Supplementary Materials for

Cascadia Subduction Tremor Muted by Crustal Faults

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This PDF file includes:

Materials and Methods
Figs. DR1 to DR4
Supplemental References

Other Supplementary Materials for this manuscript includes the following:

Files as zipped archive; tremorvsfaults.zip:
all_tremor_density.xlsx
all_inside_steepest_gradient.xlsx
inside_steepest_gradient_and_near_any_fault.xlsx
inside_steepest_gradient_and_far_from_all_faults.xlsx

Materials and Methods

Tremor Epicenters

Tremor epicenter data from 2006 to 2015 are provided by the Pacific Northwest Seismic Network (PNSN) tremor catalog, http://www.pnsn.org/tremor (*Wech,* 2010). Tremor events, i.e., five-minute windows during which coherent tremor is locatable, are post-processed to remove duplicate events from overlapping sub-networks by averaging simultaneous epicenters occurring within 25 km of each other. Epicenter uncertainties are ± 5 km and compiled on a 5 km grid. Station coverage is relatively uniform, and segmentation of tremor behavior does not correlate with network geometry (Figure DR1).

Calculation of Tremor Density

Tremor density maps were derived from 2009-2014 tremor epicenters to avoid bias from earlier, non-uniform station distribution. Maps of tremor density were calculated in two steps. First, the number of tremors occurring within a 25 km radius of each tremor were counted and normalized by the area of a circle with the same radius. Second, the normalized counts of tremors were interpolated to a 12.5 km map grid with appropriate Cartesian projection and contoured. Tremor event density ranges from 0.15 to > 8.0 events/km2. The horizontal gradient of tremor density in the direction of steepest slope was calculated directly from the tremor-density grid. The loci of maximum horizontal gradients (dots in Fig. 1C) outline the lateral distribution of concentrated tremor along strike.

Tremor density files in the supplement include:

1. all_tremor_density.xlsx = tremor density at each grid node (42,461 values).

2. all_inside_steepest_gradient.xlsx = tremor density falling inside the steepest gradient of tremor density, the black dotted line in Fig 1b (10,743 values).

3. inside_steepest_gradient_and_near_any_fault.xlsx = tremor density falling inside the steepest gradient of tremor density AND within 5 km of any fault (1938 values).

4. inside_steepest_gradient_and_far_from_all_faults.xlsx = tremor density falling inside the steepest gradient of tremor density AND >5 km from all faults (8805 values).)

Correlation of Tremor and Topography

Gridded tremor density shows a rather poor correlation with gridded topography (**Fig. DR2**), but the peak tremor density band shows a positive correlation ($R^2 = .662$) to the *averaged* topography of the forearc in the U.S. from Kelsey et al. (*1994*) (**Fig 3B**). Major rivers tend to follow tremor lows (**Fig. DR2F**). See Report for discussion.

Forearc Fault Data Sources

The largest forearc fault zones and block boundaries (**Fig. 2**) were simplified in Arc GIS from digital state geologic maps of Oregon (*Hintze, 1994*), Washington (*WADNR, 2010*), and California (*Jennings et al., 2010)* (**Fig. DR3A**), the Quaternary Fault and Fold Database of the United States (*USGS, 2010*) (**Fig. DR3B**), isostatic residual gravity anomalies of the forearc (*Blakely, 1995: Simpson et al., 1986*) (**Fig. DR3C**), upper plate seismic activity from the PNSN catalog; e.g., 1975-2008, M≥ 2.0 (McCrory et al., 2012) (**Fig. DR3C**), and block boundaries from GPS models **(Fig. 2)** (*McCaffrey et al., 2013*). Fault zones meet three or more of the following criteria: 1) regionally significant fault zone crossing the forearc and the tremor axis, at least 50 km long (longer than depth to megathrust), 2) active segment recognized in the Quaternary Fault and Fold Database, 3) upper plate seismic activity (McCrory et al., 2012), and 4) strong geophysical expression.

