Erratum

In the paper entitled "***Water hammers tremors during plate convergence***" by A. Yin published in Geology (volume 46, No. 12, p. 1031-1034), there is a typographic error for Equation (2), which should be written as follows

$$M = \frac{\Delta P(x,t)}{\Delta P(0,0)} = \left[1 - \mathrm{erf}\left(\frac{x}{2\sqrt{Dt}}\right)\right] \tag{2a}$$

$$M_{wave} = \frac{P_{wave}(x,t)}{\Delta P(0,0)} = \exp(ik - i\omega t - kx) \tag{2b}$$

where $\Delta P(x,t)$ represents the pressure evolution inside a conduit due to a sudden pulse in pore-fluid pressure at one end of the conduit, and $P_{wave}(x,t)$ is the oscillatory pressure evolution inside the conduit generated by the diffusion wave resulting from the water-hammer effect. The printing error does not affect the results of the model and the content of the paper.

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Water hammers tremors during plate convergence

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ABSTRACT

In this study, I show that rapid (~100 km/h) dip-parallel tremor migration at seismic-aseismic transition depths (15–55 km) of a convergent margin can result from pressure-wave propagation in an anisotropic viscoplastic shear zone. The anisotropy is characterized by slip-parallel conduits in the dip direction composed of high-permeability brittle mafic rocks embedded in low-permeability ductile felsic materials. At the onset of a slow-slip event, the initial compaction of a mafic conduit causes permeability reduction that in turn can lead to partial or complete blockage of flow path. Due to the water-hammer effect, the sudden blockage of flow paths can trigger a propagating pressure wave with an elevated pore-fluid pressure, which is capable of initiating a progressive shear failure expressed as migrating tectonic tremors along the conduit. For a mafic conduit with a pre-slip static permeability of ~10^{-13} m^2 and a syn-slip dynamic permeability of 10^{-15} m^2, the water-hammer model generates a pressure jump of up to 50 kPa, sufficient to initiate tremors along subduction zones and shear-zone deformation during the same slow-slip event.

INTRODUCTION

Slow earthquakes generated along subduction zones at seismic-aseismic transition depths (15–55 km) are accompanied by bursts of tectonic tremors (Obara, 2002; Rogers and Dragert, 2003). The migration of tremor fronts during slow-slip rupture has a well-established pattern: high-speed (~100 km/h) and short-duration (<2 h) along-dip (along-slip in this study) propagation (Fig. 1A) is followed by low-speed (5–10 km/h) and long-duration (days to weeks or longer) along-strike migration (Fig. 1B); the along-strike migration is in some cases accompanied by rapid (20–40 km/h) tremor reversals (Houston et al., 2011) (Fig. 1C). The origin of tectonic tremors has been attributed to fluid flow (Obara, 2002), fault slip (Shelly et al., 2007), and viscoplastic deformation (e.g., Ando et al., 2010; Gao and Wang, 2017). The directional difference in tremor propagation speeds has been variably related to updip pipe flow (Ghosh et al., 2010), rupture bifurcation across an anisotropic fault surface (Ando et al., 2010), and secondary slip along an early ruptured fault surface during the same slip event (Rubin, 2011). The pipe-flow model requires long (>65 km) conduits with an unrealistically small radius (<1.5 cm) and an infinitely large permeability, whereas the bifurcation and rupture-reactivation models do not predict the observed tremor migration sequences and patterns (i.e., either coeval along-strike and along-dip tremor propagation or along-strike tremor propagation predating along-dip tremor propagation).

The rapid along-dip tremor propagation and fast tremor reversals have been attributed to either pressure-wave propagation (Ghosh et al., 2010; Houston et al., 2011) or a fault valve–driven fluid flow (Frank et al., 2015). However, the exact mechanisms of these hypotheses have not been quantified. Inspired by these early suggestions, I propose that compaction during initial slow-slip deformation can generate a pressure wave along a high-permeability mafic conduit due to the water-hammer effect. The elevated pore-fluid pressure associated with the propagating wave triggers a progressive plastic failure of the shear zone expressed by tremor migration. As shown below, the water-hammer model is able to relate the tremor migration velocity and tremor frequency to conduit permeability, pore-fluid viscosity, and conduit length.

