Title: Localized anisotropy in the mantle transition zone due to flow through slab gaps

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Key Points:
- P_{SH}/P_{SV} amplitude ratios between *P*660*s* and *P*410*s* are useful for constraining transition zone anisotropy
- Evidence for up to 2% mantle transition zone anisotropy is found beneath the Pacific Northwest of the U.S.
- Mantle flow between slab fragments may enhance development of transition zone anisotropy

Abstract:
Measurement of anisotropy advances our understanding of mantle dynamics by linking remote seismic observations to local deformation state through constraints from mineral physics. The Pacific Northwest records the largest depth-integrated anisotropic signals across the western United States but the depths contributing to the total signal are unclear. We used the amplitudes of orthogonally polarized P-to-S converted phases from the mantle transition zone boundaries to identify anisotropy within the ~400-700 km deep layer. Significant anisotropy is found near slab gaps imaged by prior tomography. Focusing of mantle flow through slab gaps may lead to locally elevated stress that enhances lattice preferred orientation of anisotropic minerals within the transition zone, such as wadsleyite.

Plain Language Summary:

Earth's mantle convects like a fluid over geological time and it organizes mineral fabrics resulting in directional dependence of seismic velocities, i.e. seismic anisotropy. There is abundant evidence for flow-induced seismic anisotropy at depths above about 400 km, but it is less clear if anisotropy is developed in the mantle transition zone at about 400-700 km deep. Here, we use seismic waves generated from the bottom and top of the transition zone to constrain anisotropy within the layer. Localized evidence of strong anisotropy is found beneath the Pacific Northwest near locations where prior imaging studies show gaps between subducted oceanic plate fragments. We propose that focused flow through constrictions like slab gaps may cause seismic anisotropy in the mantle transition zone.

Introduction

Seismic anisotropy of Earth's mantle provides important insights into convective flow and composition at inaccessible depths. There is abundant evidence for concentrated anisotropy at depths within a few hundred kilometers of the mantle's top and bottom, but the prevalence of anisotropy at intermediate depths is more uncertain (Long & Becker, 2010). Potential reasons for diminished anisotropy in the transition zone and most of the lower mantle include decreasing anisotropy of higher-pressure olivine polymorphs (Mainprice 2015; Zhang et al., 2018), strain partitioning into localized shear zones (Girard et al., 2016), and accommodation of strain by diffusion creep rather than dislocation creep (Mohiuddin et al., 2020; Ritterbex et al., 2020). Depth-integrated measurements of mantle anisotropy like teleseismic shear wave splitting (SWS) are often assumed to be dominated by anisotropy at depths less than ~300 km. This perspective is supported by the positive correlation of fast-axis orientations with plate tectonic deformation and surface wave azimuthal anisotropy (Becker et al., 2012; Long & Becker, 2010), as well as isolated evidence that local deep earthquakes exhibit SWS comparable to teleseismic measurements (Fischer & Wiens, 1996). However, some long-wavelength global imaging studies and regional attempts to separate near-source contributions to path-integrated SWS suggest anisotropy extending to mantle transition zone depths of about 400-700 km (Huang et al., 2019; Lynner & Long, 2015; Yuan & Beghein, 2013).

The Pacific Northwest (PNW) of the U.S. is well-suited to investigate the depth distribution of mantle anisotropy (Fig. 1a). Active subduction is thought to organize vigorous mantle flow, the region has been densely instrumented with broadband seismometers, and a large depth-integrated anisotropy signal is indicated by spatially averaged teleseismic SWS measurements (Liu et al., 2014; Long et al., 2012; Supporting Information S1) (Fig. 1c). Surface wave azimuthal anisotropy constrains regional anisotropy at depths less than about 200 km, but that depth interval can only account for about half of the anisotropy indicated by SWS (Wagner & Long, 2013). Recent attempts using finite-frequency *SKS* splitting intensity suggest up to 8% anisotropy at 200-400 km to accommodate the remaining signal (Mondal & Long, 2020). However, the amplitude of the sensitivity kernels reduces with depth, leaving uncertainty about anisotropy at >400 km depth. Recent full-waveform inversion (FWI) for anisotropic velocities using regional earthquakes suggests that subduction-driven flow beneath the PNW creates anisotropy at transition zone depths (Zhu et al., 2020). The fast orientations from FWI tomography generally agree with SWS, but the depth-integrated magnitude of anisotropy is much smaller than that obtained by SWS. Thus, it is unclear how much transition zone anisotropy is needed to explain the large depth-integrated SWS signals in the PNW.

