Tremor Monitoring

Aaron Wech *(University of Washington)*

Since their discovery nearly a decade ago, advances in both instrumentation and methodology in subduction zones around the world have brought the causal connection between seismically observed tectonic tremor and geodetically observed slow slip into sharper focus—with it becoming increasingly clear that tremor serves as a proxy for slow slip. Considering geodesy's lower limits in spatio-temporal resolution together with the abundance of low-level, ageodetic tremor, this connection makes tremor a key component in monitoring when, where, and how much slip is occurring. Because slow slip transfers stress to the updip seismogenic portion of the plate interface, monitoring transient events may serve in forecasting the threat of a megathrust earthquake by inferring the temporal and spatial variations in the loading of the seismogenic zone. We use waveform envelope correlation & clustering [*Wech and Creager, 2008*] methodology to automatically detect and locate tremor. Applying this technique to TA, PASSCAL, PBO, and regional network data, we map tremor epicenters from northern California to mid- Vancouver Island and present a system that monitors and reports tremor activity in near-realtime on an interactive webpage [*Wech, 2010*]. Collectively the resulting product is an automatic margin-wide tremor catalog and a website disseminating this information in a way that is accessible and engaging to the general population yet remains valuable as a tool for scientific synergy across institutions and disciplines: www.pnsn.org/tremor

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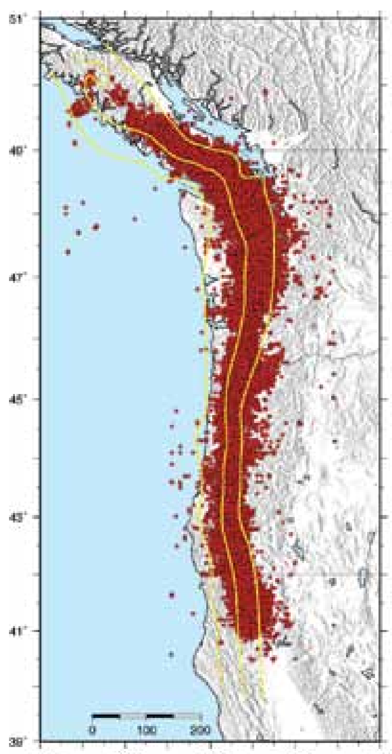
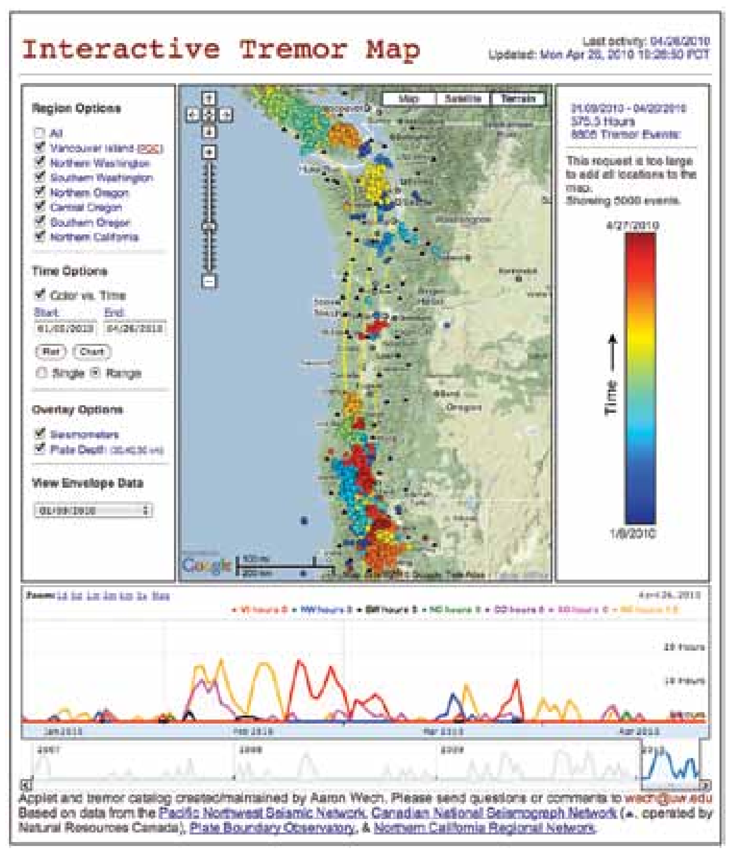


Tremor map. Margin-wide epicenters from 2006-2009 using TA, PASSCAL, PBO, and regional network data. Yellow lines are 20, 30, and 40 km isodepths from Audet et al. [2010].



A screenshot of the web product resulting from this near-realtime system.

Non-Volcanic Tremor along the Oaxaca Segment of the Middle America Subduction Zone

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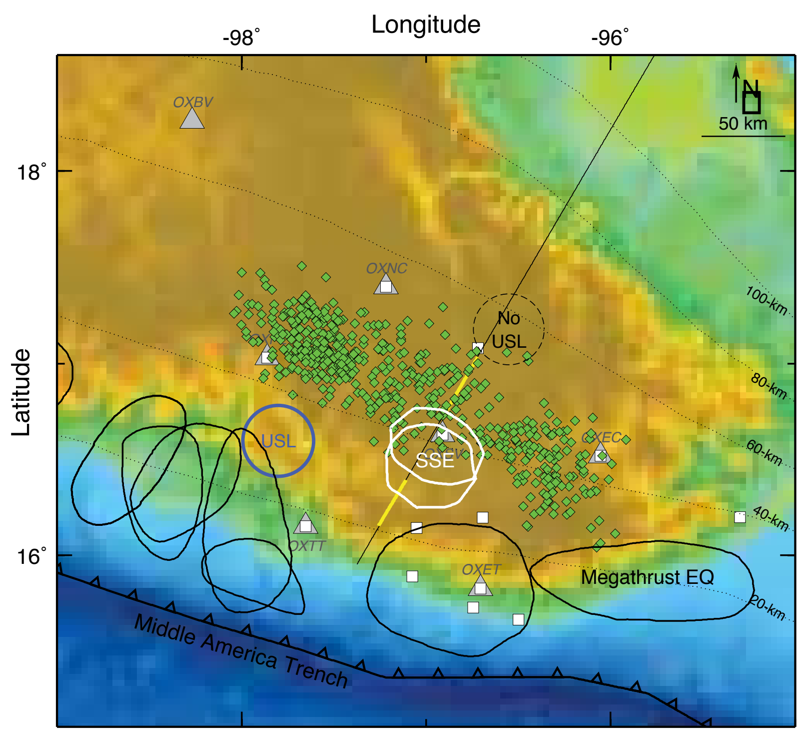
The Oaxaca subduction zone is an ideal area for detailed studies of plate boundary deformation as rapid convergent rates, shallow subduction, and short trench-to-coast distances bring the thermally defined seismogenic and transition zones of the plate interface over 100 km inland. Previous analysis of slow slip events in southern Mexico suggests they may represent motion in the transition zone, defining the downdip edge of future megathrust earthquakes. A new deployment consisting of broadband seismometers distributed inland along the Oaxaca segment provide the means to examine whether non-volcanic tremor (NVT) signals can also be used to characterize the boundary between the seismogenic and transition zones. In this study, we established that NVT exists in the Oaxaca region based on waxing and waning of seismic energy on filtered day-long seismograms that were correlated across neighboring stations, and further supported by appropriate relative time moveouts in record sections, and spectrograms with narrow frequency bands. 18 prominent NVT episodes that lasted upwards of a week were identified during the 15 months analyzed (June 2006 to September 2007), recurring as frequently as every 2-3 months in a given region. We analyze NVT envelope waveforms with a semi-automated process for identifying prominent energy bursts, and analyst-refined relative arrival times are inverted for source locations. NVT burst epicenters primarily occur between the 40-50 km contours for depth of the plate interface, except in eastern Oaxaca where they shift towards the 30 km contour as the slab steepens. NVT hypocenters correlate well with a high conductivity zone that is interpreted to be due to slab fluids. NVT is more frequent, shorter in duration, and located further inland than GPS-detected slow slip, while the latter is associated with a zone of ultra-slow velocity interpreted to represent high pore fluid pressure. This zone of slow slip corresponds to approximately 350–450°C, with megathrust earthquakes, microseismicity, and strong long-term coupling occurring immediately updip from it. This leaves NVT primarily in a region further inland from the thermally defined transition zone, suggesting that transition from locking to free slip may occur in more than one phase.