Gravity maps (**Fig DR3B**) are expressed as isostatic residual gravity anomalies (Blakely, 1995; Simpson et al., 1986), with maximum horizontal gradients over vertical density contrasts (*Blakely, 1995*), as often occurs across crustal faults. Maximum horizontal gradient was calculated from the grid of gravity anomaly values by measuring the horizontal change in gravity in the direction of maximum change. The map-view locations of maximum horizontal gradient were determined by curvature analysis (*Philips et al., 2007*).

Statistical Correlation of tremor lows with crustal faults

The Kolmogorov-Smirnov test (KS-test) allows comparison of data distributions where the nature of the distribution (e.g., normal) is unknown. The test compares the sample distribution to the distribution of a population and produces a probability p of deriving the sample from a population by random selection; very low values of p indicate a very small chance that the sample could be derived from the population by random selection. In our test, we compare the tremor density distributions within 5 km of a forearc fault to distributions far from forearc faults. We restrict the test to the axial band of maximum tremor density defined by the maximum gradients of tremor density as in **Fig. DR2**. We restrict our sample near faults to be within 5 km of large faults that completely cross the maximum tremor band (Fault criteria as in Forearc Fault Data Sources above). The distributions of tremor density near and far from faults are quite different and the p-values are very small; formally it is p=2.9e-14. The mean of the tremor far from the faults is slightly higher than the mean near the faults; the opposite is true of the medians (**Fig 4B**; means are shown by the vertical lines on the plots, and, medians can be found by the intersection of the curves with the horizontal dotted line at Cumulative Fraction=0.5. The range of tremor density values far from the faults covers a much wider range than those near the faults and this is especially true for the highest tremor densities. There are no tremor densities near faults that are above about 5.4 while 7.6% of the tremor densities far from faults are above that value. The lowest values are also only far from the faults, but this is a smaller difference with 1.8% of the values of the tremor far from faults being lower than the minimum near the faults (tremor density of 0.417). There is a lot of overlap between the two sets of tremor density, but the differences are significant, with the highest values only occurring far from faults.

Supplemental References

Blakely, R. J., 1995, Potential theory in gravity and magnetic applications: Cambridge Univ. Press, New York, 441 p.

Hintze, L. F., 1994, Digital Geologic Map of Oregon derived from G. W. Walker, and N. S. MacLeod, 1991, U.S. Geol. Surv. http://pubs.usgs.gov/sm/oregon/.

Jennings, C. W. , Gutierrez, C., Bryant, W., Saucedo, G., Wills, C., 2010, Geologic Map of California. California Geological Survey http://www.quake.ca.gov/gmaps/GMC/stategeologicmap.html

Phillips, J. D., Hansen, R. O., Blakely, R. J., 2007, The use of curvature in potential-field interpretation: Exploration Geophysics, v. 38, p. 111–119).

Simpson, R. W., Jachens, R. C., Blakely, R. J., Saltus, R. W., 1986, A new isostatic residual gravity map of the conterminous United States with a discussion on the significance of isostatic residual anomalies: Journal of Geophysical Research, v. 91, p. 8348-8372.

U. S. Geological Survey, Quaternary Fault and Fold Database of the United States. (http://earthquake.usgs.gov/hazards/qfaults/)

Washington State Department of Natural Resources, Division of Geology and Earth Resources, Digital Geology of Washington State, v 3.0. Scale 1:500,000, (2010) http://www.dnr.wa.gov/Publications/ger_readme_surface_geology_500k.htm