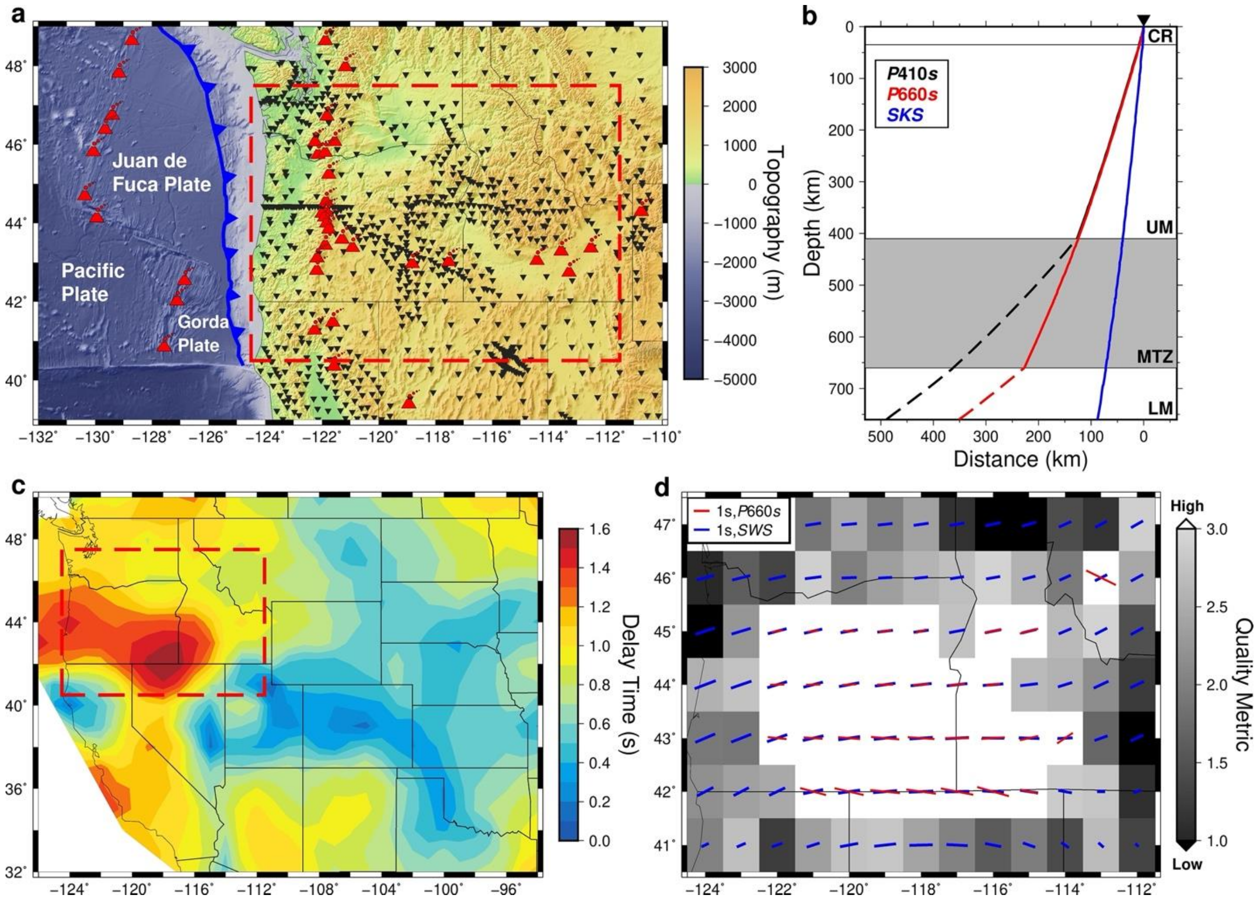

Fig. 1. Tectonic setting of the PNW and seismic observations of anisotropy. (**a**) The Juan de Fuca Plate is actively subducting beneath the PNW. Holocene volcanoes (red symbols) and broadband seismometers (black inverse triangles) are superimposed on the topography. The red dashed box outlines our study area. (**b**) Ray paths of the *P*410*s* (black), *P*660*s* (red) and *SKS* (blue) phases. Compositional layers are labeled: crust (CR), upper mantle (UM), mantle transition zone (MTZ), and lower mantle (LM). (**c**) Spatially averaged SWS delay times in the western U.S. The red dashed box outlines our study region. (**d**) Comparison between our estimated splitting parameters from the *P*660*s* (red bar) and the spatially averaged SWS results (blue bar). The grayscale background indicates the quality of the estimations from the *P*660*s*.

Data and Method

This study takes advantage of teleseismic P-to-S (*Ps*) conversions at the boundaries of the mantle transition zone to isolate potential deep contributions to anisotropy beneath the PNW. The two converted phases, *P*410*s* and *P*660*s*, almost share ray paths in the upper mantle so the paired observations can localize signals from within the transition zone (Fig. 1b). In an isotropic mantle with 1-D velocity structure, *Ps* conversions would only be observed with P-SV polarization. But constructive anisotropy along the shear wave ray path can cause splitting effect, leading to observations of *Ps* energy on SH polarization. We collected broadband waveform data from teleseismic earthquakes with magnitude greater than 5.5. For data with P wave signal-to-noise ratio (SNR) greater than 3, we extracted 3-component (P-SV-SH) receiver functions using a multimode frequency domain