Acknowledgements: NSF EAR-510812



Map of the study region focused along the Oaxaca segment of the Middle American Subduction Zone. Grey triangles (seismic) and white squares (GPS) show the state of the joint network in 2006-2007 that is used to determine the extent of non-volcanic tremor in July 2006 (green line, this study) and the 100 mm slip contour for slow slip events in early 2006 and early 2007 (white ovals) [Correa-Mora et al., 2008; 2009]. Black ovals are approximate rupture zones of large subduction thrust earthquakes over the past 50 years as estimated from locations of rupture aftershocks. Straight line is a profile of magnetotelluric measurements with areas of high conductivity near the subduction interface highlighted in yellow [Jödicke et al., 2006]. Dotted lines are isodepths of the subducting plate from analysis of seismicity [Pardo and Suarez, 1995]. Blue circle indicates where an ultra-slow velocity layer has been detected, and dashed circle indicates where it is absent.

Slow Slip and Tremor in the Northern Costa Rica Seismogenic Zone

S.Y. Schwartz *(University of California, Santa Cruz),* **J.I. Walter** *(UC Santa Cruz),* **T.H. Dixon** *(Univ. of Miami),* **K. Outerbridge** *(Univ. of Miami),* **J.M. Protti** *(OVSICORI-UNA),* **V. Gonzalez** *(OVSICORI-UNA)*

Several episodes of slow slip and tremor are believed to have occurred at the plate boundary of northern Costa Rica between 2000 and 2008. The evidence for these events varies and consists of: 1) correlated fluid flow excursions and seismic tremor recorded on ocean bottom instruments in 2000 [*Brown et al., 2005*]; 2) offsets in continuous GPS data in September 2003; 3) offsets in GPS data accompanied by seismic tremor in May 2007 [Outerbridge et al., 2010]; and 4) strong prolonged seismic tremor in August 2008. Modeling of the 2000 event suggested that slip occurred at shallow depth, between the surface and ~15 kilometers. The much better constrained slip distribution of the 2007 event consisted of 2 patches, the stronger centered at ~30 km depth, near the down dip transition from stick-slip to stable sliding, and the weaker patch located at ~6 km depth at the up dip edge of the shallow frictional transition. Tremor locations for the 2008 episode locate offshore at depths of between 6-10 km . The 2003 event was recorded on too few instruments to be modeled. These results are significant in that they are the first to suggest that slow slip occurs at the up dip transition from stick-slip to stable sliding; locations of slow slip in other environments have been limited to the down dip frictional transition.

Due to the relatively small surface displacements (1-2 cm) associated with Costa Rica slow slip events, the coincident occurrence of seismic tremor is important for their detection and study. Similar to tremor observations in southwest Japan, Costa Rica tremor consists of swarms of low-frequency earthquakes that occur as repetitive stick-slip motion on the plate interface [*Brown et al., 2009*], contains very low frequency earthquakes, with dominant energy between 20-50 s, and appears to be tidally modulated.

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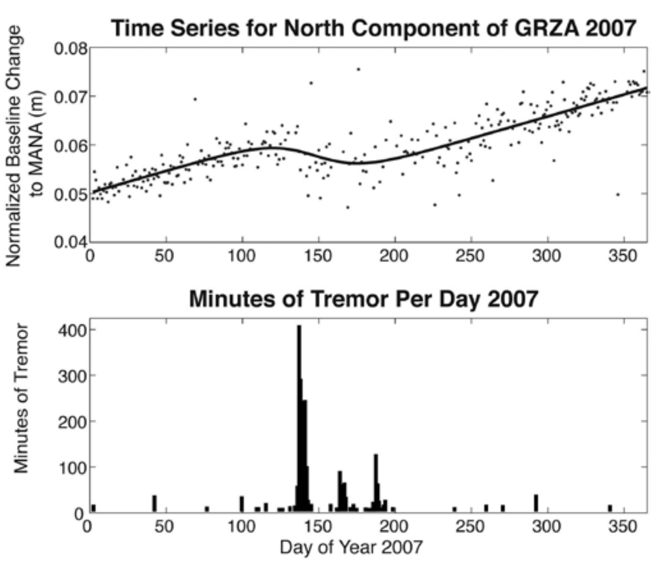
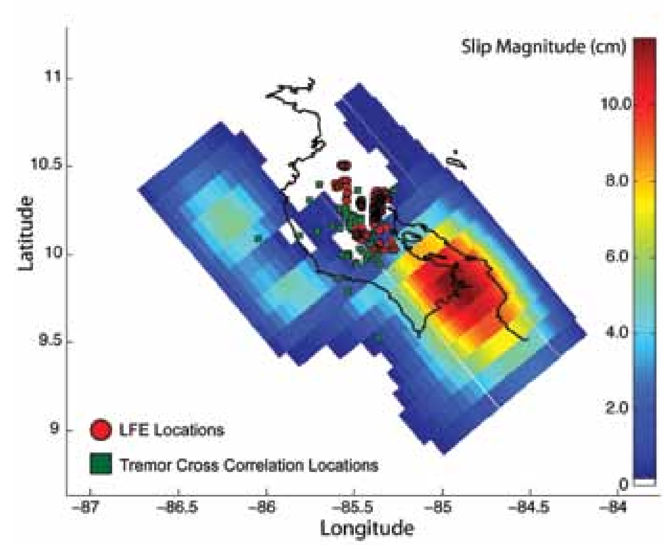
Acknowledgements: This research was supported by several grants from NSF's MARGINS and Instrumentation and Facilities programs including OCE- 0841061 and OCE-0841091 along with EAR-0842338, EAR-0506463, EAR-0502488, EAR-0842137, EAR-0502221 and EAR-0506382.