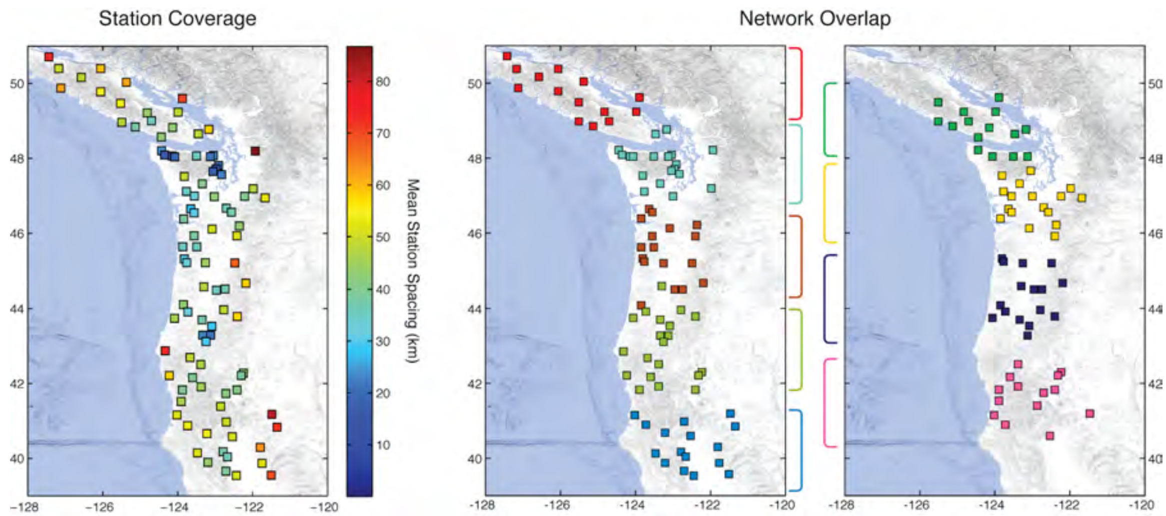

Fig. DR1.

Pacific Northwest Seismic Network stations used to locate tremor epicenters. Station density is relatively uniform, mean station spacing indicated by color code. Sub-network overlap shown center and right.

