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Seismic anisotropy beneath the Juan de Fuca plate system: Evidence for heterogeneous mantle flow

Miles Bodmer[1], Douglas R. Toomey[1], Emilie E. Hooft[1], John Nábělek[2], and Jochen Braunmiller[3]

[1]Department of Geological Sciences, University of Oregon, Eugene, Oregon 97403, USA

[2]College of Earth, Ocean and Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331-5503, USA

[3]School of Geosciences, University of South Florida, 4202 E. Fowler Avenue, NES 107, Tampa, Florida 33620-5550, USA

ABSTRACT

Here we use SKS shear-wave splitting observations from ocean-bottom seismometer data to infer patterns of mantle deformation beneath the Juan de Fuca plate and its adjoining boundaries. Our results indicate that the asthenosphere beneath the Juan de Fuca plate responds largely to absolute plate motion with an anisotropic layer developing rapidly near the ridge and persisting into the subduction zone. Geographically restricted deviations from this pattern indicate the presence of secondary processes. At discrete plate boundaries, such as the Blanco Transform fault, seismic anisotropy is attributed to relative plate motion within a narrow zone (<50 km). Beneath the deforming southern Gorda region — a diffuse plate boundary —splitting observations similarly suggest deformation dominated by relative motion between the rigid Juan de Fuca and Pacific plates but distributed over a broad zone (~200 km). Our results are inconsistent with toroidal flow around the southern edge of the subducting slab due to rollback, as

suggested by onshore studies. Instead, reorganization of upper mantle flow associated with plate fragmentation seems to dominate the anisotropic signature of southern Cascadia.

INTRODUCTION

Mantle convection and the movement of tectonic plates drive flow in Earth's viscous upper mantle. The nature of mantle flow and its relation to plate boundary evolution are relevant to plate dynamics and thus remains a topic of vigorous inquiry. Since mantle strain induces lattice preferred orientation of seismically anisotropic minerals, particularly olivine, seismic methods can be used to constrain patterns of mantle flow (Silver and Chan, 1991).

The Juan de Fuca (JdF) plate system is an excellent target for investigating the forces that drive oceanic mantle flow. In a compact region one finds all three types of discrete plate boundaries, lithospheric plates that are both intact (JdF) and internally deforming (southern Gorda), and an evolving subduction zone system susceptible to edge effects, slab rollback, and plate fragmentation (Fig. 1). The Cascadia Initiative (CI), a multi-year, onshore-offshore experiment (Toomey et al., 2014), and a complementary Blanco Transform array (Ghorbani et al., 2015) specifically target these regions and for the first time provide dense coverage of an entire oceanic plate and its boundaries.

Here we use ocean bottom seismometer (OBS) data and the well-established shear-wave splitting method to investigate mantle flow beneath the JdF plate system. Owing to the extensive coverage of our OBS array, and the spatial coherence of interstation shear wave splitting observations, we are able to detect significant heterogeneity in the oceanic mantle flow field. Our results have implications for the forces that drive asthenospheric flow and for the evolution of the complex plate interactions that define southern Cascadia.

DATA AND METHODS

We analyze seismic data from 5 onshore CI instruments, 117 OBS sites from years 1, 2, and 3 of the CI, and 30 OBSs from the Blanco array (Figs. 1 & DR1). The orientation of the horizontal components of the CI OBSs were determined by Sumy et al. (2015) with a median uncertainty in channel orientation of ± 9° at the one-sigma confidence level. We analyze the SKS phase of teleseismic events, $M_w \geq 6$, at distances of 90°-130°. All onshore instruments and 111 of the 147 OBSs recorded at least one usable event (Table DR1). The OBSs recorded an average of 4 usable events and only 14 sites recorded just a single usable event (Table DR2). Back-azimuthal event coverage is limited and has a westward bias for the OBS data due to the short deployment time (Fig. DR2).