North component of displacement at station GRZA compared to a histogram of cumulative tremor duration per day for the entire year of 2007. The onset and duration of the geodetically determined slow slip correlates well with the peaks in the tremor time series.



Locations of tremor episodes and Low Frequency Earthquakes (LFEs) compared with the 2007 slow slip distribution.

An Earthquake-Like Magnitude-Frequency Distribution of Tectonic Tremor in Northern Cascadia

Kenneth Creager *(University of Washington)*, **Aaron Wech** *(University of Washington)*, **Heidi Houston** *(University of Washington)*, **John Vidale** *(University of Washington)*

Major episodic tremor and slip (ETS) events with Mw 6.4 to 6.7 repeat every 15 ± 2 months within the Cascadia subduction zone under the Olympic Peninsula. Although these major ETS events are observed to release strain, smaller "tremor swarms" without detectable geodetic deformation are more frequent. We employ a Waveform Envelope Cross-Correlation and Clustering (WECC) [Wech and Creager, 2008] algorithm to search every 50%-overlapping 5-minute window for tremor. The resulting 20,000 tremor epicenters from 2006 through 2009 in northern Washington naturally cluster in space and time into the 91 tremor swarms analyzed here. We find that 88 inter-ETS tremor swarms account for 45% of the total duration of tremor detection during the last three ETS cycles. Considering duration as proportional to moment release, the swarms follow a standard Gutenberg-Richter frequency-magnitude relation, with the major ETS events lying on the trend defined by inter-ETS swarms. This relationship implies that 1) inter-ETS swarms are fundamentally similar to the major events, just smaller and more frequent; and 2) despite fundamental differences in moment-duration scaling, the tremor magnitude-frequency distribution has the same power law trend of normal earthquakes with a b-value of 1.

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Acknowledgements: This study was supported by the National Science Foundation/EarthScope (EAR-0545441) and the USGS (08HQGR0034, G09AP00024, G10AP00033). Primary data were supplied by PNSN, EarthScope, PBO and PGC seismometers.

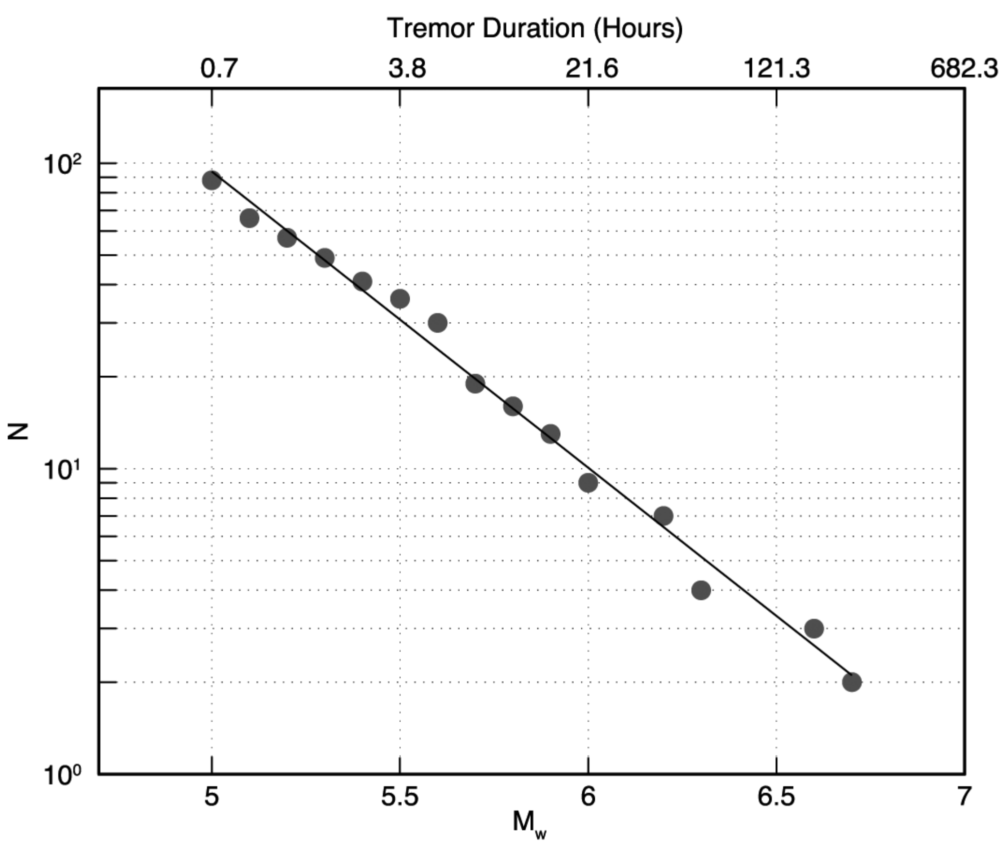


Figure 1. Log of number (N) of tremor swarms exceeding durations given on upper axis can be fit with a straight line indicating that N is proportional to τ ^-0.65 where τ is the duration of a tremor swarm. We assume that the seismic moment is proportional to tremor duration scaled by Mo (N-m) = 5.2x10^16 τ (hrs) [Aguiar et al., 2009] to equate duration (upper axis) to moment magnitude (lower axis). This allows a standard Gutenburg-Richter style analysis and produces a b-value of 1.0 (logN = a − bMw), which is within the range commonly seen for regular earthquakes.

