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Key Points:

- Low-velocity zones in the Cascadia forearc lower crust correlate with nonvolcanic tremor density and intermediate-depth seismicity
- Low-velocity zones are thick (>10 km) and indicate the presence of fluid within oceanic crust and underthrust metasediments
- Low-velocity zones, seismicity, and tremor can be linked to fluids sourced from a variably hydrated and/or permeable subducting slab

Supporting Information:

- Supporting Information S1

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Fluid Controls on the Heterogeneous Seismic Characteristics of the Cascadia Margin

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Abstract The dehydration of oceanic slabs during subduction is mainly thermally controlled and is often expressed as intermediate-depth seismicity. In warm subduction zones, shallow dehydration can also lead to the buildup of pore-fluid pressure near the plate interface, resulting in nonvolcanic tremor. Along the Cascadia margin, tremor density and intermediate-depth seismicity correlate but vary significantly from south to north despite little variation in the thermal structure of the Juan de Fuca Plate. Along the northern and southern Cascadia margin, intermediate-depth seismicity likely corresponds to increased fluid flux, while increased tremor density may result from fluid infiltration into thick underthrust metasediments characterized by very slow shear wave velocities (<3.2 km/s). In central Cascadia, low intermediate-depth seismicity and tremor density may indicate a lower fluid flux, and shear wave velocities indicate that the Siletzia terrane extends to the plate interface. These results indicate that the presence of thick underthrust sediments is associated with increased tremor occurrence.

Plain Language Summary Fluids are released from subducting oceanic lithosphere as temperature and pressure within the Earth increases. The release of these fluids is manifest by seismicity within the subducting lithosphere and nonvolcanic tremor near the subduction interface. Along the northern and southern Cascadia margin, the spatial distribution of seismicity within the slab and nonvolcanic tremor correlates with very slow shear wave velocities in the lower crust of the overriding plate. These low-velocity zones likely represent underthrust sediments containing slab-derived fluids. In central Cascadia, however, seismicity and tremor are relatively low, and a low-velocity zone in the lower crust of the forearc is not observed. Our results suggest that a combination of variations in the distribution of underthrust sediments and fluid flux along the margin may be the ultimate control on the tremor and seismicity distribution along the Cascadia margin.

1. Introduction

The subduction and subsequent release of fluids in the Earth leads to variations in mantle viscosity, magma compositions, and ultimately the creation of silicic continental crust, distinguishing the Earth from other terrestrial bodies in our solar system (Grove et al., 2012; Hirth & Kohlstedt, 1996). The depths at which slabs release this fluid are mainly dependent on the thermal structure of the margin (Hacker et al., 2003; van Keken et al., 2011), resulting in prograde metamorphic reactions that cause dehydration embrittlement, thought to be mechanically expressed as intermediate-depth seismicity (Hacker et al., 2003; Peacock, 2001). Once released, the interaction of these fluids with the overriding plate depends on the depth of dehydration. At shallow depths near the crust-mantle transition of the overriding plate, the release of fluids is thought to cause nonvolcanic tremor (NVT; Audet & Kim, 2016; Katayama et al., 2012; Peacock, 2009; Seno & Yamasaki, 2003), which is mostly constrained to subduction zones where the subducting lithosphere is young and therefore warm (Audet & Kim, 2016; Beroza & Ide, 2011; Ide, 2012; Peacock, 2009). Slightly deeper, fluids released into the cold nose of the mantle wedge lead to serpentinization of the forearc mantle (Hyndman & Peacock, 2003). Finally, at depths where the emancipated fluids migrate through the hot mantle wedge, they lead to flux melting of the mantle that ultimately sources arc volcanism (Grove et al., 2012). Thus, understanding when and where subducting slabs dewater is important for understanding the seismic, tectonic, and volcanic behavior of subduction margins.