WATER-HAMMER EFFECT AND PRESSURE WAVES

Field studies and geophysical observations of deep (15–55 km) slow-slip subduction shear zones indicate that (1) percolating pore fluid has a pressure exceeding a lithostatic-pressure value, (2) shear-zone rocks consist of brittle mafic blocks surrounded by ductile felsic materials, and (3) silica precipitation modulates pore-fluid pressure evolution (Peacock et al., 2011; Hayman and Lavier, 2014; Audet and Bürgmann, 2014; Behr et al., 2018; Audet and Schaeffer, 2018). The brittle mafic rocks may be concentrated as slip-parallel streaks in a slow-slip subduction shear zone, resulting from seamount subduction (Cloos, 1992) or metasomatism-assisted deformation (Bebout and Barton, 2002). Laboratory and field studies indicate that mafic rocks in a subduction zone at seismic-aseismic

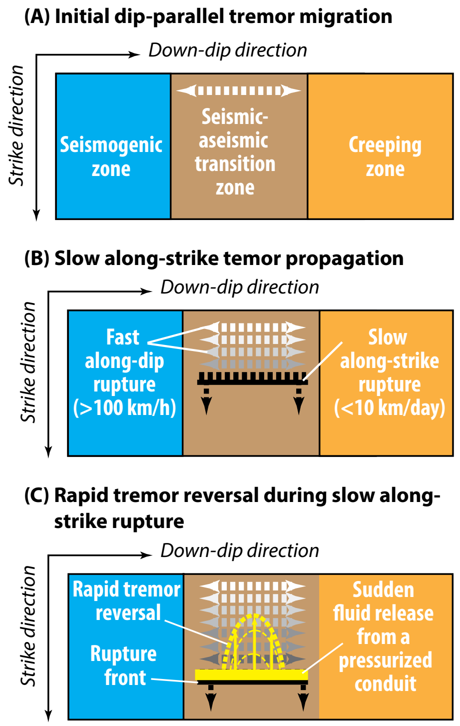

Figure 1. Typical tremor-migration sequence during slow-slip event at convergent plate margin, with white and gray arrows representing along-dip tremor propagation, black arrows representing along-strike tremor propagation, and yellow arrows representing reversed tremor propagation. A: Initial rapid (~100 km/h) tremor propagation in the along-dip direction. B: Slow (5–10 km/h) tremor propagation in the along-strike direction. C: Fast tremor reversal during slow along-strike tremor propagation.

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transition depths deform by fracturing and frictional sliding, creating a higher permeability than that of the surrounding felsic matrix (Violay et al., 2015; Behr et al., 2018). Fluids generated by dehydration reactions in the subduction zone are therefore preferentially transported along the mafic conduits with pore-fluid pressure elevated enough to create tensile fractures (Behr et al., 2018). As shown experimentally, the porosity and permeability of mafic rocks during initial elastic deformation under seismic-aseismic transition conditions decrease rapidly due to compaction of the existing pore space; this is followed by plastic deformation expressed by microcracking and porosity enhancement (Violay et al., 2015). Field observations (Behr et al., 2018) and geophysical arguments (Audet and Bürgmann, 2014) also suggest that tensile fractures experience sealing by silica precipitation when a slow-slip shear zone is locked between slip events. The above observations lead to a permeability model as shown in Figure 2. During the inter-slip phase, the shear zone is characterized by initial fracture sealing through silica precipitation , which is followed by hydro-fracturing as dehydration-produced fluids are trapped in the well-sealed shear zone while pore-fluid pressure increases. During a slow-slip event, the shear zone experiences initial compaction leading to porosity reduction and fluid expulsion, followed by plastic deformation causing dilation and fluid escape into the wall rocks. A key feature of the model is that permeability reduction by compaction is capable of initiating a propagating pressure wave due to the water-hammer effect. The pressure rise at a blockage site due to the extreme compaction effect can be determined by the Joukowsky equation based on energy balance and the assumption that the pressure-wave velocity is much greater than the backward percolation flow velocity (e.g., Ghidaoui et al., 2005):