We implemented a workflow that uses strict quality control to account for high environmental noise levels typical of OBS data. Our SKS splitting analysis was conducted using the Splitlab software package (Wüstefeld et al., 2008), which performs three common splitting methods: rotation correlation (RC) (Bowman and Ando, 1987), Silver and Chan (SC), and eigenvalue (EV) (Silver and Chan, 1991). Each method estimates the polarization direction of the fast shear wave ϕ and the delay time δt between the fast and slow shear waves (Fig. DR3). Initial measurements are filtered with a third-order, zero phase Butterworth bandpass filter (0.03–0.1 Hz). This isolates the SKS arrival within a relatively low-noise band between the microseism peak (0.1–2 Hz) and the high frequency limit of infragravity waves (<0.04 Hz). Measurements are repeated for several filter limits adjusted between 0.02 and 0.15 Hz and covering at least a full octave. Multiple measurements allow for a qualitative assessment of stability from which a final event measurement is chosen; reported measurements often include higher frequencies, even those that may obscure the previously identified SKS waveform, improving accuracy (Restivo and Helffrich, 1999). We report measurements using only the SC method due to the poor performance of the RC method on low signal-to-noise data (Vecsey et al., 2008). All three methods are used for quality control, verifying that results from the SC and EV methods are consistent and that the RC method is either consistent or yields results indicative of high noise contamination (Vecsey et al., 2008). Measurements with delay times >3.5 s or <0.5 s are discarded. Possible null measurements are not reported since they are indistinguishable from measurements with high noise levels on the transverse channel.

Maps of the transverse energy are generated by grid searching in the δt-ϕ parameter space. A single set of splitting parameters is estimated for each station by stacking the normalized energy maps (Wolfe and Silver, 1998) and a statistical F-test is applied to obtain the 95% confidence intervals (Fig. DR3) (Silver and Chan, 1991) which are converted to one sigma errors. Typical uncertainties in ϕ and δt are 8° and 0.3 s (Table S2), respectively, although in shallow water they tend to be larger. To verify that we can recover known splitting parameters, we analyzed good quality data from onshore CI stations and successfully reproduced the trench perpendicular pattern found by previous studies (e.g., Eakin et al., 2010).

RESULTS

Our SKS splitting results (Figs. 2 and 3) reveal spatially coherent patterns in fast polarization directions that are correlated with five tectonic environments (Fig. 1): (i) the JdF plate interior and northern Gorda; (ii) the southern, internally deforming Gorda and Mendocino triple junction (MTJ); (iii) the JdF ridge; (iv) the Cascadia subduction zone (CSZ); and (v) the Blanco transform fault.

The fast polarization directions within the JdF plate interior and the northern Gorda show an average trend of N63°E that extends from 50 km east of the ridge to the subduction zone (Figs. 2 and 3a). Delay times are 1 s on average and do not appear to vary with plate age (Fig. DR4). Orientations correlate poorly with the JdF-Pacific spreading direction (N107°E). To estimate the absolute plate motion (APM) of the JdF plate, we use the APM of the Pacific plate, which is well known, and the Pacific-JDF relative plate motion (RPM) calculated from the MORVEL model (DeMets et al., 2010). In this reference frame, fast polarization directions broadly correlate with APM (N30°E to N50°E, depending on location, see Fig. 3a). We note, however, that the observed fast polarization directions are systematically rotated clockwise from the APM direction (Fig. 3a).

In the southern Gorda plate we observe a region of coherent fast polarization measurements oriented N109°E (Figs. 2 and 3b). This trend extends beyond the Gorda plate into the Pacific plate, and is disrupted by neither the Gorda spreading center nor the Mendocino transform fault. The northern boundary of this region correlates well with the onset of intense lithospheric deformation of the southern Gorda plate (Chaytor et al., 2004). Measurements within 25 km of the MTJ show large variance but become consistent at greater distances (Fig. 3b). In contrast to the JdF plate interior, the observed fast polarization directions are inconsistent with JdF APM. Though similar to the APM of the Pacific (N122°E) and the relative spreading direction of the southern Gorda ridge (N98°E), fast polarization directions agree best with the relative motion between the non-deforming JdF and Pacific plates (N107°E). Delay times are 1.4 s on average with low variability and do not appear to have any spatial dependence.

Measurements within 50 km of the JdF ridge are sparse and suggest a variable pattern (Fig. 2 and 3c). Near the intersection of the JdF ridge and Blanco transform fast polarization directions correlate with JdF/Pacific RPM. Throughout most of the central ridge segments there appears to be a broad ridge parallel trend, most notably near Axial Seamount, that diminishes northward. Average delay times are 1 s.