Lateral variations in NVT density are present in many subduction zones, including Nankai (Ito et al., 2007), Mexico (Brudzinski et al., 2016), Alaska (Wech, 2016), Costa Rica (Audet & Schwartz, 2013), and Cascadia (Figure 1). In Cascadia, NVT density correlates with intermediate-depth seismicity, generally attributed to

Figure 1. Characteristics of the Cascadia margin. (a) Physiographic provinces of the northwestern United States. Green shaded region: forearc; red shaded region: volcanic arc; red box: study area; contours: depth to slab (McCorry et al., 2012), white arrows: velocities from a plate coupling model relative to North America (McCaffrey et al., 2007); colored circles: earthquakes ($M_w \geq 2.5$, depth > 30 km); small black circles: earthquakes in the Juan de Fuca Plate (JdF; depth < 20 km). Black lines offshore: boundary between the JdF and Pacific plates. Purple polygon: surface exposure of the Klamath terrane (Piotraschke et al., 2015); blue polygon: boundaries of the Siletzia terrane (Wells et al., 1998). Red triangles: Holocene volcanic centers. Gray shaded regions on seafloor: propagator wakes (Wilson, 2002). OM: Olympic Mountains. (b, c) Mapviews of tremor density (Wech, 2010) and intermediate-depth earthquake density. We find that earthquakes that occur deeper than 30 km separate crustal from intraslab (dehydration-induced) earthquakes well. See supplemental text for details of catalogues. FMC: Forearc mantle corner estimated from velocity model.

dehydration embrittlement leading to brittle failure within the slab, which can occur at rather shallow depths in Cascadia (> 20 km; Hacker et al., 2003) due to the thermal structure of the margin (Figure 1c). As both NVT and intermediate-depth seismicity are thought to be fluid mediated, these spatial variations may relate to differences in the permeability of the subducting and/or overriding plates, variable hydration in the subducting lithosphere, or both. Other clear lateral variations along the Cascadia margin are observed as well, such as the concentration and segmentation of (Quaternary) arc volcanism (Hildreth, 2007), Bouguer gravity anomalies (Blakely et al., 2005), the distribution of shallow seismicity in the oceanic plate (Figure 1a), elevation and uplift rates in the overriding forearc (Burgette et al., 2009), episodic tremor and slip recurrence intervals (Brudzinski & Allen, 2007), and plate interface locking behavior (McCaffrey et al., 2013). In order to understand the mechanisms that impart these differences, we must understand how and where the downgoing plate becomes hydrated prior to subduction, when and where dehydration and fluid release occurs during subduction, and how these fluids affect the properties of the downgoing and overriding plates. Toward this purpose, seismic techniques capable of imaging both intracrustal and uppermost mantle variations are needed.

2. Data and Methods

The Earthscope Transportable Array along with denser temporary and permanent networks in the Pacific Northwest allows for a broad but detailed analysis of the structure of the Cascadia subduction zone. In this study, we calculated P_s receiver functions (Ligorria & Ammon, 1999) from recordings of $M_w \geq 6.0$ earthquakes between 1993–1994 and 2005–2016 from 1,011 broadband seismic stations, resulting in 86,345 receiver functions after quality control. We also measured Rayleigh-wave phase velocity dispersion using cross correlations of ambient seismic noise in the 8- to 50-s period band from 796 stations operating from 2005 to 2015, resulting in a total of 206,639 high signal-to-noise (> 10) cross correlations (Bensen et al., 2007). The receiver function and dispersion measurements were then jointly inverted (Julia et al., 2000) to obtain a 3-D shear wave velocity model extending to 80-km depth along the Cascadia margin. The initial shear wave velocity

Figure 2. Shear wave velocity (V_s) structure of the Cascadian margin. (a) Average V_s in lower 10 km of the crust. Purple box: extent of areal average (Figure 3). Other symbols described in Figure 1. (b) Cross section along the Cascadia forearc (longitude: -123.4°). Black vertical lines: transition between Klamath (south), Siletzia (central), and Siletzia/Olympic Mountains (north). Lower crustal low-velocity zones (LVZs) beneath the northern and southern margin of the Cascadia forearc correlate with increased seismicity (black dots) and nonvolcanic tremor (NVT) density (red lines on topography; from Figure 1b). (c) Cross section along 48°N : LVZ parallels subducting plate (black line) and correlates with high NVT density. (d) Cross-section along 44.4°N . The Siletzia terrane shows little internal seismic variation, and tremor density is low. (e) Cross section along 41.6°N . LVZ and NVT correlation similar to that observed in the north. Black triangles: seismic stations (within 30 km of line). White line: estimated Moho depth; black line: slab surface (McCrory et al., 2012).

model for the joint inversion consisted of a uniform half-space with $V_s = 4.5$ km/s discretized into 1-km-thick layers; thus, variations in the resulting shear wave velocity model were imposed by the data rather than through a priori constraints on depth to boundaries or changes in velocity structure. More details about the model can be found in supporting information Text S1.