$$\Delta P_{\max} = \frac{\kappa_s \rho_f \rho_r g}{\eta_f} \sqrt{K_e / \rho_b}, \qquad (1)$$

where $\Delta P_{\max}$ is the pressure change at the blockage site during the onset of shear-zone compaction, κ_s is the static permeability of the conduit before compaction, ρ_f is fluid density, ρ_r is rock density, g is gravitational acceleration, η_f is pore-fluid viscosity, K_e is the bulk modulus of the conduit system consisting of pore fluid and a solid skeleton, and $\rho_b = \rho_f \varphi + (1 - \varphi)\rho_r$ where ρ_b is bulk density and φ is porosity of the conduit system. For an incomplete flow-path blockage, the pressure jump is $0 < \Delta P < \Delta P_{\max}$ (e.g., Ghidaoui et al., 2005). Using model parameters specific to deep subduction slow-slip events (i.e., temperature = 250–600 °C and pressure = 0.5–1.5 GPa), with $\varphi \approx 0.03$ (Peacock et al., 2011), $K_e \approx 10$ GPa (Fortin et al., 2014), and $\eta_f \le 10^{-5}$ Pa·s to 10^{-4} Pa·s (Abramson, 2007), the pressure jump associated with the propagating wave is as much as 55 kPa (Fig. 3A), sufficient

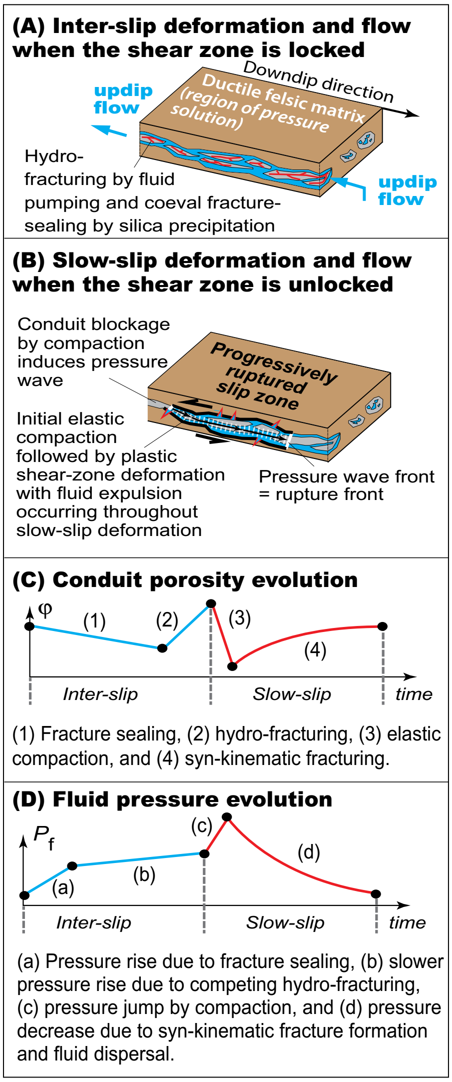

Figure 2. Water-hammer model. A: During inter-slip phase, shear zone experiences fracture sealing and hydro-fracturing due to dehydration-induced fluid pumping. B: Shear zone during slow-slip event experiences elastic deformation causing compaction, followed by plastic deformation causing dilation. Compaction locally blocks flow path, triggering pressure wave due to water-hammer effect. C,D: Porosity (φ) and fluid-pressure (P_f) evolution, which are not required to be correlative in time in open system, during and between slow-slip events.

to trigger tectonic tremors at convergent plate margins (Rubinstein et al., 2008).