Near the CSZ most fast polarization directions closely resemble those within the JdF plate interior and the western U.S. (Figs. 2 and 3d) and delay times are 1.4 s on average. The relative convergence of JdF and North America is at N56°E and the trench orientation changes from roughly N2°W to N48°W, from south to north. Relative to the trench trend, measurements in the southern and northern CSZ are roughly trench perpendicular but rotate anticlockwise toward trench parallel between 44°N and 46°N. The region of trench parallel orientations coincides with several geologic features that make central Cascadia anomalous, e.g., where subduction changes orientation and flattens (McCrory et al., 2012).

In the Blanco transform region fast polarization directions rapidly change from NW-SE to NE-SW when crossing the transform from Pacific to JdF plates and correlate well with respective APMs (Fig. 2 and 3e). Within 25 km of the transform, orientations parallel the relative motion of the JdF and Pacific plates. Delay times are 1 s on average.

DISCUSSION

We use our splitting results to infer regional-scale patterns of mantle flow by assuming that the observed fast polarization directions are subparallel to the direction of maximum shear (e.g., Silver and Chan, 1991). Our data are insufficient to explicitly test for multiple anisotropic layers (see Figs. DR5 and DR6), however, we consider the possibility of depth dependent anisotropy in our interpretations. Sites with only 1 or 2 measurements are more uncertain but the observations are supported by their consistency with neighboring sites. Given 4% mantle anisotropy, a splitting time of ~1 s would require a ~100-km-thick anisotropic layer. Since our split times are typically 1 s or more, and predicted lithospheric thickness in this region is 5 to 30 km (Fig. 2), we infer that the bulk of observed anisotropy originates in the asthenosphere.

Beneath the JdF and northern Gorda plates we attribute anisotropy to an entrained layer of asthenosphere influenced by APM and altered by a secondary process. Sub-slab entrainment has been interpreted for several Cascadia data sets (Currie et al., 2004; Eakin et al., 2010; Bonnin et al., 2010), young subduction zones (Lynner and Long, 2014), and geodynamic models (Faccenda and Capitanio, 2012). Correlation with APM in the JdF plate interior and the CSZ (Fig. 3 a and d) is consistent with the plate dragging asthenosphere into the subduction zone via viscous coupling. The systematic clockwise rotation of fast polarization directions from APM suggests some secondary process is important. One possibility is that a shallow layer of anisotropy aligned with RPM due to corner flow at the ridge results in an apparent fast axis altered by multiple layering. However, this requires a ~0.5 s delay time contribution, implying either a very thick (50 km at 4% anisotropy) or highly anisotropic (12% at 20 km thickness) layer (Fig. DR6).

While anisotropy related to plate spreading is very likely it is unclear whether it exists in the necessary magnitudes. Further, most observations near the ridge are inconsistent with the RPM direction. An alternative interpretation is that asthenospheric flow is also driven by internal convection unrelated to APM. Indeed, seismic studies of the Endeavor segment of the Juan de Fuca Ridge show that sub-ridge mantle divergence is skewed clockwise with respect to the plate-spreading direction and related to a recent change in JdF/Pacific plate motion (VanderBeek et al., 2014).

At the Blanco transform, a discrete plate boundary between the JdF and Pacific plates, we infer a narrow shear zone with deformation aligned with RPM. Rapid changes in fast polarization orientations across the transform indicate highly localized deformation within a 50-km-wide zone centered on the transform. The distribution of strain with depth is unknown, however, relatively low viscosities in the asthenosphere beneath the transform and/or very shallow anisotropic structure may be necessary to produce the rapid changes in orientation observed, particularly when considering the overlap of SKS Fresnel zones.

