

# Upper and mid-mantle anisotropy beneath the Tonga slab

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[1] Measurements of source-side splitting in S waves from events within the Tonga slab reveal anisotropy in the upper and mid-mantle beneath the slab. We observed splitting for events originating at both upper mantle and transition zone depths. Anisotropic fast directions ( $\phi$ ) are trench parallel or sub-parallel for both upper mantle and transition zone events. Delay times ( $\delta t$ ) decrease with depth for upper mantle events. The source of anisotropy for the upper mantle events is likely in the sub-slab mantle, and is likely indicative of trench parallel flow due to slab rollback. The source of anisotropy for the deeper earthquakes is more difficult to constrain, but the pattern of splitting measurements argues for an uppermost lower mantle anisotropic source, and slab induced deformation may be responsible for this anisotropy as well. Additional constraints from mineral physics studies are necessary to interpret the mid-mantle anisotropy signal in terms of geodynamical processes. **Citation:** Foley, B. J., and M. D. Long (2011), Upper and mid-mantle anisotropy beneath the Tonga slab, *Geophys. Res. Lett.*, 38, L02303, doi:10.1029/2010GL046021.

## 1. Introduction

[2] Measurements of seismic anisotropy in subduction zones can place constraints on mantle flow in these regions, which in turn yields insights about subduction zone geodynamics. Many measurements of shear wave splitting in subduction zones have been made, and these often show fast directions ( $\phi$ ) parallel to the trench, instead of the convergence-parallel  $\phi$  that would be expected from the simplest two-dimensional corner flow model. There are many possible interpretations of these observations; possible models include trench-parallel flow in the mantle due to trench migration [e.g., Long and Silver, 2008] and serpentinized cracks in the subducting slab [Faccenda et al., 2008]. To evaluate these models, it is necessary to place tight constraints on the depth distribution of anisotropy in subduction zones.

[3] If trench-parallel anisotropy does represent flow around a retreating (or advancing) slab, then there should be flow-induced anisotropy both above and beneath the slab. Anisotropy above the slab, i.e., in the mantle wedge, is likely to be influenced by water, melt, or other complications [e.g., Jung and Karato, 2001] and has been commonly measured in various subduction zones [e.g., Smith et al., 2001; Pozgay et al., 2007; Wirth and Long, 2010]. However, there are fewer direct constraints on anisotropy beneath subducting

slabs. Here we present measurements of anisotropy beneath the Tonga slab using source-side splitting from events in the slab (Figure 1). Tonga is an attractive target for such a study, since it has abundant seismicity at a range of depths, and because the northern Tonga trench has a fast migration velocity (retreating at  $\sim 10$  cm/yr [Schellart et al., 2008]). The global model of Long and Silver [2008, 2009] predicts strong trench-parallel sub-slab mantle flow in this system, a prediction we test here.

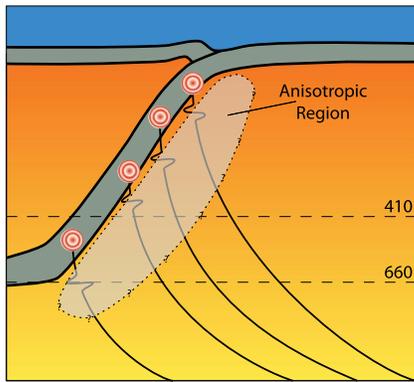
## 2. Methods

[4] To efficiently probe sub-slab anisotropy, we measure splitting in direct S waves from events originating within the Tonga slab and recorded at stations in western North America. These stations are located at epicentral distances of  $\sim 80^\circ$  from the events, ensuring that S waves have an incidence angle of less than  $35^\circ$  at the surface and do not pass through the D'' region, which might have significant anisotropy. As long as anisotropy beneath the receiver is properly accounted for [e.g., Russo, 2009; Russo et al., 2010], the remaining signal can be attributed to anisotropy near the source.