3. Results: Imaging the Structure of the Cascadia Forearc

Along the strike of the Cascadia forearc, we observe that variations in NVT density and intermediate-depth seismicity anticorrelate with seismic velocities in the lowermost forearc crust (Figures 2 and 3). While low-velocity layers (LVLs) near the plate interface have been imaged across the entirety of the Cascadian margin from receiver function and scattered wave images (Audet et al., 2010; Bostock, 2013), these LVLs appear to be stronger beneath the northern ($>46^\circ\text{N}$) and southern ($<43^\circ\text{N}$) margin of the subduction zone where NVT density and intermediate-depth seismicity are high based on our receiver function results (Figures S9–S12). Furthermore, a decrease in phase velocities in the ~ 12 - to 16-s period band along the northern and southern margin provide strong evidence for a broad low shear velocity zone at depths near the plate boundary (Figure S6). After the joint inversion of these two data sets, we find that low shear wave velocities (<3.2 km/s) characterize a zone ≥ 10 km thick parallel to but overlying the subducting plate and extending beneath the entire region of high NVT density (Figures 2 and 3a). In the north, this structure has been previously imaged by other seismic studies and has been variably interpreted as hydrated oceanic crust or underthrust sediments related to the accretionary complex of the Olympic Mountains (OM, Figure 1a; Abers et al., 2009; Calkins et al., 2011; Calvert et al., 2011). Comparisons between shear wave velocities and

Figure 3. (a) Low-velocity zone (LVZ) thicknesses in the forearc (<3.2 km/s at depths >10 km). The Juan de Fuca crystalline crust has a relatively constant thickness of ~ 6 km (Han et al., 2018). (b–d) Various characteristics as a function of latitude. Black horizontal lines demarcate transitions between forearc velocity structure (Figure 2). (b) Average shear velocity in lower 10 km of overriding crust from values within purple box (Figure 2a). (c) nonvolcanic tremor density and (d) intermediate-depth seismicity distribution (as percentage of total in catalogue). Black dots show depth distribution of earthquakes >30 km.

P wave velocities (Calvert et al., 2011) return high V_p/V_s ratios (>1.9 ; Calkins et al., 2011; ~ 2.0 , this study), consistent with the presence of fluids. A similar interpretation has been made to explain a similar lower crustal low-velocity zone (LVZ) along the southern margin (Liu et al., 2012; Figure 2e).

In contrast to the northern and southern margin, the seismic data from the central Cascadia forearc (43°N to 46°N) are characterized by monotonic increases in phase velocity with period (Figure S6), a weak negative conversion in receiver functions (Figure S11), and fast crustal shear wave velocities (>3.6 km/s; Figure 2d). This region also has low levels of intermediate-depth seismicity and NVT density (Figures 1, 3). Similar to the northern margin, a LVL interpreted as subducting oceanic crust has been imaged in central Cascadia using scattered wave imaging techniques (Bostock et al., 2002; Tauzin et al., 2017). However, this zone is likely thin (~ 6 km or less), as it does not have a significant effect on the phase velocity dispersion curves (Figure S7).

Along the entire Cascadia margin, the forearc mantle is characterized by shear wave velocities that are much slower than expected for typical upper mantle material (<4.2 vs. ~ 4.5 km/s). Our results are consistent with forearc mantle serpentinization along the entire margin (Brocher et al., 2003).

4. Discussion

4.1. Fluid Infiltration Into the Forearc Crust

The very similar velocities (Figure 2) and >10 -km thicknesses (Figure 3a) of the LVZs along the northern and southern Cascadia forearc suggest that they are generated by a similar mechanism (Figures 2c and 2e). In the north, highly reflective packages at lower crustal depths have been interpreted as underthrust sediments beneath the Siletzia terrane (Calvert et al., 2011). Given that the oceanic crustal thickness offshore Cascadia is relatively constant along the margin (~ 6 km; Han et al., 2018), these LVZs likely represent a composite of underthrusting oceanic and sedimentary material, likely associated with the Olympic Accretionary Complex in the north and the Franciscan Complex in the south.

