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Ray E. Wells

Portland State University, rwells@pdx.edu

Richard J. Blakely

U.S. Geological Survey

Aaron G. Wech

U.S. Geological Survey

Patricia A. McCrory

U.S. Geological Survey

Andrew Michael

U.S. Geological Survey

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Cascadia subduction tremor muted by crustal faults

Ray E. Wells^{1*}, Richard J. Blakely², Aaron G. Wech³, Patricia A. McCrory⁴, and Andrew Michael⁴

¹U.S. Geological Survey, 2130 SW 5th Avenue, Portland, Oregon 97201, USA

²U.S. Geological Survey, 345 Middlefield Road, MS 989, Menlo Park, California 94025, USA

³U.S. Geological Survey, Alaska Volcano Observatory, Anchorage, Alaska 99508, USA

⁴U.S. Geological Survey, 345 Middlefield Road, MS 910, Menlo Park, California 94025, USA

ABSTRACT

Deep, episodic slow slip on the Cascadia subduction megathrust of western North America is accompanied by low-frequency tremor in a zone of high fluid pressure between 30 and 40 km depth. Tremor density (tremor epicenters per square kilometer) varies along strike, and lower tremor density statistically correlates with upper plate faults that accommodate northward motion and rotation of forearc blocks. Upper plate earthquakes occur to 35 km depth beneath the faults. We suggest that the faults extend to the overpressured megathrust, where they provide fracture pathways for fluid escape into the upper plate. This locally reduces megathrust fluid pressure and tremor occurrence beneath the faults. Damping of tremor and related slow slip caused by fluid escape could affect fault properties of the megathrust, possibly influencing the behavior of great earthquakes.

INTRODUCTION

Episodic slip on the Cascadia subduction megathrust of the northwest United States and adjacent Canada occurs 30–40 km deep in the transition zone between the shallow locked fault and free slip at depth (Dragert et al., 2001; Ghosh et al., 2012). These slow slip events typically are marked by low-frequency tremor, and together the two phenomena are known as episodic tremor and slip (ETS; Rogers and Dragert, 2003) (Fig. 1A). Slow slip events and accompanying tremor have been recognized in several warm-slab subduction zones (Ide, 2012). ETS accommodates a significant part of plate convergence in Cascadia (Schmidt and Gao, 2010), potentially loading the source zone of great megathrust earthquakes updip. The periodicity and intensity of tremor vary along strike in Cascadia (Wech, 2010; Brudzinski and Allen, 2007), and intensity is lowest in the central Oregon forearc (Fig. 1). Variations in tremor occurrence appear