[5] Western North America has been shown to have complex SKS splitting [e.g., Polet and Kanamori, 2002; Long, 2010]; so we preferentially chose stations with predominantly null splitting patterns or small  $\delta t$  ( $< 0.5$  sec) in previous studies. We used a total of seven stations, five in southern California and two in Baja, Mexico (Figure 2). At these stations, the contribution to splitting from the receiver side should be minimal at periods greater than 8–10 sec. Figure 2 shows null SKS splitting measurements at these stations, from this study and from Long [2010]. While the SKS splitting patterns are overwhelmingly dominated by nulls, stations PHL, BBR, LVA2, and MONP also exhibited a few non-null splits (auxiliary material).<sup>1</sup> There is, therefore, the possibility of some small contamination from receiver-side anisotropy at these stations.

[6] S wave splitting measurements were made with the eigenvalue method and the cross-correlation method simultaneously using the software package SplitLab [Wüstefeld et al., 2008]. Data were initially bandpass filtered between 8–10 and 25–100 seconds; adjusting for each waveform to better enhance the signal to noise ratio. Only waveforms showing a clear shear wave pulse were used and we only retained measurements for which the splitting results were consistent between the two methods within the  $2\text{-}\sigma$  error spaces. Null measurements were characterized by linear uncorrected particle motion. Here, we report measurements obtained using the cross-correlation method, but the results from the eigenvalue method were similar. See the auxiliary

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**Figure 1.** Cartoon sketch of events and ray paths used in this study with the inferred location of the source of anisotropy. Events from within the slab primarily sample anisotropy in the underlying mantle.

material for a more detailed discussion including several example splitting measurements.

### 3. Results

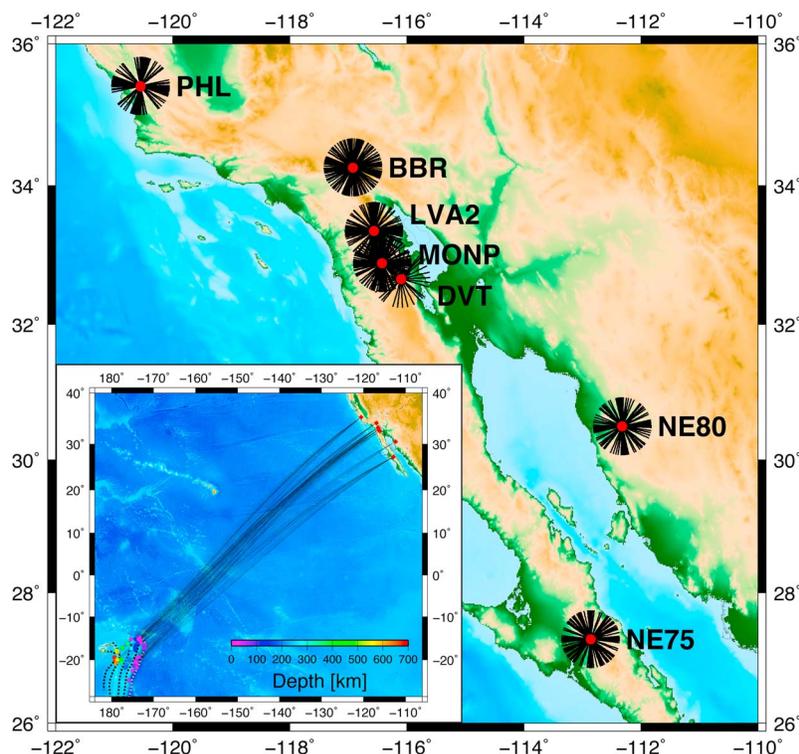
[7] The non-null results for three example individual stations, as well as all the stations combined, are shown in Figure 3. Additional maps for individual stations, along with null measurements, are shown in the auxiliary material. We consider results from the upper mantle and transition zone depths separately. For upper mantle events, which make up a majority (88 %) of the data set, the fast directions are dominantly trench parallel to sub-parallel, with delay times