deconvolution method (Mercier et al., 2006). The receiver functions were filtered using a zero-phase bandpass filter between 0.07 Hz and 0.25 Hz and corrected for normal moveout by extracting velocities along the ray paths within a previous tomographic model (Schmandt & Lin, 2014).

Since small delay times often yield undetectable *Ps* signal on the SH component (Montagner et al., 2000), stacking many waveforms is often required and attempts to use the two phases are limited to areas with strong anisotropy (Vinnik & Montagner, 1996; Kong et al., 2018). Based on their piercing points at 500 km depth, we stacked the receiver functions that sample the transition zone in 200 km radius caps. We then applied a bootstrap based quality metric to determine regions with adequate SNR to constrain transition zone anisotropy (Fig. 1d; Supporting Information S2). The region with adequate *P*660*s* signals corresponds well with the area of large SWS delay times (>1.3 s, Fig. 1c). The splitting parameters, fast-axis orientation and delay time, estimated from *P*660*s* using transverse energy minimization (Long & Silver, 2009; Walsh et al., 2013) also share great similarity with the SWS results, indicating that most of the anisotropic signals can be explained at depths above the 660 (Fig. 1d). The mean difference of the fast-axis orientation estimates is 6.1˚ with a standard deviation of 11.8˚, and the mean difference of delay times is -0.03 s with a standard deviation of 0.34 s. However, the transverse component energy minimization approach to measuring anisotropy results in large delay time uncertainties (~0.5 s) for the *P*410*s* and

*P*660*s* estimations at individual stacking points, so they are not optimal for constraining the potentially weak anisotropy in the transition zone.