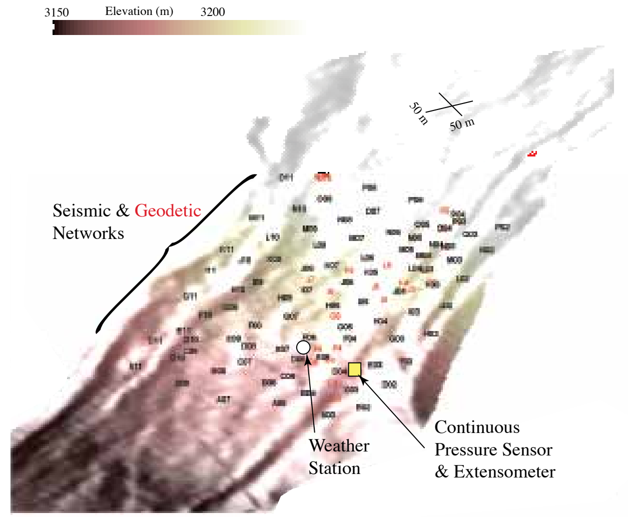
The Slumgullion Natural Laboratory

Joan Gomberg *(US Geological Survey),* **Paul Bodin** *(University of Washington),* **Bill Schulz** *(US Geological Survey),* **Jason Kean** *(US Geological Survey)*

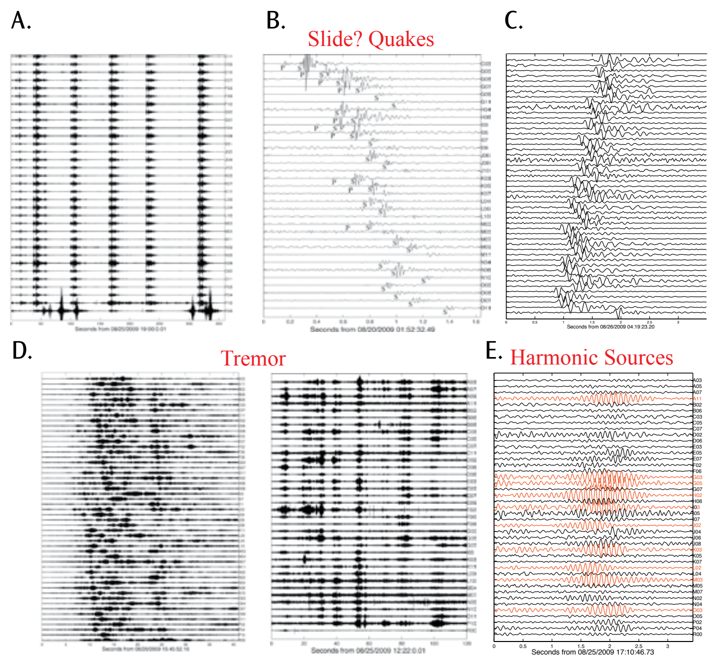
Observational advances continue to reveal diversity in the seismic signals associated with fault slip. A particularly rich example are episodes of slow fault slip near major plate boundaries that manifest as geodetically observed aseismic deformation abetted by a new family of seismic signals (named 'episodic tremor and slip' or ETS). While the driving forces and scales differ, there are striking parallels between some observations and models of ETS and of landslide behaviors. To explore common features and the underlying processes we are studying the Slumgullion landslide in southwest Colorado, and an ideal natural laboratory for observing fault slip and associated phenomena. Unlike crustal- or plate-scale studies significant deformation can be measured within a single field season, because the Slumgullion moves at average rates of up to 2 cm/day. We completed a field experiment on the Slumgullion to test several hypotheses, particularly that slip along the basal surface and side-bounding faults occurs with comparable richness of aseismic and seismic modes as crustal- and plate-scale boundaries. From August 18-26, 2009 we monitored the seismic radiation with 88 short-period vertical seismometers recorded on "Texan" seismographs from the IRIS PASSCAL facility. The seismographs, with inter-station spacings of 25-50 m, recorded continuously at 250 samples per second. In addition, we recorded deformation on several extensometers that continuously measure slip across one of the two lateral faults bounding the landslide, and tracked displacements of 29 sites on and off the slide with an automated total-station and differential GPS. More observations came from 2 borehole-mounted piezometers and a meteorological station.

The seismic data contain an abundance of network-wide coherent signals with an amazing variety of characteristics. We observed impulsive earthquakes with clear P,S, and surface wave phases. There are also "repeaters", or multiplets of slidequakes with very similar waveforms. There are episodes of tremor-like radiation coherent across our network. Noteably, a diurnal variation in the slide velocity tracks atmospheric pressure fluctuations, which correlates with the rates of repeating harmonic seismic signals. This correlation and our analyses of the wavefield associated with these events leads us to suggest that the signals are trapped waves generated at a 'sticky spot' within the side-bounding strike-slip fault.

Acknowledgements: This work was funded through the US Geological Venture Capital Program.



Topographic map of the narrowest and fastest section of the Slumgullion landslide, showing the locations of the seismographs (labeled), weather station, and pressure sensor, all of which recorded continuously. The outer-most lines of seismic stations lie outside the active slide, which is bounded by strike slip faults nearest the seismic stations numbered 03 and 02. R00 is a few meters from the nearest road. 'Geodetic' stations correspond to prisms that serve as targets for the robotic total station and 3 extensometers (2 not shown are located above and below the networks).



A. The relatively long duration waveforms of events in this vigorous sequence, which lasted several tens of minutes, suggest the sources are similar but not identical in location, mechanism, and size. B. Waveforms from a single, tiny quake show clear P and S arrivals & suggest an impulsive shear source a few hundred meters from station C03. This quake is part of a sequence containing tens of events within a few minutes. C. Example of probable Rayleigh wave packets from similar sources that occurred throughtout the experiment. D. Record of many signals with the same characteristics as tremor observed in plate-scale systems. Their durations last from several seconds to minutes. Although preliminary examination of envelope functions appears to show promise (e.g. envelopes correlate visually at multiple stations), we have yet to quantitatively analyze the tremor signals. E. Record of hundreds of events with waveforms similar to these transient harmonic signals. The largest amplitude signals are shown in orange and are recorded at stations near the side-bounding fault.

Distribution and Triggering Threshold of Non-Volcanic Tremor Near Anza, Southern California

Elizabeth S. Cochran *(University of California, Riverside)*, **Tien-Huei Wang** *(University of California, Riverside)*

To study the distribution and characteristics of non-volcanic tremor in Southern California, we use broadband data collected by the Southern California Seismic Network (SCSN) surface stations near Anza, California and five Plate Boundary Observatory (PBO) borehole stations. To determine the stress amplitude and orientation needed to trigger tremor, we examined 41 teleseismic earthquakes chosen with epicentral distances greater than 1900 km, from diverse azimuths and Mw over 7.0 from 2001 to 2008. We found that only the 2002 Mw7.8 Denali earthquake, with the largest surface wave amplitudes of all of the teleseismic events, triggered detectable tremor. We are currently determining more precise locations of individual tremor bursts in the of Denali-triggered NVT using a template-matching method [*Shelly et al., 2009*]. The templates will be used to precisely locate the tremor and to examine the spatial and temporal evolution of triggered tremor. Once the tremor are located, we will determine the precise stress pertubation caused by the Denali earthquake at the tremor hypocenter.We will then compare the triggering threshold for tremor to the stress perturbation from teleseisms that trigger local earthquakes on the San Jacinto Fault. From this study we hope to illuminate differences in the response of earthquakes and tremor to stress pertubations.

