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2 Mantle flow geometry from ridge to trench beneath the Gorda-Juan

3 de Fuca plate system

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19 Resubmission of NGS-2015-04-00698A

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Tectonic plates are underlain by a low viscosity mantle layer, the asthenosphere. Asthenospheric flow may be induced by the overriding plate or by deeper mantle convection¹. Shear strain due to this flow can be inferred using the directional dependence of seismic wave speeds - seismic anisotropy. However, isolation of asthenospheric signals is challenging; most seismometers are located on continents, whose complex structure influences the seismic waves en-route to the surface. The Cascadia Initiative, an offshore seismometer deployment in the US Pacific Northwest, offers the opportunity to analyze seismic data recorded on simpler oceanic lithosphere². Here we use measurements of seismic anisotropy across the Juan-de-Fuca and Gorda plates to reconstruct patterns of asthenospheric mantle shear flow from the Juan-de-Fuca mid-ocean ridge to the Cascadia subduction zone trench. We find that the direction of fastest seismic wave motion rotates with increasing distance from the mid-ocean ridge to become aligned with the direction of motion of the Juan-de-Fuca Plate, implying that this plate influences mantle flow. In contrast, asthenospheric mantle flow beneath the Gorda Plate does not align with Gorda Plate motion and instead aligns with the neighbouring Pacific Plate motion. These results show that asthenospheric flow beneath the small, slow-moving Gorda Plate is controlled largely by advection due to the much larger, faster-moving Pacific Plate.

The Juan-de-Fuca plate system is the northernmost section of the Farallon slab, which is approaching complete subduction beneath the North American continent³. The system is subdivided into the Explorer, Juan-de-Fuca and Gorda segments,

which subduct at $\sim 12\text{mm/yr}$ in a $\sim \text{N}60^\circ\text{E}$ direction beneath the Cascadia arc^{4,5}. The assemblage is undergoing rollback at $\sim 24\text{mm/yr}$ ⁴ and rotating clockwise as the Mendocino Triple Junction (MTJ) migrates northwards⁴.

Questions about the mantle flow geometry beneath Cascadia focus on interaction between oceanic asthenosphere and the subducting slab⁶. Shear wave splitting, a technique that quantifies the magnitude and direction of seismic anisotropy, can address such questions^{6,7}. Seismic anisotropy in the mantle develops due to the lattice-preferred orientation (LPO) of various minerals⁸. Olivine, the main component of the upper mantle, is highly anisotropic^{8,9}. Simple shearing under typical asthenosphere conditions yields olivine crystal alignment, with fast axes corresponding to the shearing direction⁸. Shear waves traversing such a medium are split into two orthogonal components, one of which is polarized in the fast direction. A delay time (δt) proportional to the strength and layer-thickness of the anisotropy is acquired as the components transit the layer. The fast axis direction (ϕ) is used to determine the shearing direction and by inference the mantle flow geometry⁷.

Onshore studies in Cascadia reveal uniformly trench perpendicular anisotropy, indicative of sub-slab mantle flow^{4,5}. Cascadia is unusual; most subduction zones demonstrate trench-parallel splitting⁶. This has been variously interpreted as rollback-induced flow⁶, the influence of B-type olivine LPO in the mantle wedge⁹, or the consequence of strong radial anisotropy in steeply dipping, entrained flow¹⁰.

We analyze data from Cascadia Initiative seismometer deployments², including 27 onshore Transportable Array (TA) sites and 70 ocean bottom seismometers (OBS), deployed in ten-month phases at 160 sites². We analyze OBS data from years 1-3 of the Cascadia Initiative and 4 years of records from the NEPTUNE cabled seafloor observatory¹¹. Public data from the X9 OBS array, deployed along the Blanco Fracture Zone in 2012-2013² are also utilized (supplementary information, S2).

Splitting parameters ϕ and δt are determined for each station-event pair using two open-source software packages, before results are stacked to produce a single measurement at each site (see methods). Shear wave splitting with OBS data is challenging due to high noise levels within the S frequency band^{12,13} and uncertainty in instrument orientation¹⁴. We generally obtain 1-4 good quality measurements per offshore station, compared to 8-15 results for the onshore sites (supplementary information, S3-S6).

The TA stations produce a uniform splitting pattern along the length of the subduction zone (figure 1). The mean fast direction and delay times are N72°E and 1.34s respectively, in agreement with previous studies and sub-parallel to the subduction direction of N60°E^{4, 5}. Offshore stations on the Juan-de-Fuca plate display a more complicated pattern: except for a single, ridge-parallel result near Cobb Hotspot, fast splitting directions (FSD) vary between the trench perpendicular and absolute plate motion (APM) direction. Alignment with the Juan-de-Fuca APM

direction increases towards the trench (figure 2). The FSD then rotate into the subduction direction as one moves onshore.