The amplitude ratio of the conversions between the two shear wave components (P_{SH}/P_{SV}) provides greater sensitivity to the magnitude of anisotropy than the delay time (Fig. S1). Consequently, the differences in the P_{SH}/P_{SV} amplitude ratios between *P*660*s* and *P*410*s* reflect transition zone anisotropy more precisely. Pairing the two *Ps* phases during the measurement further eliminates the back-azimuth component from the anisotropic effects. We again measured the amplitude ratios using stacks in 200 km radius caps and applied bootstrap resampling to assess the uncertainty (Supporting Information S3). The measurement of amplitude ratios of receiver functions is similar to the conventional method of measuring splitting intensity for the *SKS* phase (Chevrot, 2000). The splitting intensity is defined as the amplitude ratio of the *SKS* phase between the transverse component and the time derivative of the radial component. In contrast, we measured the amplitude ratio of the stacked *Ps* phase between the time integrated SH component (P_{SH}) and original SV component (P_{SV}). Mathematically, the derivative and integration processes offer identical results after removing the integration constant. The integration process we adopted here preserves the one-side polarity of the P_{SV} phase, which simplifies the measurements (Fig. S1).

Results and Discussion

The null hypothesis of an isotropic transition zone and all anisotropy above the 410 predicts indistinguishable amplitude ratio distributions for the two phases. We use Cohen's distance between the *P*660*s* and *P*410*s* amplitude ratio distributions and the corresponding paired t-test to evaluate the significance of transition zone anisotropy (Supporting Information S3). About half of the resulting Cohen's distances show a significant difference at 68% confidence (±1.0), with a few locations exceeding the 95% confidence level (±2.0) (Fig. 2, b and d, See Fig. S2 for more examples).