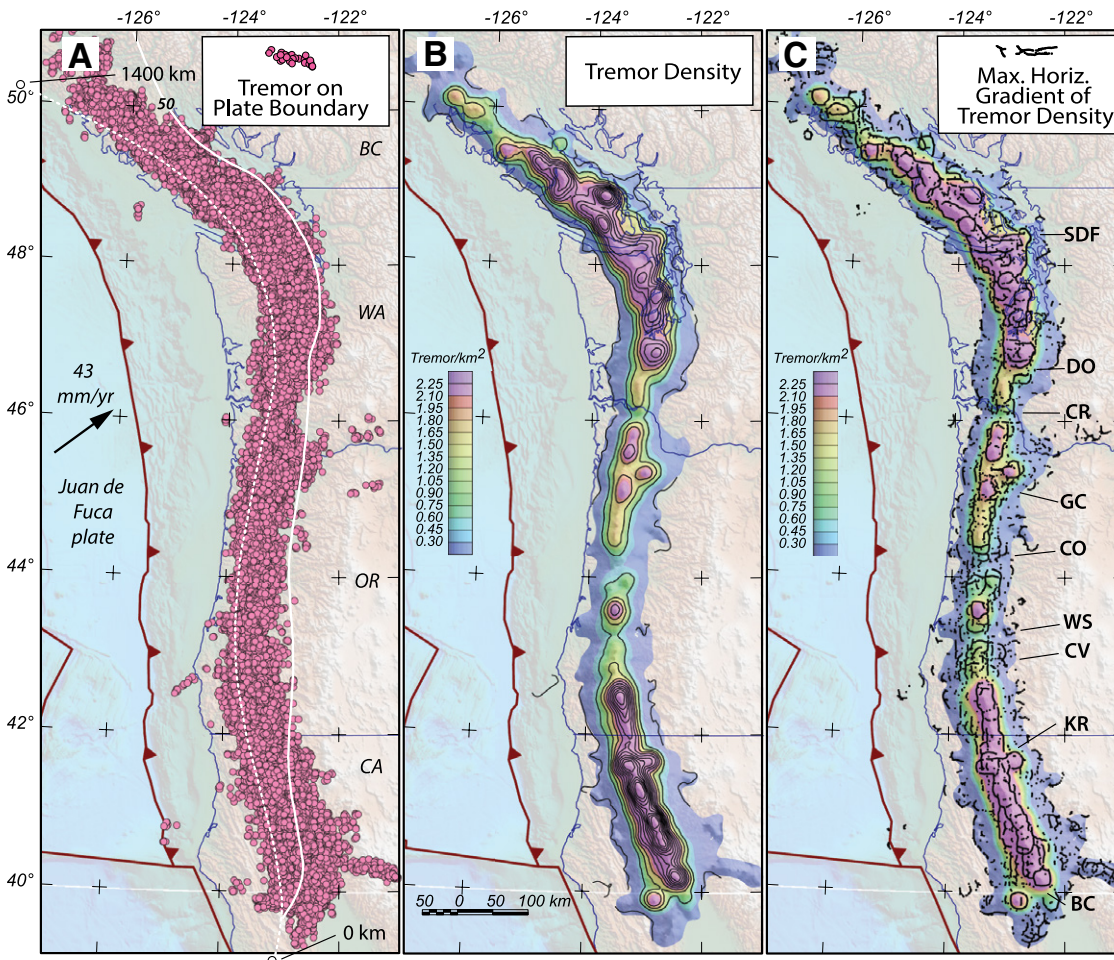


Figure 1. Tremor locations, tremor density, and maximum horizontal gradients of tremor density, Cascadia subduction zone, northwestern United States and adjacent Canada. **A:** Tremor locations from the Pacific Northwest Seismic Network tremor map PNSN, 2009–2015 (<http://www.pnsn.org/tremor/>). The 50 km contour on megathrust is white, and line of reference for Figure 3 is dotted. CA—California, OR—Oregon, WA—Washington, BC—British Columbia, Canada. **B:** Contours of tremor epicenters/km² (tremor density) show variation in tremor density along strike. **C:** Maximum horizontal (Max. Horiz.) gradient of tremor density (black dots, dotted lines) outline band of maximum tremor segmented by transverse zones of lower tremor indicated by letter code (SDF—Strait of Juan de Fuca; DO—Doty; CR—Columbia River; GC—Gales Creek; CO—Corvallis; WS—Wildlife Safari; CV—Canyonville; KR—Klamath River; BC—Battle Creek; for method, see the Data Repository [see footnote 1]).

*E-mail: rwells@usgs.gov

to correlate with the composition and topography of the overlying plate (Brudzinski and Allen, 2007), and a large drop in tremor density coincides with a major forearc block boundary fault in southwest Washington State (Bassett and Watts, 2015). On Vancouver Island, Canada, tremor density is anticorrelated with forearc earthquakes, possibly due to transient stress changes on the megathrust and in the overlying plate (Kao et al., 2009). Lower V_p/V_s (ratio of P wave to S wave velocities) values in the overlying forearc correlate with more frequent ETS occurrences along strike and downdip in Cascadia (Audet and Burgmann, 2014), and this linear correlation has been interpreted to be the result of quartz precipitation in forearc crust from slab-derived fluids expelled during slow slip episodes (Audet and Burgmann, 2014; Hyndman et al., 2015). Very high V_p/V_s ratios in the tremor source zone are interpreted to be the result of high, near-lithostatic fluid pressures on the megathrust (Audet and Burgmann, 2014; Audet et al., 2009). Observed tremor modulation by tidal forces is consistent with a very weak fault with very high fluid pressures in the fault zone (e.g., Houston, 2015).