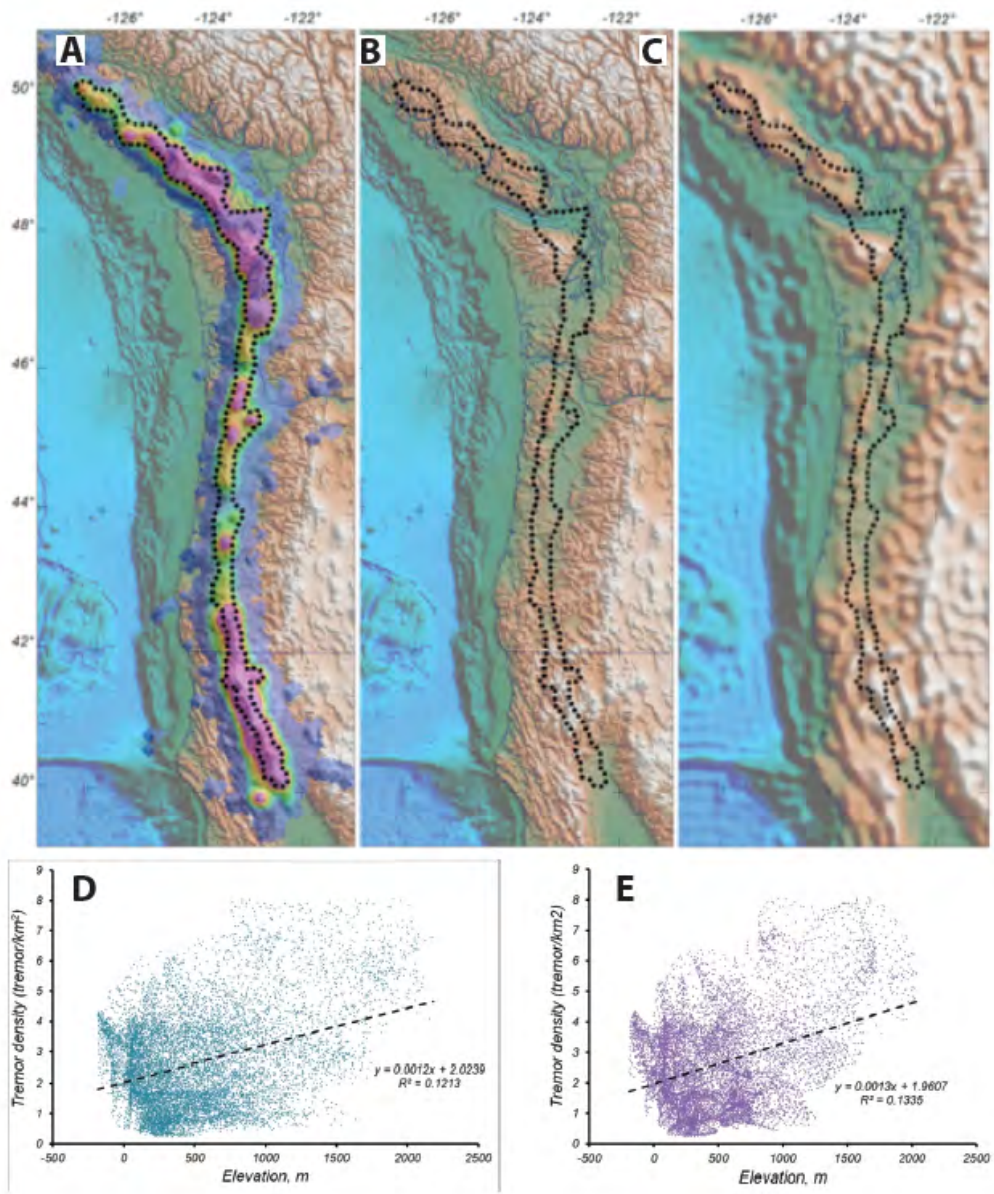

Fig. DR2 (A) Axis of maximum tremor density as outlined by maximum gradients of tremor density (see also Fig. 1); **(B)** 5 km elevation grid; **(C)** Average elevation, 25 km grid. **(D, E)** Tremor density is poorly correlated with elevation; E – 5 km grid, F – 25 km grid, but the peak tremor density band shows a positive correlation to the *averaged* topography of the forearc in the U.S. from *Kelsey et al. (1994)* in **Fig 3B**, see Report text for discussion.

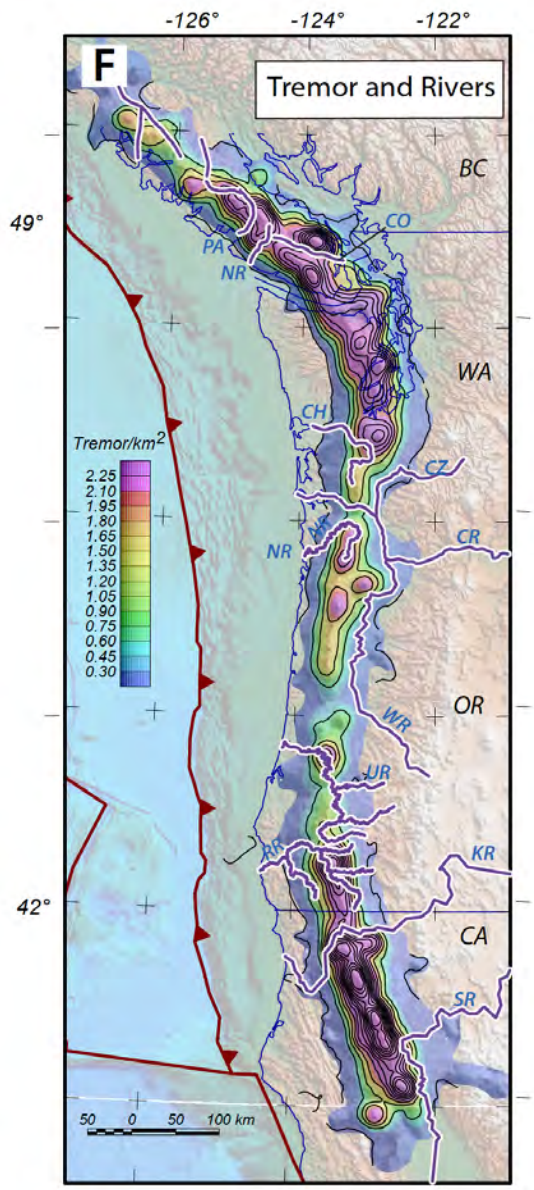

Fig. DR2 (F) Most of the largest rivers/drainages follow tremor density lows across Coast Range; from north: PA Port Alberini, NR Nitinat River, CO Cowichan River, CH Chehalis River, CZ Cowlitz River, NR Nehalem River, CR Columbia River, WR Willamette River, UR Umpqua River, RR Rogue River, KR Klamath River, SR Sacramento River.