A plane harmonic pressure wave passing through a one-dimensional (1-D) permeable conduit is governed by (e.g., Talwani and Acree, 1985; Yang et al., 2015):

$$M = \frac{\Delta P(x,t)}{\Delta P(0,0)} = \left[1 - \operatorname{erf}\left(\frac{x}{2\sqrt{Dt}}\right)\right] \cos(kx - \omega t), \qquad (2)$$

where $\Delta P(0,0) = \Delta P_{\max}$ is the pressure jump at the blockage site (distance $x = 0$) at the onset of the slow-slip deformation (time $t = 0$), $\Delta P(x,t)$ is pore-fluid pressure that varies with time and distance along the conduit, M is the normalized pressure-jump ratio (following Talwani and Acree [1985]), $D = \frac{\kappa_d K_e}{\varphi \eta_f}$ is the "diffusion" coefficient with κ_d representing the dynamic permeability when the conduit is compacted and the pressure wave is passing through, $k = \sqrt{\frac{\omega \eta_f}{2\kappa_d K_e}}$ is wave number, and ω is frequency. Note that the radius of the conduit is not considered here, as its value likely is much less than the conduit length (50–70 km) (Ghosh et al., 2010). The elevated pore-fluid pressure associated with the propagating wave can cause a progressive shear-zone failure (Talwani and Acree, 1985), which is proposed here as the cause of tremor migration along subduction zones. If the minimum threshold of shear-zone failure can be defined as a fraction of the maximum pressure jump (e.g., Talwani and Acree, 1985), the propagating rupture front can be quantified. For a maximum pressure jump of 50 kPa and the threshold of shear-zone failure at 10 kPa, the rupture front propagates ~70 km over a duration of 120 min (Fig. 3B), which is consistent with observations from the Cascadia convergent margin (offshore northwestern North America) (Ghosh et al., 2010).

The phase velocity of a plane harmonic wave traveling in the dispersive mode along a 1-D permeable conduit can be expressed as (e.g., Yang et al., 2015):

$$v_\omega = \sqrt{\frac{\kappa_d \omega K_e}{\varphi \eta_f}}. \qquad (3)$$

Equation 3 indicates that the phase velocity is unrelated to the much-slower flow velocity in the conduit. In order to match the observed tremor frequency of 0.01 Hz to 10 Hz (e.g., Obara and Kato, 2016), tremor propagation speeds of 50–250 km/h (Shelly et al., 2007; Ghosh et al., 2010), pore-fluid pressure increase of 10–50 kPa (Rubinstein et al., 2008), tremor propagation over a distance of 60–70 km (Ghosh et al., 2010), and pore-fluid viscosity in the range of 10^{-5} to 10^{-4} Pa·s (Abramson, 2007), the dynamic permeability $\kappa_d = 10^{-13}$ m^2 during the compaction phase of slow-slip deformation must be approximately two orders of magnitude lower than the static permeability of $\kappa_s = 10^{-15}$ m^2, a value suitable for generating the required pressure jump induced by conduit compaction at the onset of slow-slip deformation (Figs. 3C and 3D; cf. Fig. 3A). The observed tensile fractures in a slow-slip shear zone may be generated during the plastic phase of slow-slip deformation (Fig. 2) or through dehydration-induced fluid pumping when the shear zone is locked and the preexisting fractures are sealed (Behr et al., 2018).