Variations in tremor occurrence along strike may reflect changes in crustal composition, with low tremor occurrence beneath the central Oregon segment related to Siletzia, the accreted oceanic basalt terrane composing the Oregon forearc (Brudzinski and Allen, 2007; Audet and Burgmann, 2014). Some concentrations of tremor may reflect transient features that migrate over time owing to stress interactions under high fluid pressures (Liu, 2014). Alternatively, along-strike variations in tremor may reflect structural segmentation of the upper plate by northward motion and clockwise rotation of forearc blocks (Bassett and Watts, 2015; Wells et al., 1998, 2003; McCaffrey et al., 2013). Cascadia's megathrust rupture history (Goldfinger et al., 2012; Wang et al., 2013) and the segmented crustal structure of the forearc are consistent with a Cascadia megathrust that is seismically segmented. In addition to regional variations in tremor density, individual tremor episodes appear to initiate and terminate at favored locations (Wech and Bartlow, 2014). We consider the possibility that these patterns in tremor periodicity and lateral migration are related to the fundamental crustal structure of the overlying plate, and that tremor density may provide clues to potential rupture mode variability on the Cascadia megathrust.

TREMOR AND UPPER PLATE FAULTS

Here we examine the variability of tremor density and tremor propagation along strike and compare it to the structure of the overlying plate determined from geological and geophysical surveys. The 2009 to July 2015 tremor catalog (Wech, 2010) is shown in Figure 1A. Tremor density (epicenters/km²) is shown in Figure 1B, and the locations of maximum horizontal gradients of tremor density are shown in Figure 1C. The maximum gradients outline a 20-km-wide band of maximum tremor density beneath the forearc that widens to ~50 km beneath the Olympic Peninsula, where the megathrust dips more gently (McCrorry et al., 2012). South of the Olympic Peninsula, the band of high tremor density narrows, where it is disrupted along strike by irregular tremor-density gradients that are transverse to the margin (Fig. 1C). In these transverse zones, the tremor density is lower.

The transverse zones of lower tremor density coincide with major block-bounding forearc faults determined from geologic, potential field, and GPS data (Fig. 2). The faults are extracted from Oregon, Washington, and California state geologic databases, the U.S. Geological Survey (USGS) Quaternary fault database, potential field surveys, and seismicity (see the GSA Data Repository¹ for the data sources). These regionally significant structures cross the entire forearc, define block boundaries

¹GSA Data Repository item 2017163, materials and methods, Figures DR1–DR4, supplemental references, data tables (tremorvsfaults, zipped), is available online at <http://www.geosociety.org/datarepository/2017/> or on request from editing@geosociety.org.