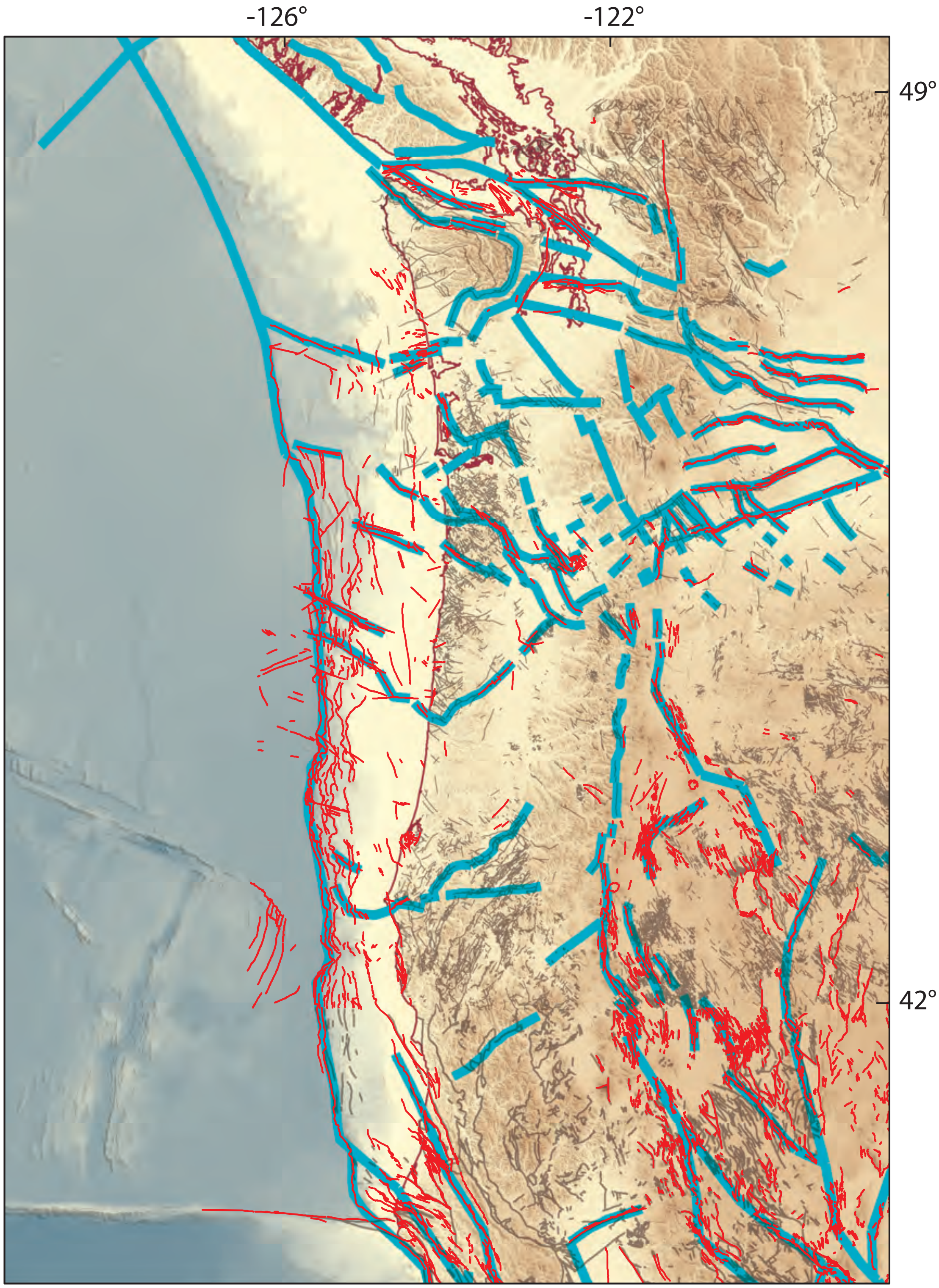

Fig. DR3 (A) Simplified Cascadia forearc fault model of Fig. 2, blue, derived from: State fault databases of western Oregon, Washington, and California (black lines); USGS Quaternary Fault database (red lines). Model relation to gravity anomalies and seismicity in **Figs. DR3B-C**. Web links in DR text.