ranging between  $\sim 0.8$ –4 sec. There is a large amount of scatter in the delay times, but an overall trend of delay times decreasing with depth exists. Using all results, a linear best fit line yields a slope of  $-2.6 \times 10^{-3}$  sec/km with a poor correlation coefficient of  $R = 0.346$ . However, averaging the delay times in 40 km depth bins reduces the scatter, and produces a nearly identical slope with a correlation coefficient of  $R = 0.848$  (Figure 4). This slope corresponds to  $\sim 0.26$  sec of splitting per 100 km in the upper mantle, or roughly 1 % average anisotropy. However, given the amount of scatter in the data set, significant lateral or depth heterogeneity is likely.

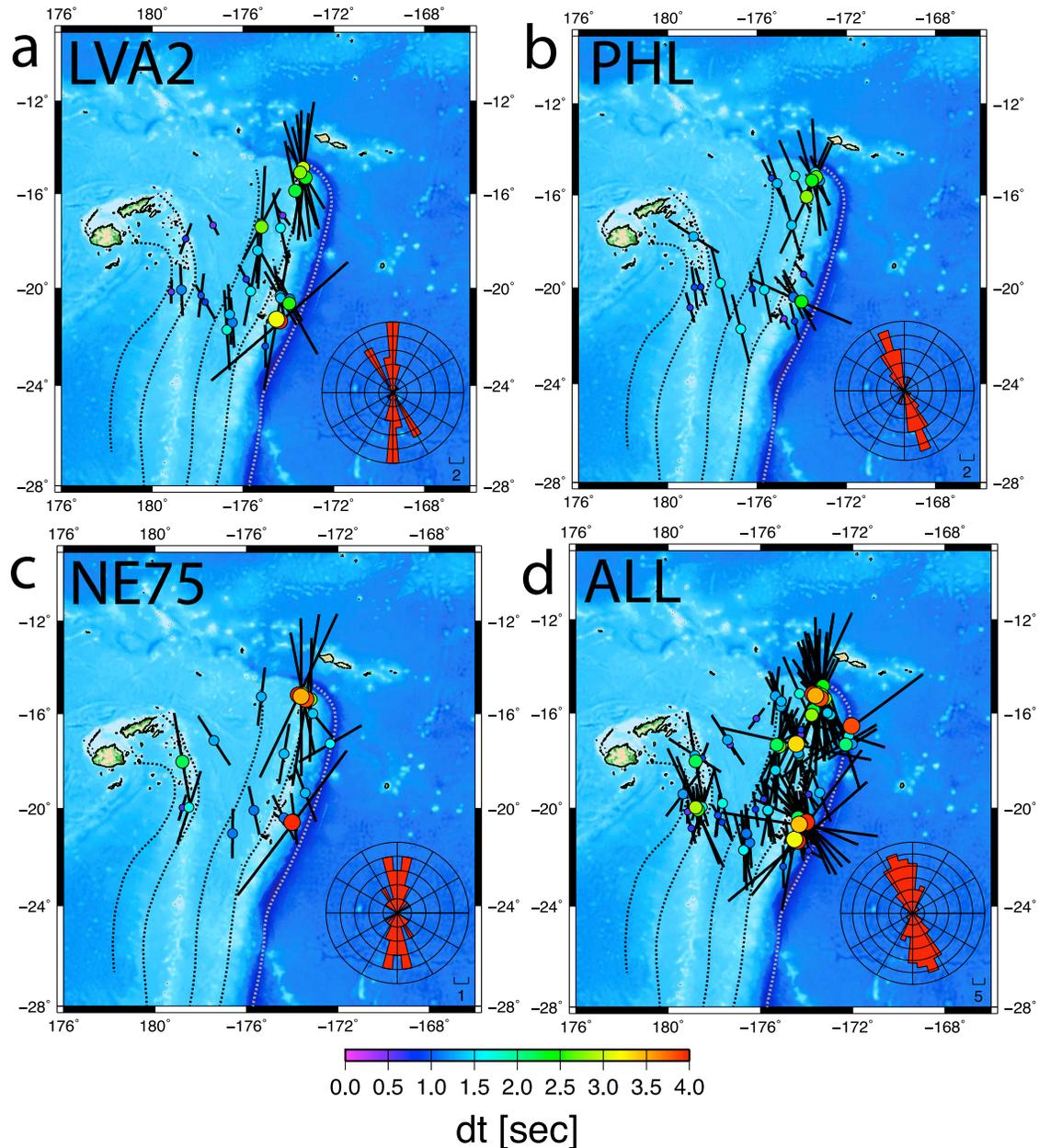
[8] There are significantly fewer measurements for events in the transition zone since there is less seismicity, and these events fall outside of the preferred distance range for some stations. Fast directions are dominantly trench parallel or sub-parallel, similar to the upper mantle results, with delay times typically larger than for events in the lower upper mantle (Figure 4). There is no obvious trend in  $\delta t$  with depth, but several measurements from the lower transition zone exhibit significant splitting.