Given the expected pressure-temperature conditions where we image these LVZs (~ 1 GPa, $\sim 390^\circ\text{C}$; Syracuse et al., 2010), these sediments would metamorphose to a metasedimentary rock, such as a quartz-mica schist

or metagraywacke (V_s ~3.6 and 3.4 km/s, respectively; Christensen, 1996). Hence, fluids are likely necessary to obtain the observed shear wave velocities (<3.2 km/s) beneath the northern and southern margin. These fluids are likely sourced from deeper in the subduction zone (i.e., from metamorphic dehydration reactions), as syndepositional fluids originally trapped in pore spaces are thought to be expelled at shallower depths (<7 km) than the LVZs (Saffer & Tobin, 2011). In contrast, the shear wave velocities in most of the central Cascadia forearc (43–46°N) are typical of dry intermediate-to-mafic crystalline material consistent with the Siletzia terrane (>3.6 km/s; Christensen, 1996; Figures 2a and 2d). The thickness of the Siletzia terrane is thought to vary from 30 km in central Cascadia to ~15 km in the north around 46° (Trehu et al., 1994), implying that it extends to very near plate interface in central Cascadia. A reflective zone interpreted as underthrusting sediment is present beneath central Cascadia but is much weaker and at greater depths than the highly reflective, thicker packages imaged further north (Calvert et al., 2011; Trehu et al., 1994). It is also worth noting that north of the Olympic Accretionary Complex, LVZs on the scale of what we image in northern and southern Cascadia are absent (Calvert et al., 2011; Savard et al., 2018). These results indicate that the spatial distribution of underthrusting accretionary material, in combination with fluid distribution, may control the distribution of LVZs in the forearc (Figure 4).

NVT is thought to be enabled by the fluid overpressure near a sealed plate interface (Audet & Burgmann, 2014; Hyndman et al., 2015; Liu & Rice, 2007; Obara, 2002; Tauzin et al., 2017; Wells et al., 2017). Attempts to locate the hypocenters of NVT and low-frequency earthquakes consistently place them near the subduction interface (La Rocca et al., 2009; Royer & Bostock, 2014; Shelly et al., 2006) and perhaps well into the overriding crust (Kao et al., 2009). Faulting of the forearc has been proposed to both correlate (Tauzin et al., 2017) and anticorrelate (Wells et al., 2017) with NVT density by modulating the buildup of pressure near the plate interface. For example, forearc faulting either (1) provides a pathway for fluids to escape from the plate interface, preventing the buildup of high fluid pressures and NVT (Wells et al., 2017), or (2) causes increased tremor due to overpressure within the overriding plate assuming that NVT locations in the overriding plate are reliable (Tauzin et al., 2017). In order for (1) to be possible, the fluids that penetrate into the overriding crust in central Cascadia must be (1) small volume, (2) transient, or (3) consumed via mineral reactions in the lower crust, as no anomalous shear velocities are observed. In contrast, the lower crustal forearc velocity structure of the northern and southern margin provides evidence for the presence of free fluids, indicating that not only are fluids infiltrating into the overriding crust but that they are also trapped over a large enough region to lower its seismic velocity. Observations from field studies of exhumed subduction zones from depths consistent with relatively shallow NVT (~20–40 km) show quartz precipitation in fractures within subcreted metasedimentary rocks, a process requiring vast amounts of fluid infiltration (Breeding & Ague, 2002; Fisher & Brantley, 2014). Thus, underthrusting metasedimentary material may facilitate tremor through fluid overpressure in anisotropically permeable foliation subparallel with the plate interface and explain why LVZs and increased NVT distribution correlate along the margin.