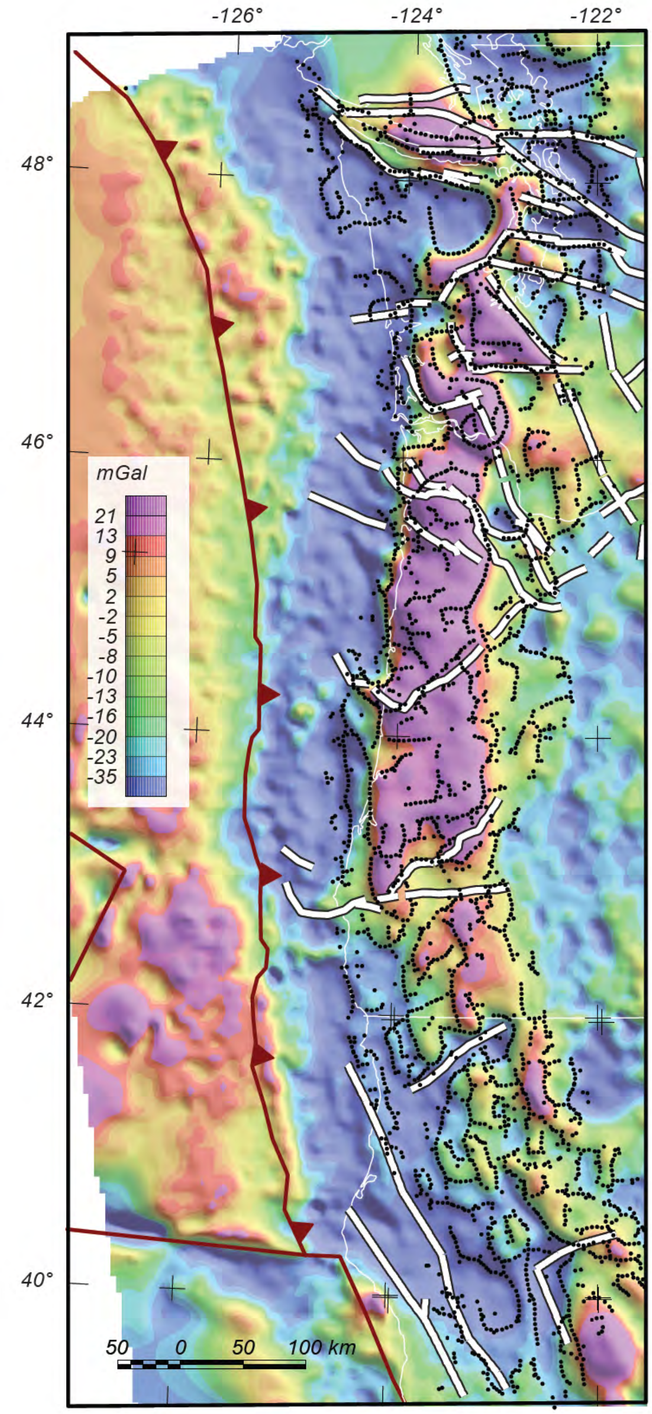

Fig DR3 (B). Fault model of Fig 2 (white lines) on isostatic residual gravity of forearc (*Simpson et al, 1986)* with maximum gravity gradients (black dots).