### 4. Discussion

[9] To properly interpret these results, we must consider the possible sources of anisotropy, and therefore its inferred mechanism. We can rule out a primary contribution from anisotropy beneath the receiver, because the stations used in this study exhibit overwhelmingly null SKS splitting for a wide range of backazimuths. The bulk of the lower mantle is thought to be isotropic [e.g., *Meade et al.*, 1995], so the splitting most likely occurs in the mantle beneath the slab, or



**Figure 2.** Event and station locations used in this study. Null SKS splitting measurements for each station are shown from Long [2010] and this study. Inset: Map of station-event great circle paths. Events are colored by depth and Tonga trench slab contours at 100, 300, 500, and 700 km depth are plotted.



**Figure 3.** Splitting results for Tonga slab events for stations (a) LVA2, (b) PHL, (c) NE75, and (d) all stations. Fast directions are reflected over the backazimuth to transform  $\phi$  into the reference frame of the downgoing ray at the source and plotted at the event location in horizontal projection. Circular histograms show fast direction distribution. Contours of the Tonga slab (dashed black) at 100, 300, 500, and 700 km depth, and the Tonga trench (dashed gray) are shown.

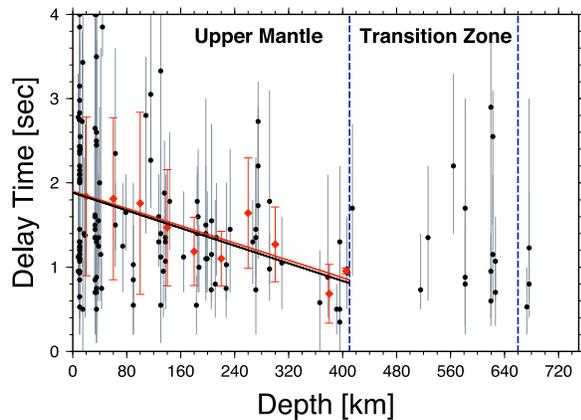
in the slab itself. As in our presentation of the results, we consider measurements from events in the upper mantle separately from those in the transition zone.

#### 4.1. Upper Mantle Anisotropy: Sub-slab Flow due to Trench Migration

[10] Since the events used in this study do travel through the slab for  $\sim 50$ – $100$  km before entering the sub-slab mantle, a primary question is whether splitting is due to anisotropy in the sub-slab mantle or the slab itself. *Faccenda et al.*'s [2008] model proposes that the dominant anisotropic signal in subduction zones comes from serpentinized normal faults cutting through the slab. In this case, delay times should be uncorrelated with event depth, as the

splitting is controlled by path length through the slab. Furthermore, antigorite is likely not stable below  $\sim 100$ – $150$  km, and our results show consistent upper mantle anisotropy below this depth. We infer, therefore, that while anisotropy in the slab may make a small contribution to the splitting we observe, it is not the dominant effect.