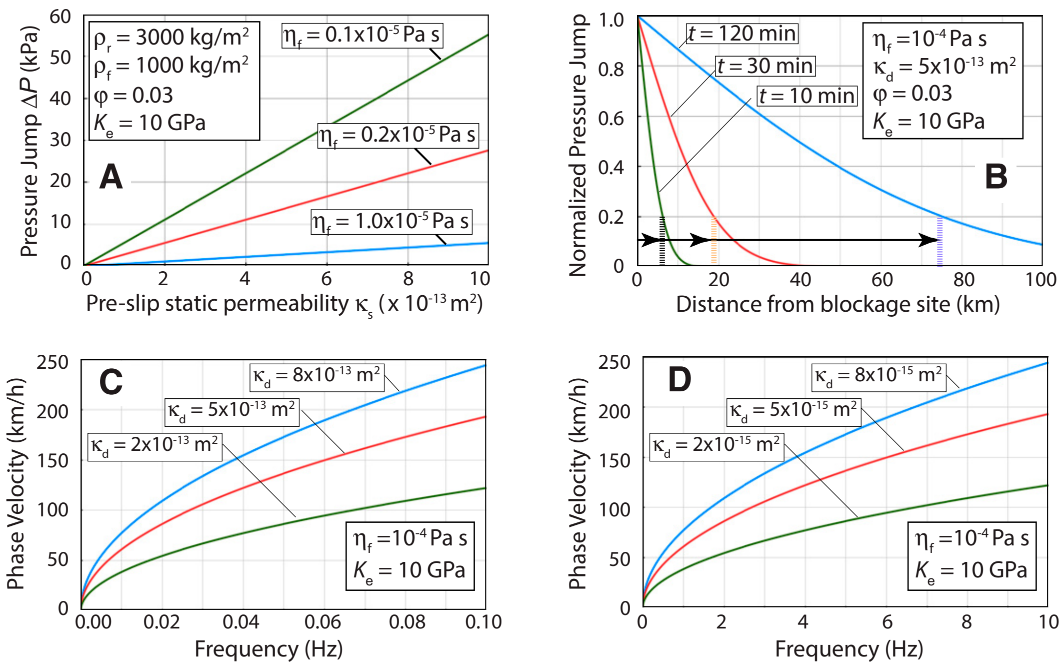

Figure 3. Model results. A: Maximum jump of pore-fluid pressure as function of static permeability and pore-fluid viscosity. B: Along-dip propagation of pressure wave front with time. Pressure fronts with magnitude of ≥20% of maximum pressure jump at 10, 30, and 120 min are shown as thick dashed lines. C,D: Propagation speeds of pressure wave as function of two ranges of frequency and variable dynamic permeability. *t*—time; κ_s—static permeability of the conduit between slip events when the shear zone is locked; κ_d—dynamic permeability during a slow-slip event when the shear zone is unlocked ρ_r—rock density; ρ_f—fluid density; η_f—fluid viscosity; K_e—bulk modulus of the conduit containing fluid; φ—conduit porosity.

A fluid transport system that hosts tectonic tremors may consist of a network of conduits with different sizes and geometry (e.g., Ghosh et al., 2010). Treating a conduit as a linear spring allows us to relate its natural frequency ω_n to its length L by $\omega_n = \frac{1}{L}\sqrt{\frac{K_e}{\rho_b}}$, where K_e and ρ_b are bulk modulus and density as defined above. For $K_e = 10$ GPa, $\rho_b = 2700$ kg/m^3, and $\omega_n = 0.04$–4.0 Hz, the required L ranges from 50 km to 500 m.