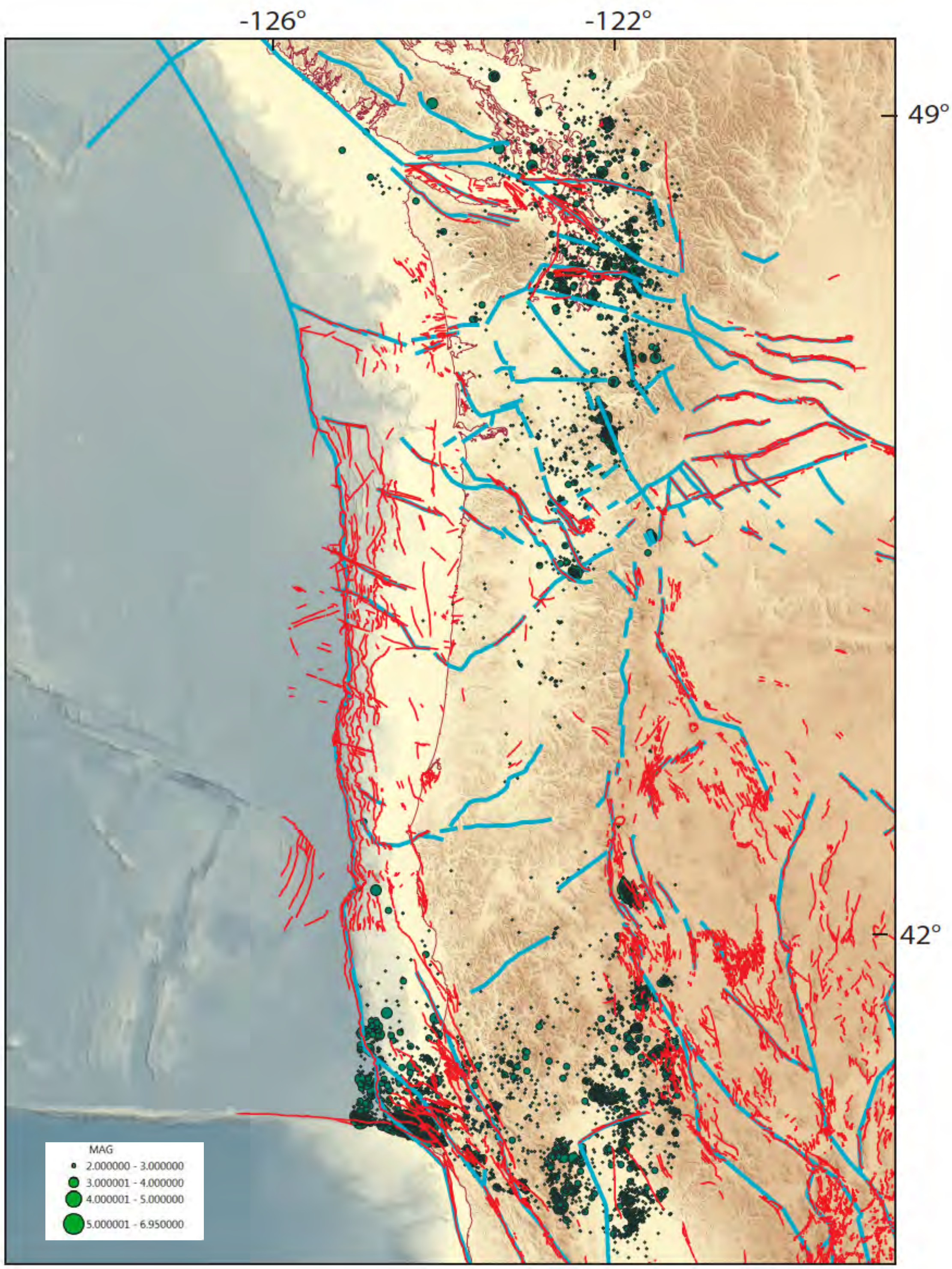

Fig DR3 (**C**) Fault model (blue) on upper plate forearc seismicity 1975-2009, Mb > 2.0 from McCrory et al. (2012).