[11] We interpret the trench-parallel splitting as being due to anisotropy in the sub-slab mantle, associated with a trench-parallel mantle flow in an A type or similar olivine fabric regime [*Karato et al.*, 2008] beneath the Tonga slab. *Long and Silver* [2008, 2009] proposed that mantle flow, and therefore anisotropy, beneath most subducting slabs is controlled by the retreat (or advance) of the slab. The Tonga trench is one of the fastest moving trenches on Earth, so



**Figure 4.** Delay time,  $\delta t$ , plotted with depth for all non-null measurements (black circles). Nominal 410- and 660-km discontinuity depths are shown with dashed lines.  $2\text{-}\sigma$  formal errors on individual measurements are shown. A best fit line for all upper mantle results is shown in black, as well as average  $\delta t$  for 40 km depth bins (red diamonds, with  $2\text{-}\sigma$  error bars) and a best fit line for the binned averages (red). Events that originate at transition zone depths do not show a convincing trend, but  $\delta t$  is large for some events ( $\sim 1\text{--}3$ ).

Long and Silver's [2008, 2009] model predicts strong trench parallel flow and anisotropy beneath this slab. The observations presented here support such a model. We note that local S splitting measurements show evidence for trench-parallel flow above the northern Tonga slab as well [Smith *et al.*, 2001].

#### 4.2. Anisotropy in the Transition Zone and Uppermost Lower Mantle

[12] Our results also show splitting, typically with delay times of  $\sim 1\text{--}3$  seconds and a trench parallel fast direction, from earthquakes originating at transition zone depths. As with the upper mantle events, the anisotropy we measure is most likely in the sub-slab mantle; therefore, these results indicate anisotropy in the transition zone and/or uppermost lower mantle beneath the Tonga slab (Figure 1). Only a few studies have found robust observations of anisotropy in the mid-mantle. For example, Trampert and van Heijst [2002] found evidence for transition zone azimuthal anisotropy from an inversion of global surface wave overtone data. Wookey and Kendall [2004] measured mid-mantle anisotropy using S wave splitting from Tonga events measured in Australia, an approach similar to our own. Finally, Chen and Brudzinski [2003] found transition zone anisotropy near Tonga, measuring S waves from deep events at local stations. Both body wave studies indicate mid-mantle anisotropy in the back arc region (above the subducting slab), while our results indicate similar anisotropy beneath the slab (see auxiliary material for a more detailed discussion).

[13] Interpreting observations of mid-mantle anisotropy is difficult, because experiments and models on the formation of LPO at transition zone and lower mantle conditions are in their infancy [e.g., Mainprice, 2007; Tommasi *et al.*, 2004]. Wadsleyite is a possible source of anisotropy in the upper transition zone, while ringwoodite does not have significant intrinsic anisotropy [e.g., Mainprice, 2007] and the possibility for anisotropy in perovskite is poorly known. We

observe splitting from events below the wadsleyite stability field (Figures 3 and 4), so the source must lie in the lower transition zone or in the uppermost lower mantle. Given the ray path geometry in our study (Figure 1), the anisotropy is most likely due to deformation in the uppermost lower mantle, perhaps induced by the subducting slab.

#### 5. Conclusions

[14] Source-side shear wave splitting measurements on teleseismic S waves show trench-parallel anisotropic fast directions beneath the Tonga slab. These fast directions most likely correspond to trench-parallel sub-slab mantle flow, because the observed pattern of delay times with depth argues for a source in the sub-slab upper mantle, which should be dominated by A, C, or E-type olivine fabric [Karato *et al.*, 2008]. The observations support sub-slab flow induced by slab rollback, as proposed by Long and Silver [2008, 2009]. Splitting from deep earthquakes (410–680 km) is also observed, which we attribute to anisotropy in the lower transition zone or uppermost lower mantle. This anisotropy may be indicative of mid-mantle flow or interaction with the downgoing slab, though further experimental constraints on the deformation mechanisms of transition zone and lower mantle minerals are needed to interpret the results in terms of geodynamical processes.

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