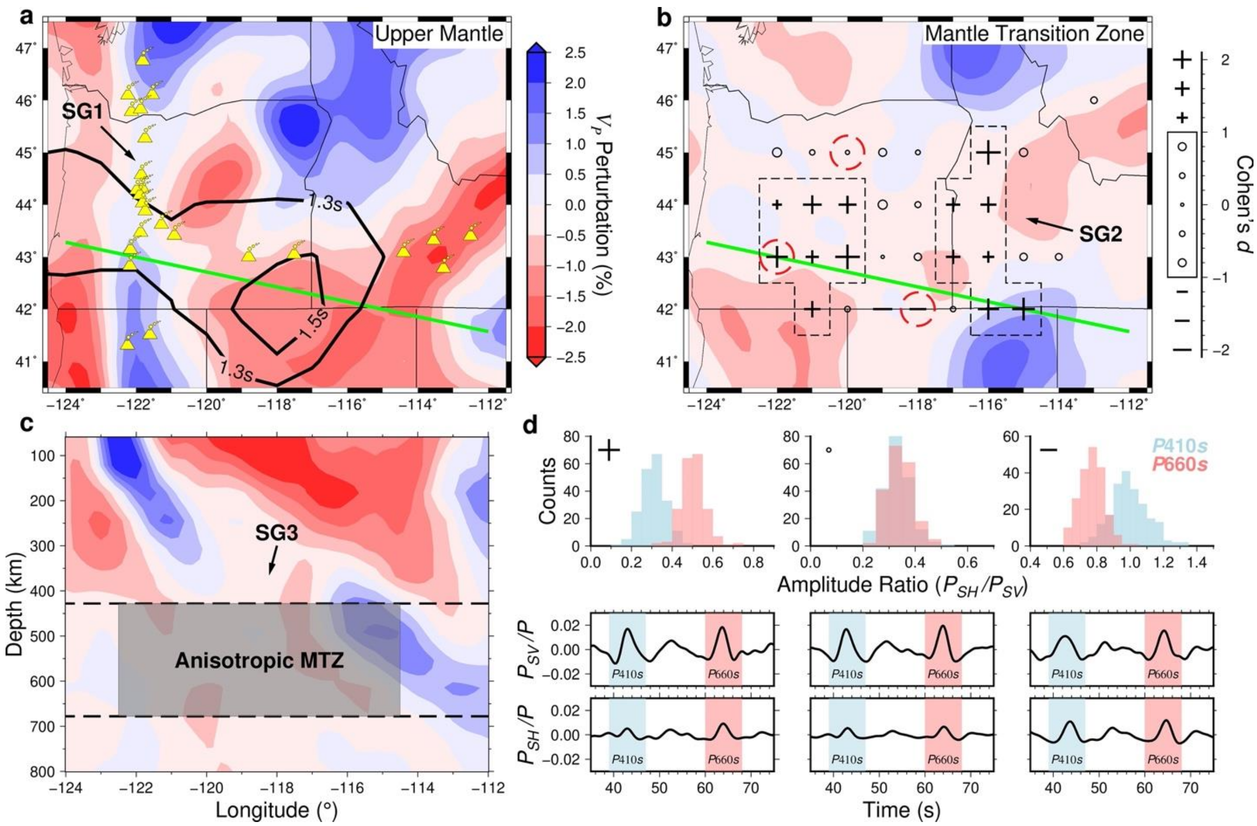

Fig. 2. Seismic tomography of the study region and amplitude ratio evidence for anisotropy. Depth averaged V_P perturbation within (**a**) the upper mantle (60-350 km) and (**b**) the mantle transition zone (435-635 km). The positions of slab gaps are labeled by SG. Holocene volcanoes (yellow symbols), contoured spatially averaged SWS delay times (1.3s and 1.5s, black lines), and observed Cohen's distances are superimposed on the tomography. (**c**) Cross section of the V_P perturbation beneath the green line on the maps. The gray box outlines where mantle transition zone (MTZ) anisotropy is required by the observations. (**d**) Examples of the observed amplitude ratios and stacked waveforms from the locations with red dashed circles in panel b. The amplitude ratios from the *P*410*s* are in red while those from *P*660*s* are in blue.

We defined three categories for the observed results: constructive interference where *P*660*s* amplitude ratios are greater than *P*410*s* amplitude ratios (labeled '+'), destructive interference where *P*410*s* amplitude ratios are greater than those of *P*660*s* (labeled '-'), and neutral where there is no significant difference (labeled '○'; Fig. 2b). The neutral observations fail to reject the null hypothesis of an isotropic transition zone. Two larger areas of constructive interference and one smaller area of destructive interference indicate localized transition zone anisotropy inboard of the Cascades volcanic arc (Fig. 2c).

The two constructive interference areas exhibit greater path-integrated anisotropy from the 660 to the surface compared to that from the 410 to the surface. Such observations can be fit with a common fast orientation for an anisotropic layer extending through the upper mantle and into the transition zone. Both constructive interference areas lie within gaps between high-velocity slab fragments identified by seismic tomography (Schmandt & Lin, 2014; Hawley & Allen, 2019) (Fig. 2, a and b, labeled SG; see Movie S1 for 3D illustration). The western area is located near an along-strike slab gap in the upper mantle beneath the central to southern Oregon backarc region that is hypothesized to focus mantle flow beneath backarc volcanic provinces (Hawley & Allen, 2019). The eastern area of constructive interference is located between two high-velocity features interpreted to be older slab fragments located further beneath the continental interior (Liu & Stegman, 2011; Schmandt & Humphreys, 2011). The southern edge of the eastern constructive interference area appears to overlap the position of the high-velocity slab beneath northern Nevada.

Two stacking points that exhibit destructive interference of transition zone and upper mantle anisotropy are located at the southern edge of the well-resolved area (Fig. 2b). Deconstructive interference of splitting within the transition zone and above it due to changing fast orientation with depth can create a larger P_{SH}/P_{SV} amplitude ratio of the *P*410*s* compared to that of *P*660*s* (Fig. S3; Supporting Information S4). Given the small area that exhibits destructive interference and the tradeoffs among estimating the thickness, fast orientation, and magnitude of anisotropy for the two layers, we refrain from further interpretation of these two stacking points.