4.2. The Role of the Downgoing Plate

While the structure of the overriding plate can be used to explain the distribution of the LVZs and possibly NVT along the margin, it is not clear why these characteristics should correlate with intermediate-depth seismicity. Ultimately, all of these processes are linked to fluids sourced from the downgoing oceanic plate. Therefore, in order to understand how these processes are interrelated, we must also investigate the role of the downgoing oceanic lithosphere. We offer two end-member hypotheses to explain the lateral variations in the fluid-mediated processes of NVT, intermediate-depth seismicity, and the LVZs: (1) there exist significant lateral variations in the hydration state of the downgoing oceanic lithosphere, and (2) hydration does not significantly differ and the correlations we observe are a result of variable fluid flux due to variations in downgoing plate permeability. This could either be imparted via offshore deformation prior to subduction or from brittle deformation of the slab at depth due to bending during subduction, as noted by McCrory et al. (2012).

The idea that variable hydration in the downgoing JdF plate controls the lateral variations we observe requires that intermediate-depth seismicity is a direct manifestation of dehydration embrittlement (i.e., that variable hydration in the downgoing plate is the primary control on the distribution of intermediate-depth seismicity). Thus, seismicity within the downgoing slab could be used as a proxy for hydration state and fluid flux along the margin. Brittle deformation (i.e., faulting) in the downgoing plate prior to subduction is known

Figure 4. Conceptual figure of the controlling mechanisms that impart lateral variations in the manifestation of subduction along the Cascadia margin. (a) Hypothesis (1): lateral variations in permeability and hydration related to offshore brittle deformation prior to subduction controls the lateral heterogeneities along the Cascadian margin. Top: Forearc shaded by NVT density (Figure 1b). Black dots: shallow seismicity in the oceanic plate. Bottom: NVT density projected onto slab surface. Dark red shading: source region for volcanism. (b–d): interpreted sections from Figure 2) Hypothesis (2) lateral variations in overriding and downgoing plate permeability control lateral variations in fluid-mediated processes. (b) Northern Washington: intraslab seismicity indicates higher fluid flux due to either increased dehydration reactions (variable slab hydration) or higher permeability (variable deformation). Fluids serpentinize the wedge, cause increased tremor density, and infiltrate subcreted sediments. (c) Central Oregon: The lack of intermediate-depth earthquakes indicates either low fluid content in the slab or low permeability due to lack of deformation, which when combined with lack of subcreted sediments leads to less NVT. Alternatively, if hydration/flux along margin is constant, then forearc-scale faulting in the Siletzia block may be able to prevent fluid overpressure (e.g., Wells et al., 2017). (d) Northern California: The Gorda subplate may be pervasively hydrated due to intraplate deformation prior to subduction, leading to high NVT and seismicity densities. Otherwise, buoyancy anomalies could be deforming the downgoing plate to increase fluid flux out of the slab, similar to Northern Washington. NVT = nonvolcanic tremor; OM = Olympic Mountain.

to play an important role in controlling the amount of hydrated material subducted beneath the margin (Faccenda et al., 2009), and these preexisting faults are thought to facilitate slip during intermediate-depth earthquakes (Ranero et al., 2005). These structures would increase the permeability of the slab, acting as pathways that control the ability of water to infiltrate/escape the downgoing lithosphere. In the south, the Gorda subplate is characterized by ubiquitous internal seismicity, experiencing such a high degree of deformation that it no longer behaves as a rigid plate (Chaytor et al., 2004). Further to the north, the JdF plate contains multiple propagator wakes (Wilson, 2002) that result from internal plate shearing during plate reorganization (Figure 1a). These propagator wakes are thought to be zones of increased porosity and permeability, leading to enhanced hydration by allowing fluids to be transported deeper into the crust and possibly upper mantle. As many of these propagator wakes can be projected beneath northern Washington, these zones of increased hydration could result in increased tremor density once they reach conditions where metamorphic dehydration reactions occur (Nedimovic et al., 2009) (Figure 4). Thus, the locations of subducted propagator wakes and the Gorda subplate are expected to be more hydrated than typical oceanic crust due to deformation and may control the distribution of NVT and intermediate-depth seismicity distribution through modulating hydration in the downgoing plate.