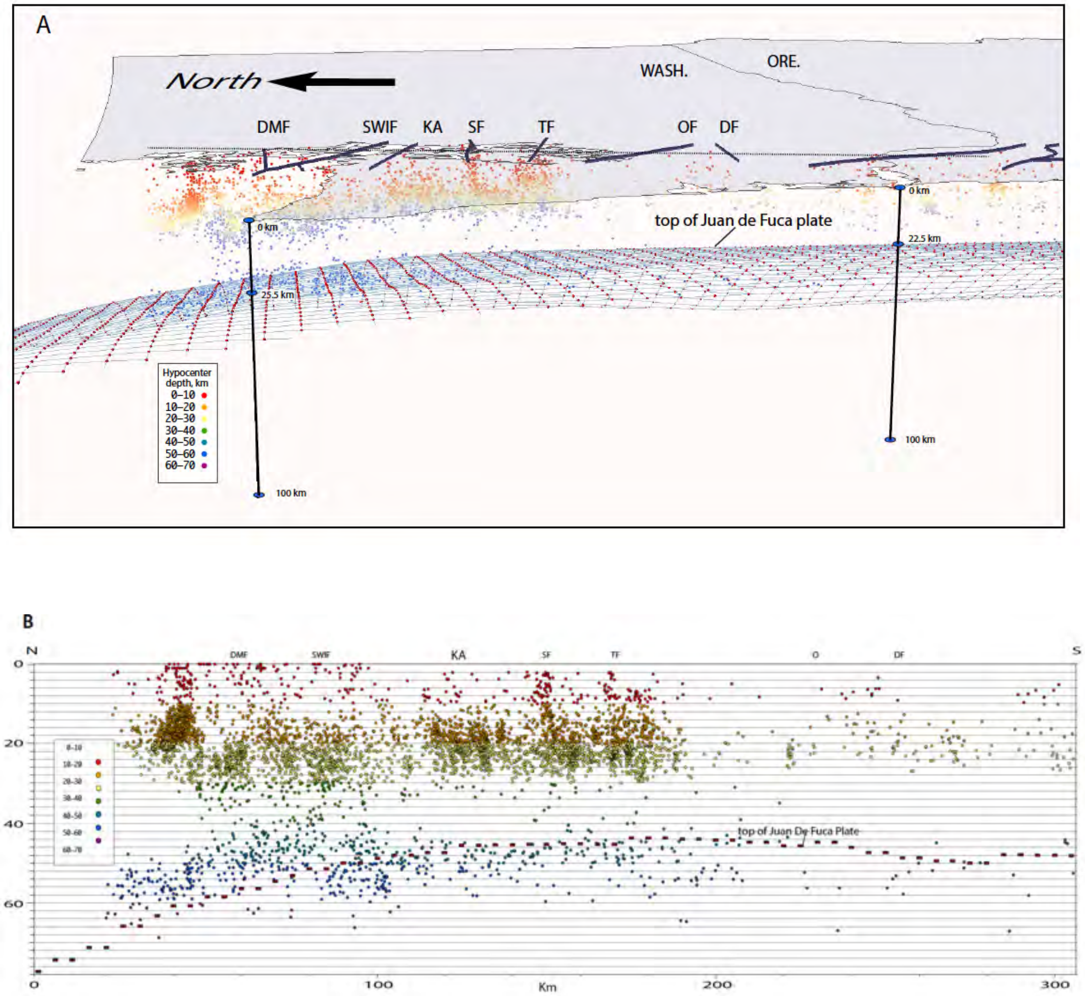

Fig. DR4

Upper plate seismicity beneath forearc faults. (**A**) Oblique view of northwest Washington State showing upper plate seismicity, forearc faults (black lines; DMF – Devils Mountain Fault, SWIF – S. Whidbey Is. Fault, KA – Kingston Arch, SF – Seattle Fault, TF – Tacoma Fault, O – Olympia Fault, DF – Doty Fault) and top of the Juan de Fuca plate; depth to plate shown by blue ovals at intersection with plumb lines dropped from coast. (**B**) 1:1 Profile view looking east at upper plate seismicity projected onto line normal to Seattle Fault (dotted line in A) beneath forearc faults and above the Juan de Fuca plate. Faults as in A.