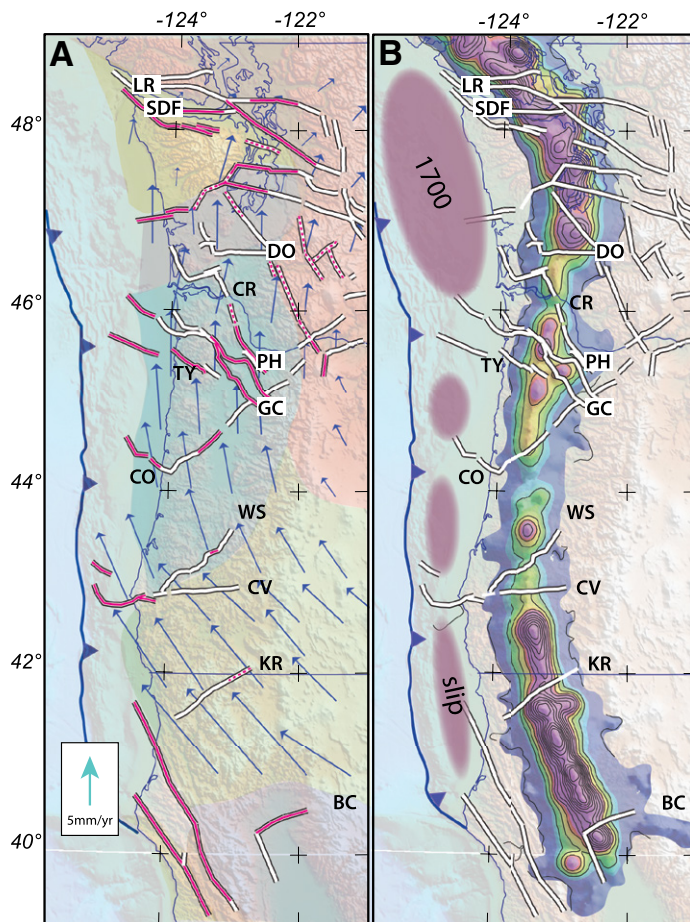


Figure 2. Forearc blocks and tremor in the Cascadia forearc. A: Block-bounding forearc faults (white lines—large faults from state geologic databases; red fill—Quaternary faults; red dots—defined by seismicity; Fig. DR3; see footnote 1). Fault names: LR—Leech River; SDF—Strait of Juan de Fuca; DO—Doty; CR—Columbia River; GC—Gales Creek; TY—Tillamook-Yamhill; CO—Corvallis; WS—Wildlife Safari; CV—Canyonville; KR—Klamath River (see database links and Fig. DR3; see footnote 1). PH—Portland Hills; BC—Battle Creek. Blue arrows show secular motion with respect to stable North America from geodetic block models (pale colors, modified from McCaffrey et al., 2013). B: Tremor density is lower beneath forearc faults. Offshore ovals outline greatest slip in the A.D. 1700 earthquake determined from variations in coastal subsidence (Wang et al., 2013).

in geodetic models, and are represented in the USGS Quaternary fault database (Fig. DR3 in the Data Repository). The faults accommodate margin-parallel dextral shear and north-south compression resulting from northward translation and clockwise rotation of forearc blocks (Wells et al., 1998; McCaffrey et al., 2013). The tremor lows have persisted over a decade of monitoring (Fig. 3A; <http://www.pnsn.org/tremor/>) and, given the systematic coincidence with crustal faults, may reflect fundamental characteristics of forearc structure. However, some larger ETS events have migrated across faults that seem to segregate smaller events (Fig. 3A), and it is possible that rare slow slip may occur in the absence of detectable tremor (Wech and Bartlow, 2014).

Statistical Significance

Tremor density is lower where overlain by large forearc faults (Fig. 2), and we consider the significance of this coincidence. We compare statistical distributions of tremor density near faults crossing the axis of maximum tremor to tremor density distributions along the axis of maximum tremor, but away from faults (Fig. 4). A Kolmogorov-Smirnov test