Recent offshore results, however, suggest that the northern JdF plate is less hydrated and deformed than offshore central Cascadia (Canales et al., 2017; Han et al., 2016, 2018), the opposite of what would be expected should variable hydration be controlling the lateral variations in NVT density, seismicity, and

shear wave velocity. Also, a broad propagator wake extends beneath central Cascadia that does not show a strong correlation with tremor density (Wilson, 2002; Figures 1, 2, and 4a), and recent hypocenter locations using oceanic bottom seismometers offshore Cascadia show that the central JdF plate is not as seismically quiet as previously thought (Stone et al., 2018). While these recent studies provide results inconsistent with lateral variation in hydration as a strong control on seismicity and NVT density, it cannot be completely ruled out, as many of the studies with the resolution to map hydration are confined to the central portion of the JdF plate.

If variable hydration in the JdF plate is not the cause of the along-strike changes in subduction characteristics and we assume an end-member case where hydration is constant along the margin, then the correlations we observe could be primarily related to the depths at which fluids are released. Dehydration of the oceanic plate is mainly controlled by the thermal structure of the subduction margin. However, the relatively low variability in JdF plate age at the trench (between 5 and 10 Myr) suggests that differences in the thermal structure of the margin are likely too small to cause large variations in the depth of dehydration reactions. This implies that it is not *where* the dehydration reactions take place that control heterogeneity along the Cascadia margin but *whether the fluid can actually escape* from the subducting lithosphere once released. This is ultimately controlled by the permeability of the downgoing slab. If intermediate-depth earthquakes are driven by deformation/contortion of the JdF plate at depth rather than dehydration embrittlement (or through some combination of the two; McCrory et al., 2012), this would create new permeable pathways along which liberated fluids could escape from the downgoing plate. Recently, large low-velocity anomalies interpreted as buoyant asthenosphere below the JdF plate were interpreted to control the variations in tremor and locking behavior along the margin (Bodmer et al., 2018). These buoyancy anomalies may also provide the differential stresses necessary to deform the subducting slab, contributing to the distribution of intermediate-depth seismicity along the Cascadia margin. This seismicity could create permeable pathways for fluids to escape from the downgoing slab, which could migrate updip along the subduction interface and concentrate near the base of the crust-mantle transition and ultimately cause NVT. Finally, these fluids could infiltrate into the thick metasedimentary packages in the lower crust of the forearc in the north and south and cause the LVZs that we image. In central Cascadia, the lack of subslab low-velocity anomalies (and thus intermediate-depth seismicity) may indicate less fluid release at depth relative to the north and south. Any fluids that are present may be able to escape through crustal-scale forearc faulting, relieving fluid overpressure, and thus decreasing the amount of NVT that can occur along the plate boundary (Wells et al., 2017; Figures 4b–4d).

5. Conclusion

The margin-wide correlations between NVT density, intermediate-depth seismicity, and LVZs in the lower crust of the Cascadia are ultimately related to the distribution of fluids along the margin. These correlations could be related to variations in fluid flux along the margin through two end-member hypotheses: (1) variations in hydration state of the JdF plate and (2) variations in permeability structure of the JdF plate and/or overriding lithosphere. There is insufficient evidence to distinguish which of these is the primary control, but the lateral variations in the initial hydration state required to explain these correlations appear inconsistent with offshore results, where increased hydration in the JdF Plate projects to regions of lower tremor density and intermediate-depth seismicity. Variations in the permeability structure of the downgoing plate after subduction may be more likely, as contortion due to subslab buoyancy anomalies could explain the distribution of intermediate-depth seismicity and impart increased permeability within the downgoing slab through deformation. Fluids within the downgoing plate would then be released into the mantle wedge and propagate updip to near the crust-mantle transition of the overriding plate to cause the observed NVT distribution. The LVZs we image are likely a result of these fluids penetrating into underthrust metasediments along the northern and southern margins, which may also facilitate increased NVT. In order to better differentiate between the two end-member hypotheses, a more complete understanding of how preexisting deformational structures in the downgoing plate relate to the hydration and permeability structure of subduction zones is necessary and could be obtained through more extensive offshore seismic studies. Further knowledge of these processes will not only help us constrain the controlling mechanisms of NVT along the Cascadia margin, but also inform our understanding of other margins that show heterogeneous distributions in NVT as well.

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