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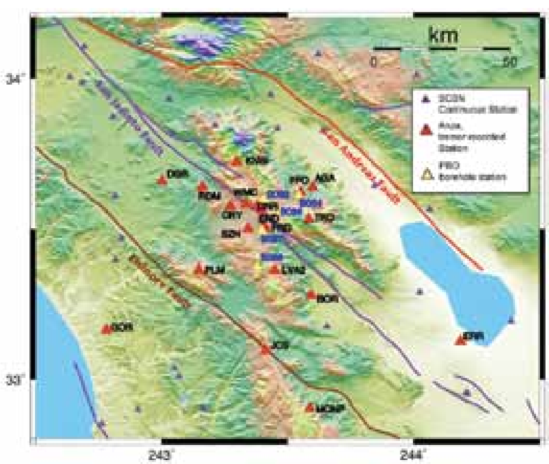
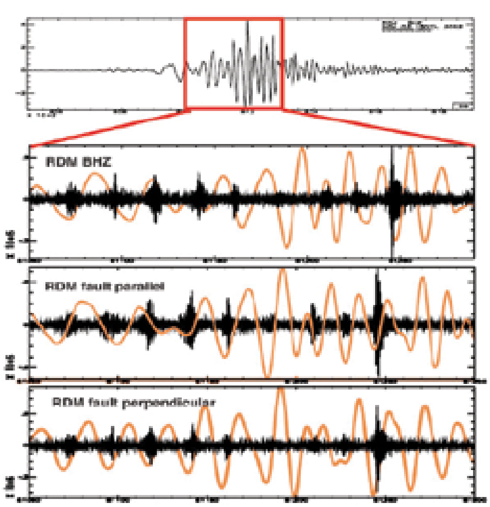
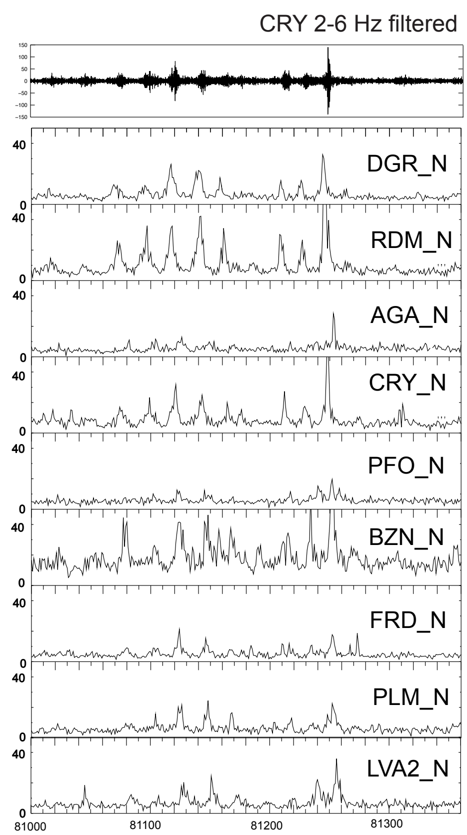
Acknowledgements: This work is supported by NSF (EAR0943892) and SCEC (09054).



Map of seismic stations using the analysis. SCSN stations that detected tremor are shown by red triangles, borehole stations that detected tremor are shown by yellow triangles, and other SCSN stations are shown by blue triangles.



Waveform examples of Denali tremor on station RDM that is triggered by the passing surface waves of the Denali earthquake. The upper panel shows the Denali earthquake recorded on the vertical component of RDM. The region that is expanded in the lower panels is highlighted in red. The lower panels span 250 seconds and show all three components (vertical, fault parallel, and fault perpendicular). The orange curves show the surface waves of the earthquake in nm/sec and the black curves show the data filtered between 2-8 Hz (amplitude is exaggerated by 20,000).



Filtered seismogram (top) and envelope functions of all surface stations that recorded the tremor triggered by the Denali surface waves. Large amplitude bursts are well-correlated in time. Borehole station records are not included in this analysis since most PBO stations were installed after 2006.

Intimate Details of Tremor Observed by a Dense Seismic Array

Abhijit Ghosh *(University of Washington),* **John E. Vidale** *(University of Washington),* **Justin R. Sweet** *(University of Washington),* **Kenneth C. Creager** *(University of Washington),* **Aaron G. Wech** *(University of Washington),* **Heidi Houston** *(University of Washington),* **Emily E. Brodsky** *(University of California Santa Cruz)*

We installed a dense small aperture seismic array in Cascadia, and captured the episodic tremor and slip event in May 2008. We developed a new beam-backprojection (BBP) method to detect and locate non-volcanic tremor [Ghosh et al., 2009]. BBP method detects up to 4 times more duration of tremor during a weak episode, and gives unprecedented resolution in relative tremor location, compared to a conventional envelope cross-correlation method. We track tremor minute-by-minute using BBP method, and map spatiotemporal tremor distribution over different time scales. Over short time scale (several minutes), tremor shows rapid, continuous, slip-parallel migration with a velocity of ~50 km/hr [Ghosh et al., 2010a]. Over the time scale of several hours, slip-parallel tremor bands sweep Cascadia along-strike with a velocity of ~10 km/day [Ghosh et al., 2010b]. Finally, over the time scale of several days, tremor develops distinct moment patches that overlap with geodetic slip patch on the interface [Ghosh et al., 2009]. While heterogeneity on the plate interface may cause tremor moment patches, along-strike stress transfer can explain slow along-strike marching of tremor bands. These varied and intriguing observations lead toward a unified view of tremor distribution in space and time.