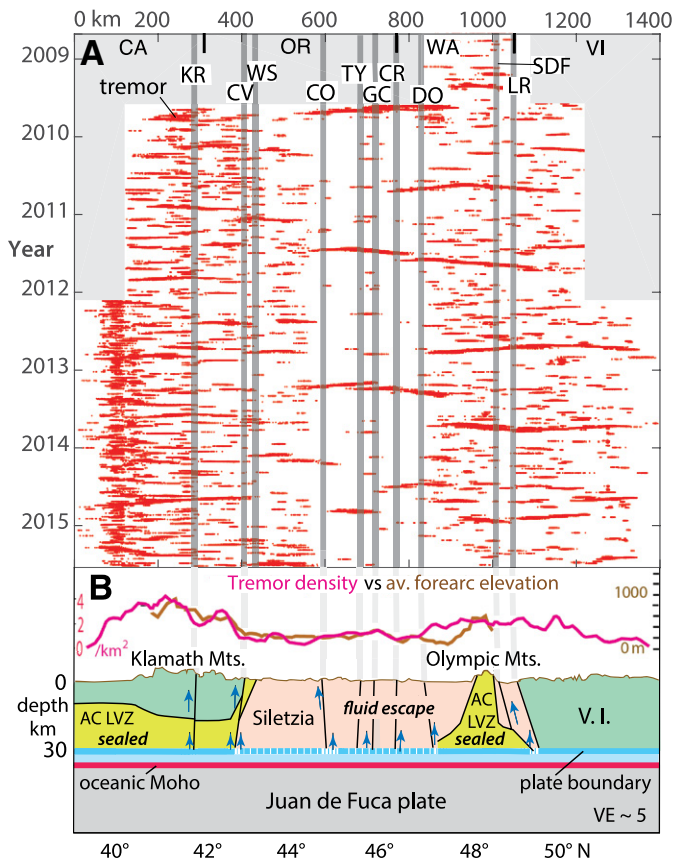


Figure 3. Tremor migration 2009–2015 compared to forearc structure. Fault labels are from Figure 2. Other abbreviations: CA—California, OR—Oregon, WA—Washington, VI—Vancouver Island. Tremor and fault locations are projected updip to dotted line in Figure 1A. A: Faults define boundaries of tremor termination and initiation; larger tremor bursts may cross faults. B: Faults likely extend to megathrust, providing a route for fluid escape (blue arrows), thus reducing fluid pressure and tremor occurrence on the plate boundary. Tremor density highs (red line) along tremor axis in Figure 1C correlate with average (av.) forearc topography (brown line; Kelsey et al., 1994) and low-velocity zones (LVZ; see text) interpreted as underplated Olympic and Franciscan accretionary complexes (AC). VE—vertical exaggeration.

shows that tremor density distributions within 5 km of major forearc faults are deficient in high values and have a miniscule ($\ll 10^{-6}$) chance of being a random sample of the tremor density population far from faults. This can be visualized by comparing the tremor density distribution near forearc faults to random samples of tremor density in Figure 4B. In 1000 random samples drawn from all tremor densities, there were none that resemble the tremor density distribution near the faults. Thus the correlation between large transverse forearc faults and low tremor density is strong, and it indicates a connection between upper plate faults and the tremor source zone along the megathrust at 30–40 km depth.

DISCUSSION

Major forearc faults extend to substantial depths. They are resolvable to depths of 25–30 km with seismic tomography (Calvert et al., 2011), and to >35 km depth as subvertical zones of seismicity beneath lowland faults (McCrory et al., 2012; Fig. DR4). Although some faults have been mapped as thrust or reverse faults, others appear to be high-angle faults that bound rotating blocks. Dips are not well constrained at depth (Calvert et al., 2011). Mantle helium has been observed off Tohoku, Japan, after the 2011 M9 earthquake (Sano et al., 2014), in the Nankai and New Zealand forearcs, and in the Cascadia forearc (McCrory et al., 2016).