Anisotropy within the transition zone could arise on account of lattice preferred orientation (LPO) of olivine polymorphs. Wadsleyite is the stable polymorph of olivine in the upper transition zone and has a maximum single-crystal shear wave anisotropy of ~9% (Zhang et al., 2018). The peak anisotropy is smaller than that of olivine above the 410 (Fig. S4), but deformation experiments have successfully produced up to 2% anisotropy of wadsleyite (Kawazoe et al., 2013; Ohuchi et al., 2014). At lower transition zone depths, the stable polymorph of olivine is ringwoodite and it is elastically almost isotropic at transition zone pressures (Mainprice, 2015). Therefore, it is unlikely to contribute to the observed anisotropic signals. Atypical anisotropic minerals formed near or within the subducted slab may contribute to anisotropy. At relatively low mantle temperatures, two strongly anisotropic minerals, phase E and akimotoite, could form at transition zone depths (Hao et al., 2019; Satta et al., 2019). Phase E is a reaction product between olivine and water at upper transition zone depths (Satta et al., 2019). Akimotoite is enriched in the refractory harzburgitic lithosphere of the slabs at lower transition zone depths (Ishii et al., 2019). Both minerals have single-crystal shear wave anisotropy up to ~20%, which makes them alternative candidates for the origin of observed anisotropic signals in the transition zone.

The deformation mechanisms for the mantle transition zone minerals depend on many factors, such as temperature, flow stress, strain rates, and grain size. The laboratory determined glide-driven dislocation creep of transition zone minerals can cause development of LPO (Kawazoe et al., 2013). However, a recent theoretical study suggests that deformation in the mantle transition zone is dominated by climb-driven dislocation creep, which does not develop LPO (Ritterbex et al., 2020). The glide-driven dislocation creep is favored by high stress and strain rates in the laboratory, whereas typical flow stress and strain rates in the ambient mantle are several orders lower. Therefore, the development of LPO may be expected only in areas of stress concentration, such as where mantle flow is focused through constrictions (Alisic et al., 2012; Király et al., 2020).

Based on the mineral physics' constraints, we constructed three types of forward models to illustrate a range of potential anisotropic structures (Fig. 3a; Supporting Information S5). The simplest model includes only upper mantle anisotropy extending from the Moho to 400 km depth, such that anisotropy is consistent with only an olivine LPO origin (Fig. 3a, #1). Since there is no anisotropy within the transition zone, the first model can explain the neutral observations where the P_{SH}/P_{SV} amplitude ratios from the *P*660*s* and *P*410*s* are indistinguishable.