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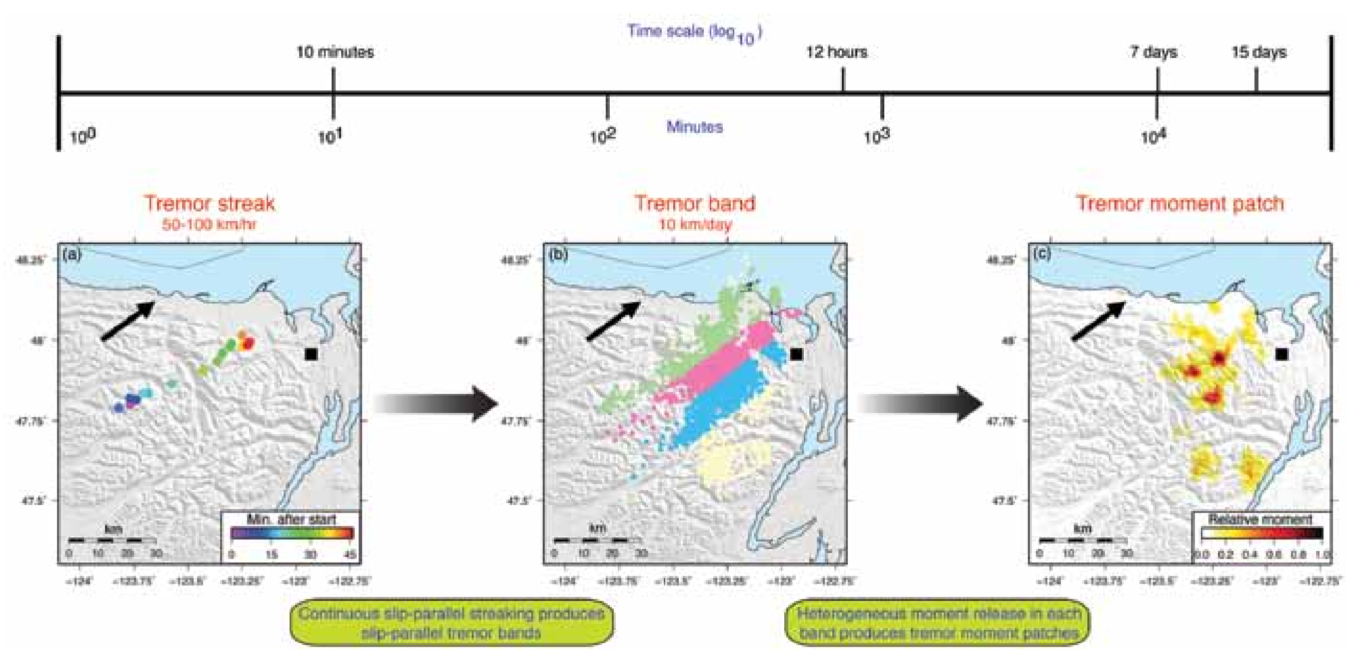

A unified view of tremor distribution in time and space: a time scale (log10) is shown at the top. The maps show different elements of spatiotemporal tremor distribution observed over different time scales. Positions of the maps along the time scale approximately correspond to the time scales over which these elements are typically observed. Arrow in each map indicates slip direction of CSZ. Black solid square marks the Big Skidder array. (a) Slip-parallel tremor streak. Colored circles represent tremor locations. Time is color-coded to show rapid tremor migration over short time scale. (b) Slip-parallel tremor bands defining the long-term slower along-strike tremor migration over time-scales of hours to a day. Solid colored circles are tremor locations. Blue, pink, and green locations define the tremor bands. Faint yellow locations fall outside the tremor bands. (c) Relative band-limited tremor moment patches that release much of the seismic moment during an ETS event.

Tidal Triggering of LFEs Near Parkfield, CA

Amanda Thomas *(University of California - Berkeley)*, **Roland Burgmann** *(University of California - Berkeley)*, **David Shelly** *(United States Geological Survey)*

Studies of nonvolcanic tremor (NVT) in Japan, Cascadia, and Parkfield, CA have established the significant impact of small stress perturbations, such as the solid earth and ocean tides, on NVT generation [*Thomas et al., 2009 and references therein*]. Similar results irrespective of tectonic environment suggest that extremely high pore fluid pressures are required to produce NVT. We analyzed the influence of the solid earth and ocean tides on a catalog of ~500,000 low frequency earthquakes (LFEs) constituting 88 event families distributed along a 150-km-long section of the San Andreas Fault centered at Parkfield [*Shelly, D. R. and J. L. Hardebeck, 2010*]. LFEs comprising the tremor signal are grouped into families based on waveform similarity and precisely located using waveform cross-correlation. Analogous to repeating earthquakes, LFE families are thought to represent deformation on the same patch of fault. While the locations of repeating earthquakes are assumed to be coincident with the location of asperities in the otherwise aseismically creeping fault zone, NVT occur below the seismogenic zone, where fault zones behave ductilely. We explored the sensitivity of each of these LFE families to the tidally induced shear (RLSS) and normal (FNS), and stresses on the SAF [*Thomas et al., 2010*]. Nearly all of the 88 LFE families are triggered by positive RLSS and in general correlation increases as a function of depth. Some LFE families experience enhanced triggering during times of extensional normal stress while others preferentially respond to compression. The level of correlation appears to be spatially continuous along the fault but exhibits no depth dependence. Future research efforts will focus on using the LFE response to tidal influence to place constraints on the mechanical properties of the deep San Andreas fault.

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Acknowledgements: This work was supported by the NSF and the USGS.

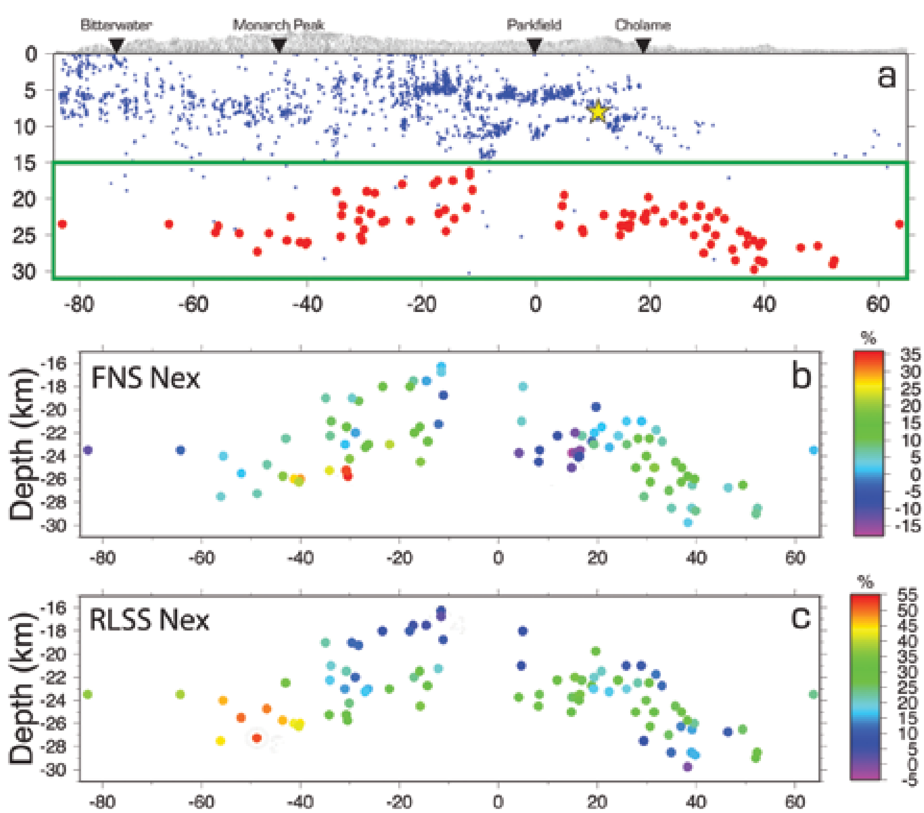

Figure 1: (a) Along-fault cross section of the SAF viewed from the south-west. Vertically exaggerated topography is shown in grey. Local towns are marked by inverted triangles. Hypocenters of SAF seismicity, the 2004 Parkfield earthquake, and LFE locations are shown as blue dots, yellow star, and red circles respectively. Panels (b) and (c) are delineated by the green box. (b) LFE locations color coded by their FNS Nex (percent excess = [actual number of LFEs during times of positive FNS – expected number of LFEs during times of positive FNS]/expected number of LFEs during times of positive FNS). (c) LFE locations color coded by the RLSS Nex values.