DISCUSSION AND CONCLUSIONS

The proposed compaction at the onset of a subduction-zone slow-slip event contradicts the existing slow earthquake models (e.g., Rubin, 2011) that invoke exclusively the dilation effect for quenching a potentially unstable sliding process associated with a slow-slip event. As shown by Yin et al. (2018), the presence of viscous felsic materials in a viscoplastic shear zone provides an alternative quenching mechanism, as viscous deformation itself is a velocity-strengthening process. Here I illustrate an additional feature of this type of model: the permeability evolution of the plastic shear-zone material is capable of initiating a pressure wave, which in turn can trigger rapidly propagating shear-zone failure expressed as tremor migrations. Although the pressure-wave model does not address the origin of slow-speed (5–10 km/day) tremor propagation, the drastically different (by up to two to three orders of magnitude) propagation speeds indicate that the fast and slow tremor migration along subduction zones may have fundamentally different physical mechanisms. For a viscoplastic slow-slip shear zone, the potentially slow converging rate from elastic energy to viscoplastic dissipation may lead to slower along-strike rupture. However, the viscoplastic dissipation–driven versus pressure wave–induced tremor migration may interact with one another during a single slow-slip event. For example, a rapid tremor reversal event (Houston et al., 2011) may be caused by a sudden fluid release from a pressurized conduit when it is intersected by a slow-moving rupture front (Fig. 1C). The pressure-wave mechanism explains well the generation of secondary slip fronts commonly observed along subduction shear zones (Bletery et al., 2017). For a shear zone consisting of multiple slip planes with each hosting dip-parallel conduits, slip-induced deformation may jam flow paths on one slip plane while opening paths on other planes in the same shear zone. This situation can lead to propagation of pressure waves in the same map-view area as secondary slip fronts without involving slip-zone reactivation during the same event. When a conduit is bounded at the two ends, a pressure wave can travel back and forth, expressed as tremor migration along the same path and sharing the same one-way travel time during a slow-slip event (Ghosh et al., 2010). Finally, the model raises several interesting questions such as what happens to the fluid after tremor migration, what terminates tremor migration, and how much fluid is needed to renew episodic tremor and slip events at convergent margins.

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REFERENCES CITED

Abramson, E.H., 2007, Viscosity of water measured to pressures of 6 GPa and temperatures of 300 °C: Physical Review E, v. 76, 051203, https://doi.org/10.1103/PhysRevE.76.051203.

Ando, R., Nakata, R., and Hori, T., 2010, A slip pulse model with fault heterogeneity for low-frequency earthquakes and tremor along plate interfaces: Geophysical Research Letters, v. 37, L10310, https://doi.org/10.1029/2010GL043056.

Audet, P., and Bürgmann, R., 2014, Possible control of subduction zone slow-earthquake periodicity by silica enrichment: Nature, v. 510, p. 389–392, https://doi.org/10.1038/nature13391.

Audet, P., and Schaeffer, A.J., 2018, Fluid pressure and shear zone development over the locked to slow slip region in Cascadia: Science Advances, v. 4, eaar2982, https://doi.org/10.1126/sciadv.aar2982.

Bebout, G.E., and Barton, M.D., 2002, Tectonic and metasomatic mixing in a high-*T*, subduction-zone mélange—Insights into the geochemical evolution of the slab-mantle interface: Chemical Geology, v. 187, p. 79–106, https://doi.org/10.1016/S0009-2541(02)00019-0.

Behr, W.M., Kotowski, A.J., and Ashley, K.T., 2018, Dehydration-induced rheological heterogeneity and the deep tremor source in warm subduction zones: Geology, v. 46, p. 475–478, https://doi.org/10.1130/G40105.1.

Bletery, Q., Thomas, A.M., Hawthorne, J.C., Skarbek, R.M., Rempel, A.W., and Krogstad, R.D., 2017, Characteristics of secondary slip fronts associated with slow earthquakes in Cascadia: Earth and Planetary Science Letters, v. 463, p. 212–220, https://doi.org/10.1016/j.epsl.2017.01.046.

Cloos, M., 1992, Thrust-type subduction-zone earthquakes and seamount asperities: A physical model for seismic rupture: Geology, v. 20, p. 601–604, https://doi.org/10.1130/0091-7613(1992)020<0601:TTSZEA>2.3.CO;2.

Fortin, J., Pimienta, L., Guéguen, Y., Schubnel, A., David, E.C., and Adelinet, M., 2014, Experimental results on the combined effects of frequency and pressure on the dispersion of elastic waves in porous rocks: The Leading Edge, v. 33, p. 648–654, https://doi.org/10.1190/tle33060648.1.