Beneath the southern Gorda region — a diffuse plate boundary — we attribute anisotropy to a broad shear zone accommodating Pacific-JdF RPM (Fig. 3b and 4). In response to northward movement of the Pacific plate, the southern Gorda lithosphere is undergoing internal deformation, which is evident in bathymetry (Fig. 1), magnetic anomalies (Fig. 2), anomalous orientations of the Gorda ridge and Mendocino transform, bookshelf faulting (Chaytor et al., 2004), and geodynamic models of regional stress (Wang et al., 1997). Correlation of our observations with both the region of crustal deformation and the Pacific-JdF RPM suggests a common causal factor for both lithospheric and asthenospheric deformation. In our proposed model (Fig. 4) the southern Gorda region is a weak zone separating two rigid plates and thus accommodates the relative motion between them with both asthenosphere and lithosphere undergoing deformation and upper mantle strain aligned with RPM. Our results, in conjunction with those near the Explorer plate (Mosher et al., 2014), suggest that reorientation of upper mantle flow plays a critical role in plate fragmentation with RPM alignment beneath the Gorda representing an intermediate state before full detachment.

Our results are inconsistent with the rollback induced toroidal flow model commonly invoked for onshore anisotropy near the MTJ (e.g., Zandt and Humphreys, 2008). Geodynamic models suggest that beneath a downgoing plate toroidal flow results in strong trench parallel deformation (Faccenda and Capitanio, 2012), which is inconsistent with our results by ~65° (Fig. 2 and 3b). Further, observed orientations and delay times do not vary with distance from the slab edge and abruptly change orientation at the northern limits of the Gorda deformation zone. We conclude that there is no large-scale toroidal flow due to slab rollback or that the deformation is weak resulting in minimal influence on measurements. Diversion of ambient flow around the southern slab edge is another possible source of deformation (Eakin et al., 2010). However, due to the lack of variation with distance from the slab edge, large delay times, and correlations with Gorda deformation we assert that its contribution to the anisotropic structure is, if present, secondary.

CONCLUSIONS

Seismic anisotropy of the upper mantle beneath the Juan de Fuca plate system is remarkably heterogeneous, indicating that a variety of forces drive flow in the oceanic asthenosphere. Beneath rigid plates, absolute plate motion is a significant driver of flow that entrains asthenosphere and drags it into subduction zones. There is also evidence of a secondary source of anisotropy possibly related to non-APM convective processes. Near plate boundaries anisotropy records relative plate motion (e.g., Blanco), but in some cases is complex (e.g., Juan de Fuca Ridge and Mendocino transform). Plate fragmentation occurring within the diffuse plate boundary in the southern Gorda region is accompanied by reorganization of upper mantle flow.

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Figure Captions

Figure 1. Bathymetric and topographic map showing location of seismometers (red circles) and geographic regions defined by tectonic setting and observed splitting patterns: (blue) Juan de Fuca plate interior, (red) Cascadia subduction zone, (orange) Juan

de Fuca ridge, (yellow) Blanco transform, (green) Mendocino triple junction and southern Gorda region.

Figure 2. SKS splitting results overlaying magnetic anomalies (light colored bands) and propagator wakes (gray bands) (from Nedimović et al., 2009). Thick bars indicate our measurements color coded by zone (see Fig. 1). Orientation of a bar shows the fast polarization direction and its length is scaled by the delay time. Yellow arrows are the absolute plate motions (modified from MORVEL, DeMets et al., 2010). Blue bars are SKS splitting measurements from land studies (Currie et al., 2004; Eakin et al., 2010; Bonnin et al., 2010). Thin black lines are depth to slab contoured at 10 km intervals (McCrory et al., 2012). (Upper left) top scale shows the seafloor age and corresponding lithospheric thickness for a half-space cooling model and the bottom scale shows layer thicknesses and percent anisotropy for a 1 s delay time.

Figure 3. Plots of the fast polarization direction (degrees clockwise from N) as a function of distance or latitude for each of the zones shown in Figure 1; measurements (circles) are color coded by zone (see Fig. 1). Colored lines show orientations predicted by various scenarios. Purple band (b) represents the region within 25 km of the MTJ and the yellow band (d) is the region of anomalous observations in central Cascadia.

Figure 4. Schematic of upper mantle anisotropy beneath the JdF plate interior and the southern Gorda region. Top layer: Yellow arrows indicate absolute plate motions. The red double arrow represents the relative motion of Pacific-JdF. Black arrows represent N-

S compression of southern Gorda. Small black arrows depict the Mendocino transform fault and strike-slip faulting within the Gorda plate. Bottom layer: Typical splitting orientations color coded by zone (see Fig. 1); fast polarization directions beneath the JDF are rotated CW from APM and within the Gorda region parallel Pacific-JdF relative motion.

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