Global Search of Triggered Tremor and Low-Frequency Earthquakes

Zhigang Peng *(Georgia Institute of Technology)*

Deep "non-volcanic" tremor and episodic slow-slip events are among the most interesting discoveries in earthquake seismology in the last decade. These events have much longer source durations than regular earthquakes, and are generally located near or below the seismogenic zone where regular earthquakes occur. Tremor and slow-slip events appear to be extremely stress sensitive, and could be instantaneously triggered by distant earthquakes and solid earth tides. We have conducted a global search of triggered tremor and low-frequency earthquakes (LFEs) associated with large regional and teleseismic earthquakes. These include the Parkfield-Cholame section of the San Andreas Fault [Gomberg et al., 2008; Peng et al., 2009], the Calaveras fault in northern California and the San Jacinto Fault in southern California [*Gomberg et al., 2008*], and beneath the Central Range in Taiwan [Peng and Chao, 2008]. In several places, we found that tremor is often initiated by the Love waves, and continues to be modulated during the subsequent Rayleigh waves. Many LFEs were identified during the triggered tremor episode, and triggered LFEs sometimes showed fast migrations along the fault strike, similar to ambient LFEs/tremor and possibly reflecting triggered micro-slow-slip events. Long-period and large-amplitude surface waves from both regional and teleseismic events have a greater potential of triggering tremor, and inferred triggering threshold is on the order of ~1kPa, suggesting that the deep faults are critically stressed, most likely due to near-lithostatic fluid pressures.

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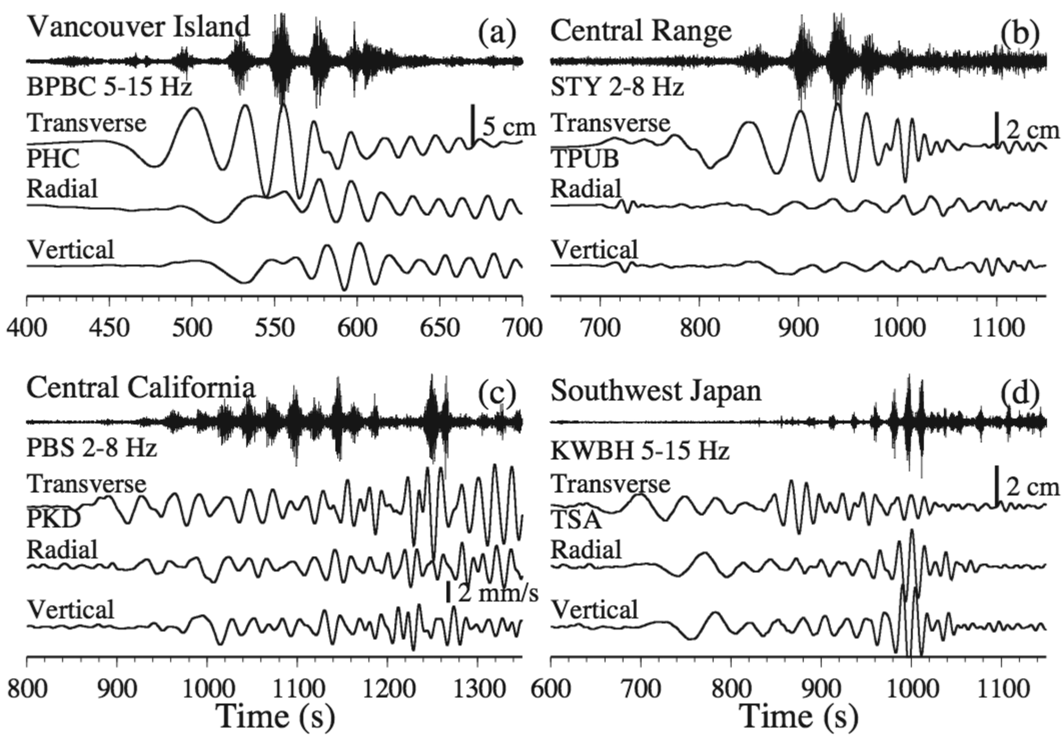

A comparison of surface waves of large teleseismic earthquakes and triggered tremor beneath (a) Vancouver Island in British Columbia [Rubinstein et al., 2007], (b) the Central Range in Taiwan [Peng and Chao, 2008], (c) the San Andreas Fault in Central California [Peng et al., 2009], and (d) the subduction zone is Southwest Japan [Miyazawa et al., 2008]. The traces have been time-shifted to reflect the relationship between the surface waves and tremor at the source region.

Cascadia Transition Zone: Tremor as a Fault Strength Indicator

Aaron Wech *(University of Washington)*, **Ken Creager** *(University of Washington)*

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. We use automatically detected tectonic tremor as a slow slip indicator in northern Cascadia to observe updip migration and a depth-dependent transition in slip size and periodicity. 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.