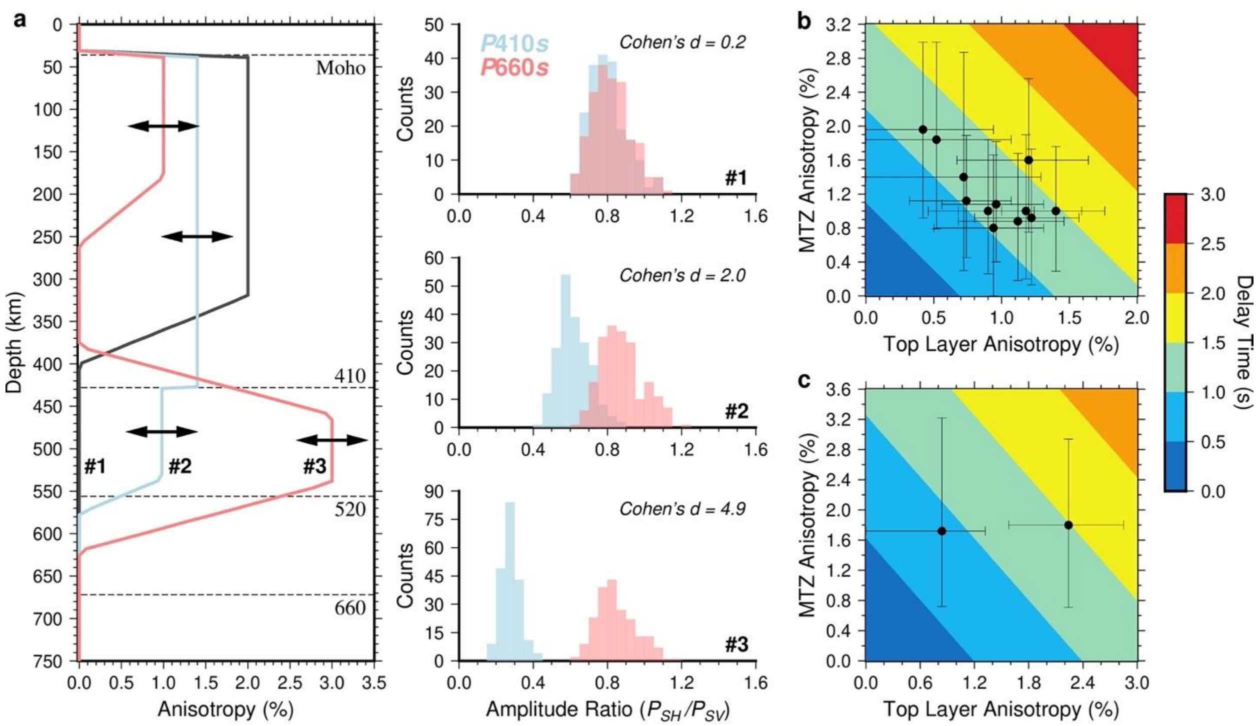

Fig. 3. Forward models and the inverted mantle transition zone anisotropy. (**a**) Three types of forward models (#1-3) and their corresponding amplitude ratios distributions. The Cohen's distances are denoted by the histograms. (**b**) Inverted mantle transition zone (MTZ) anisotropy for most of the constructive interference areas using parameterization of model #2. The error bar

represents the 68% confidence intervals. The color background represents the delay time from a vertically propagated shear wave. (**c**) Inverted results for the two stacking points in the southeastern corner using parameterization of model #3.

The second model also contains upper mantle anisotropy, but it is underlain by an anisotropic layer in the upper part of the transition zone where wadsleyite is stable (Fig. 3a, #2). This model yields constructive interference of transition zone and upper mantle splitting effect and then offers a plausible explanation for places with a larger *P*660*s* amplitude ratio. With this model parameterization, we used a grid search of upper mantle and transition zone anisotropy magnitudes to find the best model for explaining the observations (Supporting Information S6). Using a ray parameter and back-azimuth distribution identical to the observational data, the inverted results show that inclusion of ~1-2 % anisotropy in the upper mantle transition zone can reproduce the observed differences between the two amplitude ratios for most stacking points exhibiting constructive interference (Fig. 3b).

The third model is built on the idea that subducted slab is present in the transition zone, thus atypical minerals which are not expected in the ambient mantle may contribute to anisotropy (Fig. 3a, #3). In this case, the anisotropy within the transition zone is allowed to extend to deeper depths where wadsleyite is no longer stable. The deeper anisotropy may arise from akimotoite associated with the cool slab fragment, such as beneath the southeastern corner of the well-resolved area (Fig. 2b). When modeling the two stacking points in the southeastern corner, the additional thickness of the anisotropic layer prevents requiring unreasonably large anisotropy in the wadsleyite stability field (Fig. 3c).

The three anisotropic structures suggest various geodynamic settings (Fig. 4). The first model represents upper mantle flow due to absolute plate motion and subduction zone corner flow in the shallow upper mantle. In this conventional context, anisotropy is primarily due to olivine LPO created by flow-induced dislocation creep. The second model requires focused mantle flow caused by slab ruptures as hypothesized by prior geodynamic modeling of regional mantle flow and anisotropic fast orientations (Zhou et al., 2018). If flow through slab gaps induces locally high stress at transition zone depths, the LPO of wadsleyite could contribute a portion (up to 0.4 s in this study) of the total splitting delay time. The additional anisotropy at transition zone depths helps explain the large discrepancy between estimated splitting delay times from surface wave azimuthal anisotropy studies and observed teleseismic SWS in the central Cascades backarc (Wagner & Long, 2013). The third model represents the potential influence of compositional heterogeneity due to a slab fragment at transition zone depths, which is a scenario that may be even more important for subduction zones with older and colder slab fragments in the transition zone.