Sites on the Gorda plate produce a highly uniform pattern, but are neither aligned with Gorda **APM** nor the subduction direction. Their mean FSD of N66°W aligns with the motion of Pacific plate (~N57°W⁴) and with the ridge-perpendicular orientation (~N67°W). A marked change in FSD is observed just east of the trench in this region, where the fast directions rotate approximately 70° into a trench-perpendicular orientation (Figure 2a). Results from stations situated on the Pacific plate align well with APM, featuring a mean direction of N60°W.

This study compliments previous shear wave splitting results from ocean basins^{15,16} and enhances coverage of the region. A notable feature of the existing onshore pattern is the arcuate splitting geometry observed south of the MTJ in northern California, which follows the southern edge of the down-going Gorda slab^{4,17} (Figure 1). The subducting slab is imaged by body wave tomography as a segmented, high velocity anomaly with a ‘gap’ beneath northern Oregon¹⁸. **This ‘gap’ does not appear to influence the splitting pattern, however.**

Limited back-azimuthal coverage makes it difficult to model dipping or multi-layer regional anisotropy in our study. We follow previous teleseismic splitting studies^{4,5} of this area in interpreting a single anisotropic layer.

On oceanic plates, the dominant splitting signal likely arises from a combination of fossil anisotropy in the lithosphere and viscous shearing of the asthenosphere by plate motion⁷. According to the model of Nishimura and Forsyth¹⁹, the lithospheric component should lie in the fossil spreading direction, while the asthenospheric component should align with the direction of present day mantle flow. Both are parallel to the spreading direction close to mid-ocean ridges, but diverge beneath older lithosphere as the asthenosphere is dragged in to the APM direction¹⁹. Shear wave splitting studies of the East Pacific Rise¹⁵ and in French Polynesia¹⁶ generally support this idea.

Given realistic estimates of 50km, 4% and 4.6km/s for the thickness, percentage anisotropy, and shear wave velocity for the Juan-de-Fuca plate, respectively, a lithospheric splitting time contribution of 0.43s is predicted^{4, 7}. This is significantly smaller than the OBS splitting times, implying that the asthenosphere is an important source of anisotropy.

The rotation of FSDs into the APM orientation east of the Juan-de-Fuca ridge implies the influence of competing flow components. A variety of anisotropic fabrics might be expected in the vicinity of a mid-ocean ridge: upwelling asthenosphere in response to passive spreading, oriented melt pocket anisotropy along the ridge itself due to dyke intrusion²⁰, lateral flow away from the ridge²¹ and basal drag fabrics as the plate moves away from the ridge¹⁹.

Splitting directions close to the Juan-de-Fuca ridge generally lie between APM and ridge-perpendicular direction, suggesting that lateral flow and basal drag are the strongest influences. We do not see a concentration of null results at stations located close to the ridge (see methods), suggesting that the influence of vertically oriented LPO due to upwelling is minimal or confined to a narrow region.

One exception to the pattern occurs at site J39, just east of Axial Seamount. The splitting parameters here are well constrained and suggest strong ridge-parallel anisotropy (supplementary information, S7). This may be the result of aligned pockets of melt present near the ridge axis as observed on land in Ethiopia, a subaerial region of incipient oceanic spreading²⁰.

On the Gorda section of the plate system there is no significant variation in FSD with distance from the ridge. The FSD are instead well aligned with the direction of Pacific plate motion and with results from the Pacific plate west of the Gorda ridge and south of the Mendocino Fracture Zone. This implies that asthenospheric flow beneath the Gorda plate, west of the trench, is determined by the regional pattern of shearing induced by the north-westward motion of the Pacific plate, which moves at $\sim 60\text{mm/yr}^{22}$. An alternative suggestion posits that because flow in this region is ridge perpendicular, it is driven primarily by spreading of the Gorda ridge. This is less likely given the apparent limited influence of the faster-spreading Juan-de-Fuca plate on the splitting pattern to the north. The splitting geometry on Gorda does not

suggest major contributions from motion of the plate itself or rollback of the trench, which operates at less than half the speed of the Pacific plate.