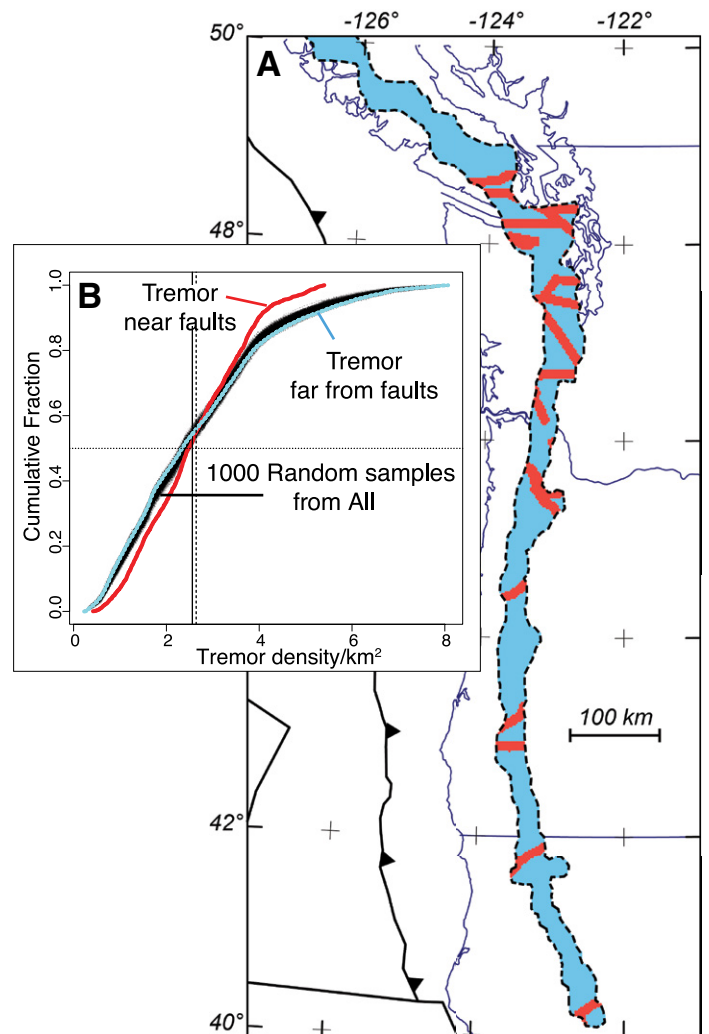


Figure 4. A: Axial tremor high defined by maximum horizontal gradients in tremor density (dashed lines from Fig. 1C). Red zone is near-fault tremor within 5 km of forearc faults in Figure 2. Blue zone is tremor far from fault, more than 5 km away from faults. B: Cumulative distributions comparing near-fault tremor density distribution to tremor distribution far from faults shown in A. Red line shows tremor density distribution within 5 km of the faults; blue line shows tremor density distribution >5 km from the faults. Black swath is 1000 random samples of the axial tremor band (each same n as in red zone) drawn from all tremor densities. Horizontal dashed line shows the median level; vertical solid and dashed lines show the means of the near-fault and far-from-fault distributions.

Cascadia forearc faults appear to extend to depths sufficient to interact with the megathrust.

Crustal faults that extend to the megathrust could provide paths for fluid escape. The sensitivity of tremor to small stress changes and its episodic occurrence indicate a system responsive to fluid pressure changes. Localized reduction of fluid pressure on the megathrust by fluid escape along crustal faults may be the cause of reduced tremor occurrence and termination of slip migration. Major rivers in the forearc, most following fault zones, also follow tremor lows (Fig. DR2). The long-wavelength correlation of high average forearc topography and tremor in Figure 3B can be explained by underplating of lower velocity, quartz-rich sediment of the Olympic and Franciscan accretionary complexes (Calvert et al., 2011; Porritt et al., 2011), locally uplifting the northern and southern Cascadia forearc (Brandon et al., 1998) and providing a quartz source to effectively seal the megathrust. These observations strengthen the apparent

correlation between tremor, high fluid pressure, and quartz sealing of the fault (Audet et al., 2009; Hyndman et al., 2015).

Block boundary faults in the forearc may interact with the megathrust in complex ways. Deformation along block-boundary faults extends offshore (McNeill et al., 1998), bridging the gap (Gao and Wang, 2017) between the ETS source and the seismogenic megathrust (Fig. 2). Loading and slip of these transverse faults by northward block motion is slower than loading of the megathrust by margin normal convergence (Wells et al., 1998; McCaffrey et al., 2013), and differences in the seismic cycles are likely to produce stress concentrations at fault intersections with the megathrust. Forearc block rotation and variable locking of the megathrust could result in seismic segmentation of the shallow Cascadia megathrust similar to the Nankai margin of southwestern Japan (Wells et al., 2003). Slip patches on the shallow megathrust determined from modeling of coastal subsidence from the A.D. 1700 Cascadia great earthquake (Wang et al., 2013) are bound by the same forearc deformation zones that affect tremor distributions (Fig. 2B).

The reduction in tremor beneath large crustal faults and the correlation of both tremor and 1700 slip patches with crustal blocks in the forearc suggest that the megathrust and the forearc faults act as an integrated fault system. Damping of tremor beneath forearc faults, if sustained, could locally increase stresses on the deeper megathrust and might induce seismicity in overlying faults in the forearc through fluid injection from below. Fluid transfer between faults may be an important process in linking megathrust segmentation and upper plate behavior. Large forearc faults are potential targets for study of mantle helium, and the further study of interactions between upper plate structures and the megathrust may help us better understand the potential diversity of behavior along Cascadia and other subduction zone megathrusts.

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