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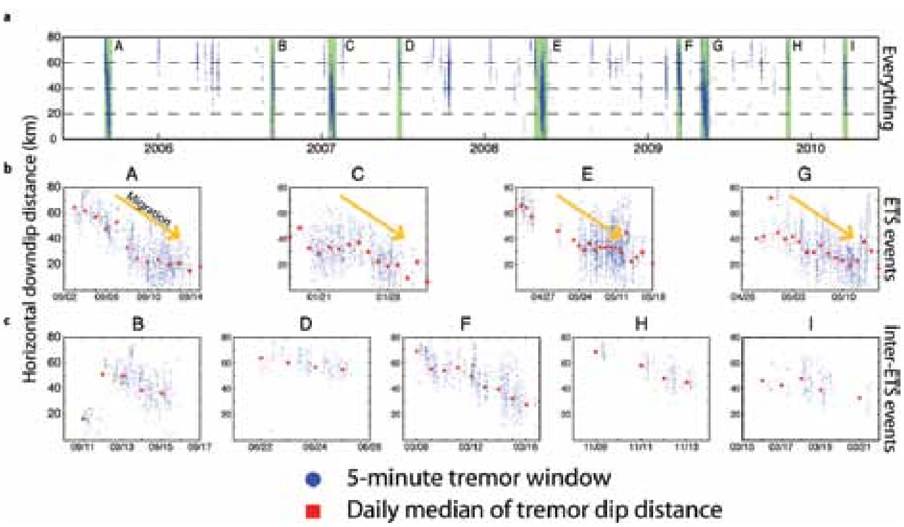
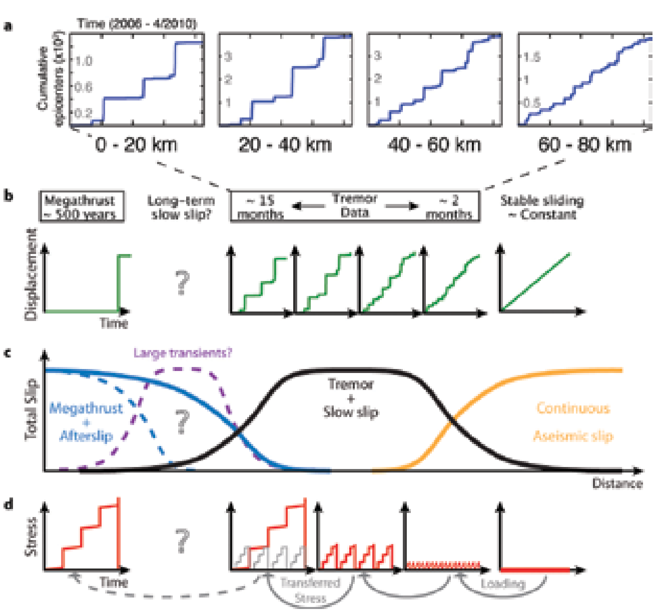


Updip tremor migration. (a) Horizontal downdip tremor distance versus time of northern Washington catalog showing many small swarms downdip and larger swarms initiating deep and migrating updip. (b) Migration for the past 4 ETS episodes. Blue dots represent tremor epicenters and red squares show median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

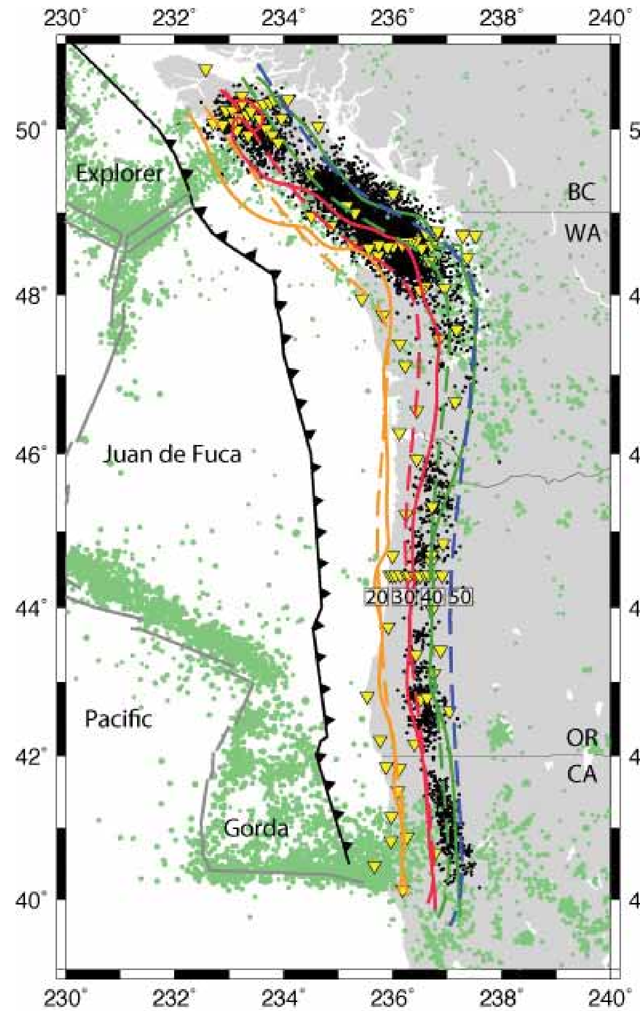


Displacement history profiles and transition zone model. (a) Cumulative tremor profiles in each strike-perpendicular bin showing a transition from small, frequent slip downdip to larger, less frequent slip updip. (b) Profiles of displacement timelines from the locked zone to stable sliding with results 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.

Slab Morphology in the Cascadia Fore Arc and Its Relation to Episodic Tremor and Slip

Pascal Audet *(University of California Berkeley)*, **Michael Bostock** *(University of British Columbia)*, **Devin Boyarko** *(Miami University)*, **Mike Brudzinski** *(Miami University)*, **Richard Allen** *(University of California Berkeley)*

Episodic tremor and slip (ETS) events in subduction zones occur in the general vicinity of the plate boundary, downdip of the locked zone. In developing an understanding of the ETS phenomenon it is important to relate the spatial occurrence of nonvolcanic tremor to the principal structural elements within the subduction complex. In Cascadia, active and passive source seismic data image a highly reflective, dipping, low-velocity zone (LVZ) beneath the fore-arc crust; however, its continuity along the margin is not established with certainty, and its interpretation is debated. In this work we have assembled a large teleseismic body wave data set comprising stations from northern California to northern Vancouver Island. Using stacked receiver functions we demonstrate that the LVZ is well developed along the entire margin from the coast eastward to the fore-arc basins (Georgia Strait, Puget Sound, and Willamette Valley). Combined with observations and predictions of intraslab seismicity, seismic velocity structure, and tremor hypocenters, our results support the thesis that the LVZ represents the signature of subducted oceanic crust, consistent with thermal-petrological modeling of subduction zone metamorphism. The location of tremor epicenters along the revised slab contours indicates their occurrence close to but seaward of the wedge corner. Based on evidence for high pore fluid pressure within the oceanic crust and a downdip transition in permeability of the plate interface, we propose a conceptual model for the generation of ETS where the occurrence and recurrence of propagating slow slip and low-frequency tremor are explained by episodic pore fluid pressure buildup and fluid release into or across the plate boundary.



Depths contours of the top of the plate interface from receiver functions (this study, solid lines) and a compilation of various studies (dashed lines, McCrory et al., 2006) along the Cascadia margin. Earthquake epicenters from the GSC and USGS catalogues for M > 2 are shown as green dots; tremor epicenters appear as black dots. Broadband stations used in the analysis are displayed as inverted yellow triangles. Numbers indicate depth (in km) to each contour. Solid black line with arrowheads indicates the location of the trench offshore.

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