Frank, W.B., Shapiro, N.M., Husker, A.L., Kostoglodov, V., Bhat, H.S., and Campillo, M., 2015, Along-fault pore-pressure evolution during a slow-slip event in Guerrero, Mexico: Earth and

Planetary Science Letters, v. 413, p. 135–143, https://doi.org/10.1016/j.epsl.2014.12.051.
Gao, X., and Wang, K., 2017, Rheological separation of the megathrust seismogenic zone and episodic tremor and slip: Nature, v. 543, p. 416–419, https://doi.org/10.1038/nature21389.
Ghidaoui, M.S., Zhao, M., McInnis, D.A., and Axworthy, D.H., 2005, A review of water hammer theory and practice: Applied Mechanics Reviews, v. 58, p. 49–75, https://doi.org/10.1115/1.1828050.
Ghosh, A., Vidale, J.E., Sweet, J.R., Creager, K.C., Wech, A.G., Houston, H., and Brodsky, E.E., 2010, Rapid, continuous streaking of tremor in Cascadia: Geochemistry Geophysics Geosystems, v. 11, Q12010, https://doi.org/10.1029/2010GC003305.
Hayman, N.W., and Lavier, L.L., 2014, The geologic record of deep episodic tremor and slip: Geology, v. 42, p. 195–198, https://doi.org/10.1130/G34990.1.
Houston, H., Delbridge, B.G., Wech, A.G., and Creager, K.C., 2011, Rapid tremor reversals in Cascadia generated by a weakened plate interface: Nature Geoscience, v. 4, p. 404–409, https://doi.org/10.1038/ngeo1157.
Obara, K., 2002, Nonvolcanic deep tremor associated with subduction in southwest Japan: Science, v. 296, p. 1679–1681, https://doi.org/10.1126/science.1070378.
Obara, K., and Kato, A., 2016, Connecting slow earthquakes to huge earthquakes: Science, v. 353, p. 253–257, https://doi.org/10.1126/science.aaf1512.
Peacock, S.M., Christensen, N.I., Bostock, M.G., and Audet, P., 2011, High pore pressures and porosity at 35 km depth in the Cascadia subduction zone: Geology, v. 39, p. 471–474, https://doi.org/10.1130/G31649.1.
Rogers, G., and Dragert, H., 2003, Episodic tremor and slip on the Cascadia subduction zone: The chatter of silent slip: Science, v. 300, p. 1942–1943, https://doi.org/10.1126/science.1084783.
Rubin, A.M., 2011, Designer friction laws for bimodal slow slip propagation speed: Geochemistry Geophysics Geosystems, v. 12, Q04007, https://doi.org/10.1029/2010GC003386.
Rubinstein, J.L., La Rocca, M., Vidale, J.E., Creager, K.C., and Wech, A.G., 2008, Tidal modulation of nonvolcanic tremor: Science, v. 319, p. 186–189, https://doi.org/10.1126/science.1150558.
Shelly, D.R., Beroza, G.C., and Ide, S., 2007, Complex evolution of transient slip derived from precise tremor locations in western Shikoku, Japan: Geochemistry Geophysics Geosystems, v. 8, Q10014, https://doi.org/10.1029/2007GC001640.
Talwani, P., and Acree, S., 1985, Pore pressure diffusion and the mechanism of reservoir-induced seismicity: Pure and Applied Geophysics, v. 122, p. 947–965, https://doi.org/10.1007/BF00876395.
Violay, M., Gibert, B., Mainprice, D., and Burg, J.-P., 2015, Brittle versus ductile deformation as the main control of the deep fluid circulation in oceanic crust: Geophysical Research Letters, v. 42, p. 2767–2773, https://doi.org/10.1002/2015GL063437.
Yang, D., Li, Q., and Zhang, L., 2015, Propagation of pore pressure diffusion waves in saturated porous media: Journal of Applied Physics, v. 117, 134902, https://doi.org/10.1063/1.4916805.
Yin, A., Xie, Z., and Meng, L., 2018, A viscoplastic shear-zone model for deep (15–50 km) slow-slip events at plate convergent margins: Earth and Planetary Science Letters, v. 491, p. 81–94, https://doi.org/10.1016/j.epsl.2018.02.042.

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