The uniform, subduction-parallel splitting pattern seen on the North American plate east of the trench is interpreted as a consequence of entrained mantle material beneath the down-going slab. Fossil anisotropy in the continental lithosphere and subducted slab has been shown to be insufficient to explain the observed high delay times⁴, thus implying an asthenospheric source⁴. Furthermore, the mantle wedge is thin or non-existent within most of study area, so the only region thick enough to produce delay times commensurate to those observed is the sub-slab mantle^{3,4}. Nevertheless, onshore FSD tend towards North American APM at great distances from the trench (figure 2b), suggesting some influence from plate-motion induced flow in the mantle wedge, or from lithospheric anisotropy. There is no significant change in delay times, however (supplementary information, S8).

Immediately east of the trench of the Juan-de-Fuca plate, splitting geometry rotates smoothly from an APM-parallel direction into a trench-perpendicular direction. This is indicative of entrained easterly flow beneath the slab. In contrast, **across the Gorda-North America plate boundary** there is a sharp change in FSD (figure 2a). This is difficult to justify with a single layer interpretation because it would imply dramatic changes in flow direction. Instead, this region could host two layers of mantle flow: A shallow layer induced by motion of the Pacific plate and a deeper layer related to entrainment by the subducting slab.

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184 Our observation provides a test for the models of Conrad et al.¹ and Debayle &
185 Ricard²³, which suggest that plates moving slower than 40mm/yr²³ and within
186 500km of a constructive plate margin¹ are less able to influence asthenospheric
187 flow. Both Gorda and Juan-de-Fuca meet these criteria, so the observation that Juan-
188 de-Fuca does affect the asthenosphere perhaps sets lower bounds on the age and
189 speed of a tectonic plate that can induce asthenospheric flow.

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191 The Gorda plate is young ($< 10\text{My}^{24}$), has a low absolute velocity²², is undergoing
192 internal deformation²⁴ and may have had its current APM for less than 2Ma^{24} . In
193 contrast, the neighboring Pacific plate is large, intact and fast moving. We have
194 constructed a 2D model of this situation using the method of Hager & O'Connell²⁵ to
195 show that Pacific plate motion is capable of generating westward flow beneath the
196 width of the Gorda plate, assuming that flow is largely confined to the uppermost
197 mantle within a thin, low viscosity asthenosphere (viscosity contrast 100, channel
198 thickness 100 km^{26} – see methods) beneath Gorda. This simple model demonstrates
199 the plausibility of our interpretation of the splitting pattern (figure 3).

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201 This leads to discussion of the arcuate spitting geometry observed south of the MTJ
202 and interpreted as flow forced eastwards around the slab edge by rollback⁴. This
203 pattern, however, could be asthenospheric flow induced by drag from the N60°W
204 drifting Pacific plate. A larger scale arcuate splitting pattern, situated much further

east, may instead be the result of deep toroidal flow around the slab edge, which extends below 400km in this region¹⁷ (supplementary information, S9)

In summary, we propose that the splitting observed on the Juan-de-Fuca plate system is mainly the result of APM-driven asthenosphere flow. At depth, below the Cascadia fore-arc, the downgoing slab entrains underlying mantle material. West of the subduction zone, the Juan-de-Fuca plate is sufficiently large and fast moving to influence mantle flow geometry while the Gorda plate is not. Flow directly beneath Gorda is instead induced by Pacific plate motion. This places bounds on the size of plate capable of inducing asthenospheric flow.

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Acknowledgements

The data used in this research was provided by instruments from the Ocean Bottom Seismograph Instrument Pool (<http://www.obsip.org>), which is funded by the National Science Foundation under cooperative agreement OCE-1112722. The work benefitted from discussions with J. Lodewyk, A. Frassetto and C. Eakin. We also thank the editor and three anonymous reviewers for their helpful comments. GMT (Wessel & Smith²⁷) and MATLAB where used to create the figures.

Author contributions

This study was carried out and written up by Robert Martin-Short, under supervision of Richard Allen. Ian Bastow assisted with data analysis and helped write the paper. Eoghan Totten and Mark Richards provided advice and minor modifications to the text.

Competing financial interests statement

I declare that the authors have no competing interests as defined by Nature Publishing Group, or other interests that might be perceived to influence the results and/or discussion reported in this article.

Figure captions

Figure 1

Stacked splitting results determined by this study (red bars) and previous work (back bars; from Eakin et al.⁴ and Wustefeld et al.²⁸).

The displayed tomography is a 100-400km vertical average through the DNA13 P-wave velocity model of Porritt²⁹. This depth range corresponds to that part of the asthenosphere considered most likely to be the source of the observed anisotropy⁹. All splits are plotted at seismography station/OBS locations. Black lines indicate plate boundaries, while the red lines are slab depth contours spaced at 10km intervals³⁰. Black arrows show the direction and magnitude of absolute plate motion in a hotspot reference frame²³, while purple arrows show the subduction direction⁴. Insert maps show regions featuring a high concentration of splitting results.