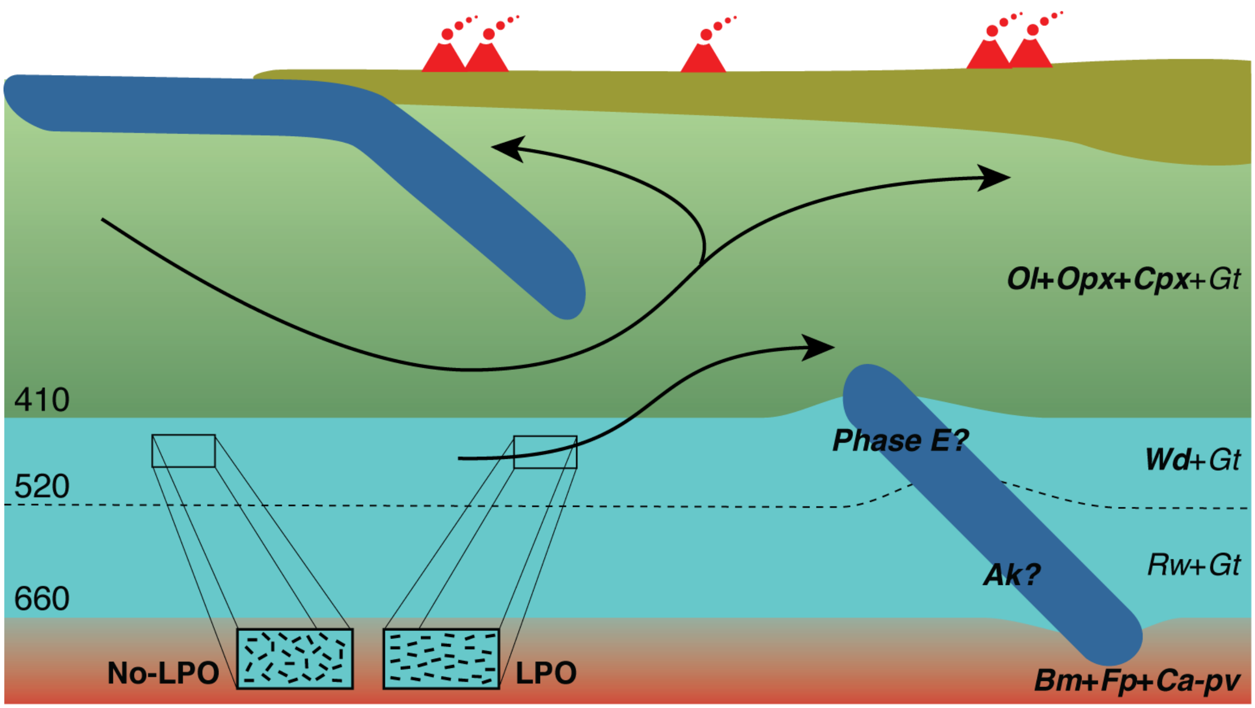

Fig. 4. Schematic model of flow going through slab gap. The rupture of a continuous slab induces enhanced flow near the slab gap. The resulting flow concentrates stress and develops lattice preferred orientation (LPO) of anisotropic minerals at transition zone depths. Common minerals are labeled using italic font with anisotropic minerals in bold: olivine (Ol),

orthopyroxene (Opx), clinopyroxene (Cpx), garnet (Gt), wadsleyite (Wd), ringwoodite (Rw), bridgmanite (Bm), ferropericlase (Fp), Ca-perovskite (Ca-pv), akimotoite (Ak).

Conclusions

The new results support the potential development of seismic anisotropy at mantle transition zone depths, with magnitudes that can be similar to those in the upper mantle. However, in contrast to upper mantle anisotropy that is observed ubiquitously, it appears that transition zone anisotropy may be restricted to areas of locally high stress such as focused flow through fragmented slabs.

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Acknowledgments:

We thank K. H. Liu and S. S. Gao for sharing their SWS dataset. We also thank H. Zhu for sharing full waveform inversion results. This study is supported by NSF grants EAR-1554908 and EAR-1664471. H.Z. acknowledges support from the Caswell Silver Fellowship of the Earth and Planetary Science Department at the University of New Mexico.

Data Availability

The raw seismic data used in this study are publicly available through the IRIS Data Management Center. The receiver functions data are available at Zenodo (https://doi.org/10.5281/zenodo.3981446).