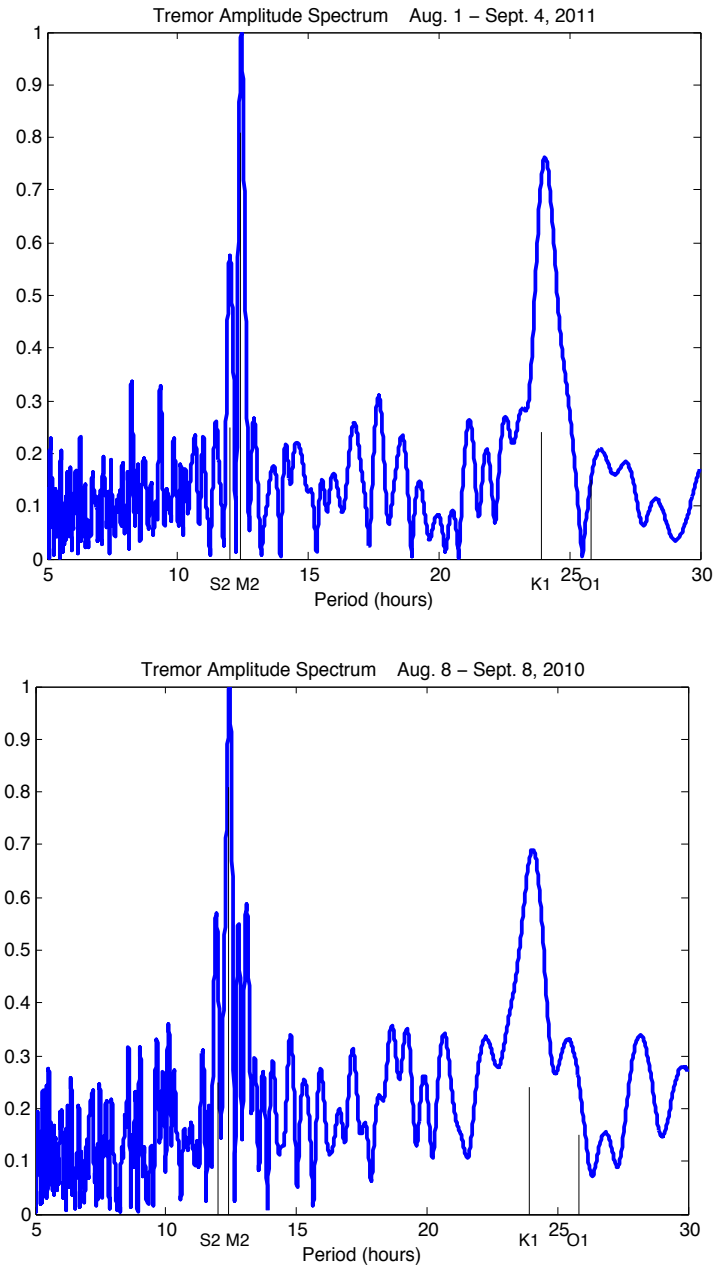

Figure 3. Tremor amplitude spectra for 2010 (top) and 2011 (bottom) ETS events. Both events have prominent peaks around the 12.4 hour M2 and 23.9 hour K1 periods.

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 (currently at http://old.pnsn.org/tremor/) but should switch to 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 [*Dragert et al.*, 2001], data from a preselected subset of ~100 of these incoming streams are broken into 7 overlapping regional sub-networks spanning from northern California to mid- 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 (Figure 4).