Figure 2

Two distinct patterns in the variation of splitting fast directions with distance from the trench.

2A displays results with latitudes between the Mendocino Triple Junction (MTJ) and the southern tip of the Blanco Fracture Zone. 2B shows sites between latitudes of the southern and northern tips of the Juan-de-Fuca ridge. In 2A, one population of

splits lies west of the trench and is aligned with Pacific plate motion, while another aligns with the subduction direction. 2B shows continuous variation in splitting direction with trench distance. Blue and red markers indicate offshore and onshore results respectively. **Error bars indicate the 95% confidence interval.**

Figure 3

Two-dimensional modeling to simulate mantle flow below the Gorda plate as induced by motion of the Pacific plate.

The green plate is stationary while the red plate moves to the left at 60mm/yr. This approximates the situation in profile perpendicular to the Gorda ridge (see methods for more detail). The setup consists of an ‘asthenosphere’ from 50-150km and an ‘mesosphere’ below. In our preferred model (3A), the viscosity of the mesosphere is 100 times that of the asthenosphere.

3B shows details of the model set-up, including the imposed periodic surface velocity field, region of interest and large scale induced flow structure. The motion of the red plate is seen to generate flow beneath the adjacent stationary plate.

Methods

Shear wave splitting

We determine the splitting parameters ϕ and δt for each station-event pair using Splitlab³¹ and SHEBA³². Splitlab uses three standard techniques: the rotation-correlation method (RC; Bowman and Ando³³), the minimum energy method (SC;

Silver and Chan⁸⁾ and the eigenvalue method (EV; Silver and Chan⁸⁾). This allows measurement classification as 'good', 'fair' or 'poor' according to the criteria of Wustefeld & Bokelmann³⁴. SHEBA uses the eigenvalue method alone and incorporates a cluster analysis algorithm, thus decreasing subjectivity in phase arrival picking³². A total of 631 'fair' or 'good' measurements were made and subsequently stacked using the method of Wolfe and Silver³⁵. This number includes high quality null results, which occur where the anisotropy is very weak, or aligned parallel or perpendicular to the initial polarization of the seismic wave³⁴ (see supplementary information S3 and S5 for more information). We used events with moment magnitudes greater than 6.0 and with epicentral distances of between 85 and 130 degrees. Teleseismic SKS and SKKS phases were utilized because their passage through the core as P-waves removes source-side anisotropic effects⁷. Given that the lower mantle is approximately isotropic, the main splitting signal source observed in teleseismic studies is likely within the upper 400km of earth structure, directly beneath the seismometers⁷.

The short deployment time of the OBS stations and small number of high quality splitting results obtained limits backazimuthal convergence and makes difficult to model this dataset with more than a single layer of anisotropy. Given this constraint, we chose not to include information about backazimuth in the stacking process.

Shear wave splitting of OBS data is complicated by the potential for component misorientation (e.g. Lodewyk¹⁴). This arises because OBS instruments settle on the

seabed in unknown orientations that must be determined after recovery in order to rotate the horizontal components into the true 'East' and 'North' directions. The horizontal orientations of the Cascadia Initiative and X9 stations were determined using the surface wave polarization method of Stachnik³⁶. The accuracy of the results was then checked during the splitting process by comparing initial polarization estimates to backazimuth directions and ensuring separation of approximately 0 or 180 degrees.

A further check on the orientations can be carried out by virtue of how the three methods respond to misaligned components³⁷. It has been shown that EV and RC splitting time estimates are unaffected by component misorientation, whereas small inaccuracies in orientation introduce large errors for the SC method³⁷. Our measurements were only characterized as 'good' or 'fair' when there was satisfactory agreement between the delay time predictions of the three methods. SC method results are reported singularly in this paper because this technique has been determined to be least sensitive to noise and exhibits the highest accuracy proximal to null measurements³⁴.