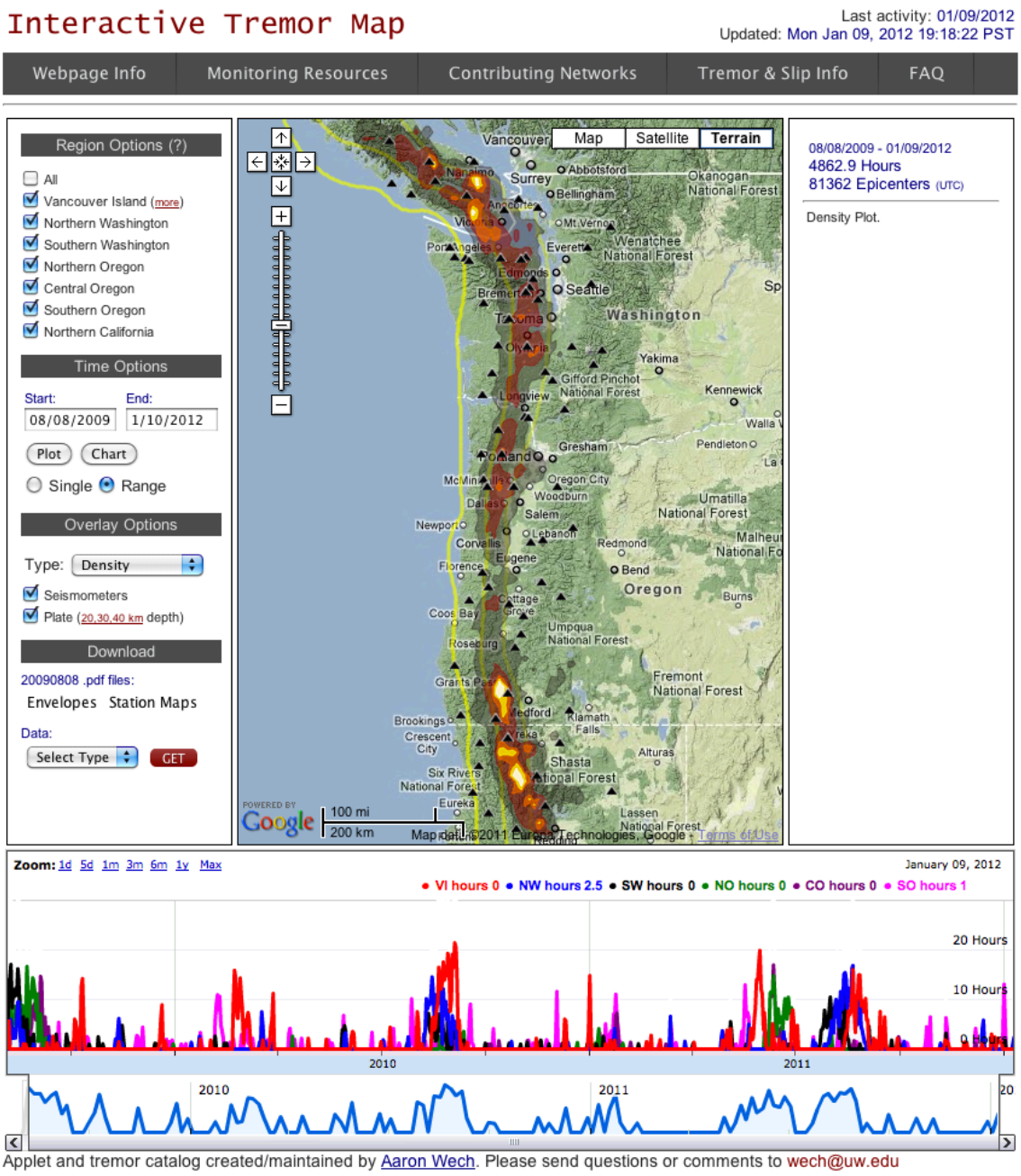

Figure 4. A screenshot of the web product resulting from this near realtime system. The left panel contains the interactive options. The user can choose a region and date range. Locations may be uniform, color-coded with time or displayed as a density plot. The bottom panel shows a time series of tremor duration by day for the entire available time range (bottom) and zoomed in time range (top) with color-coded regional. The right panel contains a summary of plotted info (top) and the colorbar or event table if <1000 events are requested with no color-coding.
URL: www.pnsn.org/tremor

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* These two publications resulted from the work performed under this award.