High levels of long period noise are present in the OBS data^{12,13}. Filtering was used to optimize noise reduction without unduly compromising the splitting measurements. The characteristic frequency of teleseismic SKS waves ranges between 0.08-0.13 Hz but most onshore studies utilize bandpass filters such as 0.02-0.20Hz, which capture the full range of SKS energy^{3,7}. The presence of strong 0.16-

0.2Hz secondary microseismic noise peaks in the OBS data¹², however, means that such filter bands are not typically useful in this case. OBS data is further affected by strong compliance noise ranging from 0.01 - 0.04Hz, attributed to infragravity waves¹¹. This suggests an optimal filter band close to the ‘noise notch’ of 0.03-0.1Hz, as identified by Webb¹³. Typically we choose a region of 0.05-0.15Hz, but employ frequencies between 0.03 and 0.18Hz on an event-by-event basis to optimize the signal-to-noise ratio (SNR). In order to limit subjectivity many events had their splitting parameters determined in multiple frequency bands and multiple time windows. Only events with SNR greater than 4.0 were used in the stack. Upper filter corner frequencies below 0.14Hz were omitted to avoid signal energy reduction, which makes measurements appear increasingly null. For further details, see S2-S5 of the supplementary information.

Geodynamic modeling

Our simple two-dimensional (2D) model of the mantle flow field beneath diverging plates was constructed as a test of our interpretation of the splitting geometry observed beneath the Gorda plate. The propagator matrix method for 2D periodic flow given in the appendix of Hager and O’Connell²⁵ was used to solve for instantaneous, incompressible, Newtonian viscous (Stokes) flow with piecewise-constant horizontal (plate) motions imposed at the top of the mantle. Solutions are obtained in Fourier series form with periodic boundary conditions horizontally. To approximate the situation along a profile perpendicular to the Gorda ridge, we

430 model one plate as stationary while the other diverges at a constant speed
431 (60mm/yr). We focus on flow within a 400km horizontal window centered at the
432 velocity jump, and choose a horizontal periodic boundary condition whose
433 fundamental length scale is much larger than this window length (Figure 3, bottom
434 panel). We follow Richards et al.³⁸ by assuming a two-layer structure featuring a
435 thin, low viscosity and thick, underlying mantle layer. We base our viscosity contrast
436 and layer thickness estimates (100km and a viscosity contrast of 100) on the work
437 of Fjeldskaar²⁶, although we acknowledge that the width and viscosity of the
438 asthenosphere is poorly constrained (supplementary information, S10). Recent
439 seismic constraints, especially seismic anisotropy studies beneath the Pacific Plate³⁹
440 , suggest strongly that the base of the highly anisotropic asthenosphere is at
441 approximately 200 km depth, which is consistent with geodynamic constraints as
442 long as the viscosity contrast is at least 2-3 orders of magnitude⁴⁰. Thus, our choice
443 remains somewhat arbitrary, although the thickness and viscosity parameters we
444 employ reflect the findings of recent studies. Our model extends to 660km in depth,
445 where the vertical flow field is set to zero at the bottom of the layer. Figure 3A
446 shows our preferred model, where the asthenosphere viscosity is reduced by a
447 factor of 100. The model does not account for complicated features such as the 3D
448 plate geometry or the subduction zone, but clearly the weak asthenosphere causes
449 flow to be induced immediately beneath the stationary plate that is strongly aligned
450 with motion of the moving plate. We therefore propose that the large, fast-moving
451 Pacific plate induces asthenospheric flow beneath the small, fragmented, slow-
452 moving Gorda plate that is strongly aligned with Pacific plate motion, as observed.

Data availability

The facilities of IRIS Data Services, and specifically the IRIS Data Management Center, were used for access to waveforms, related metadata, and/or derived products used in this study. IRIS Data Services are funded through the Seismological Facilities for the Advancement of Geoscience and EarthScope (SAGE) Proposal of the National Science Foundation under Cooperative Agreement EAR-1261681

The DNA13 North American tomography model, which was used in the creation of figure 1, can be downloaded from

<http://seismo.berkeley.edu/~rallen/pub/2014porritt/data.php>

The high-resolution bathymetry/topography dataset used in the creation of supplementary information S2A was obtained from http://www.gebco.net/data_and_products/gridded_bathymetry_data/gebco_30_second_grid/

Shear wave splitting measurements from previous studies were obtained from

<http://splitting.gm.univ-montp2.fr/DB/>

We plan to add our new results to this database.

Code availability

The shear wave splitting software packages *Splitlab* and *Sheba* are publically available:

The version of *Splitlab* used in this project can be downloaded from <https://robporritt.wordpress.com/software/>

Sheba can be downloaded from <https://github.com/jwookey/sheba>

The code used to orient the OBS instruments can be obtained from <http://www.obsip.org/data/obs-horizontal-orientation>

We have opted not to make the code associated with our geodynamic modeling study available because it is tailored to a very specific situation and more generic software based on the method of Hager & O’Connell²⁵ is already widely available. However, we would be happy to provide our code if requested by email.

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