Geochemistry, Geophysics, Geosystems

DATA ARTICLE
10.1029/2023GC011070

# Global Compilation of Deep Mantle Anisotropy Observations and Possible Correlation With Low Velocity Provinces

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**Key Points:**

- We compile a global digital database of seismic anisotropy observations in the D′′ layer
- We compute the global ray coverage of different methods used to detect deep mantle anisotropy
- In the context of a global compilation, there is no preferential occurrence of seismic anisotropy at large-low velocity province edges

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**Citation:**
Wolf, J., Long, M. D., Li, M., & Garnero, E. (2023). Global compilation of deep mantle anisotropy observations and possible correlation with low velocity provinces. *Geochemistry, Geophysics, Geosystems*, *24*, e2023GC011070. https://doi.org/10.1029/2023GC011070

Received 31 MAY 2023
Accepted 13 SEP 2023

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**Abstract** We compile and make publicly available a global digital database of body wave observations of seismic anisotropy in the D′′ layer, grouped using the method used to analyze deep mantle anisotropy. Using this database, we examine the global distribution of seismic anisotropy in the D′′ layer, evaluating the question of whether seismic anisotropy is more likely to be located at the edges of the two large-low velocity provinces (LLVPs) in Earth's mantle than elsewhere. We show that this hypothesis lacks statistical justification if we consider previously observed lowermost mantle anisotropy, although there are multiple factors that are difficult to account for quantitatively. One such factor is the global lowermost mantle ray coverage for different phases that are commonly used to detect deep mantle anisotropy in shear wave splitting studies. We find that the global ray coverage of the relevant seismic phases is highly uneven, with LLVP edges and their interiors less well-sampled than the global average.

**Plain Language Summary** Seismic waves caused by earthquakes sometimes travel at different speeds in different directions. This material property, called seismic anisotropy, indicates convective flow and deformation in the mantle and has been detected in the lowermost mantle. We compile a database of lowermost mantle anisotropy locations from the previously published literature. Previous studies have reported strong seismic anisotropy at the edges of large features with lower than average seismic velocities in Earth's mantle, called large-low velocity provinces. Here, we test whether seismic anisotropy is also more likely at large-low velocity province edges than elsewhere. Our statistical analysis of our database suggests that this may not be the case. This analysis, however, did not explicitly account for the fact that the number of seismic waves traveling through the lowermost mantle is different from region to region.

## 1. Introduction

Seismic anisotropy, or the directional dependence of seismic wave speed, has been detected at a range of depths in the Earth. For example, the crust (e.g., Barruol & Kern, 1996; Erdman et al., 2013) and the upper mantle (e.g., Savage, 1999; Silver, 1996; Zhu et al., 2020) are anisotropic in many regions. While the bulk of the lower mantle appears largely isotropic (e.g., Chang et al., 2015; Panning & Romanowicz, 2006), seismic anisotropy has been found in the lowermost 200–300 km of the mantle (e.g., Asplet et al., 2023; Lay et al., 1998; Nowacki et al., 2010; Wolf & Long, 2022; Wookey et al., 2005), known as the D′′ layer. Seismic anisotropy can be induced by deformation and alignment of minerals due to mantle convection. Thus, observations of seismic anisotropy are helpful to infer dynamic processes in Earth's interior (e.g., Long & Becker, 2010). Seismic anisotropy can be detected through the analysis of shear waves, specifically how they split into fast and slow components in the presence of anisotropy (e.g., Long & Silver, 2009).

Through analyses of deep mantle anisotropy, better knowledge about flow patterns at the base of the mantle can be obtained, potentially elucidating several big-picture aspects of mantle dynamics, such as the origin and evolution of large-low velocity provinces (LLVPs), the fate of subducted slabs, and core-mantle boundary (CMB) heat flow (e.g., Bercovici & Karato, 2003; Hernlund et al., 2005; Wenk & Romanowicz, 2017; Wolf & Evans, 2022). Based on several previous regional studies (e.g., Cottaar & Romanowicz, 2013; Deng et al., 2017; Lynner & Long, 2014; Reiss et al., 2019; Wang & Wen, 2004), it has been suggested that lowermost mantle anisotropy is particularly strong, and thus easily observable, near LLVP edges (e.g., Reiss et al., 2019; Wenk & Romanowicz, 2017). This may reflect strong deformation, perhaps due to mantle flow impinging on their sides (e.g., Li & Zhong, 2017; McNamara et al., 2010), or due to the generation of mantle plumes at LLVP edges (e.g., Li & Zhong, 2017; Steinberger & Torsvik, 2012). Subducting slabs likely represent one of the main drivers of

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flow and deformation at the base of the mantle (e.g., Bercovici & Karato, 2003; Chandler et al., 2021; McNamara et al., 2002; Tackley, 2000), and several studies have identified seismic anisotropy associated with slab remnants at the base of the mantle (e.g., Long, 2009; Nowacki et al., 2010; Wolf & Long, 2022), in locations away from LLVP edges. More observations, with increased resolution of anisotropic regions of the lowermost mantle, will continue to shed light on the patterns and drivers of flow in the deepest mantle, the interactions among different deep mantle structures (e.g., LLVPs, hotspots, ULVZs, and subducted paleoslabs), and their respective roles in deep mantle dynamics and evolution.

In this study, we compile a global digital database of seismic anisotropy locations in the D′′ layer that have been detected to date (Table 1; Figure 1). We make this database openly available on GitHub (https://github.com/wolfjonathan/Deep_Mantle_Anisotropy_Database) and in a data repository (Wolf et al., 2023c), in the hope that it will enable future investigations of D′′ anisotropy in the context of deep mantle composition and dynamics. We use these global data set to investigate whether there is a statistical spatial correlation between D′′ anisotropy locations and edges of LLVPs, as has been suggested previously (e.g., Wenk & Romanowicz, 2017).

## 2. Strategies to Analyze Deep Mantle Anisotropy

D′′ anisotropy has been explored with different strategies using a variety of seismic body wave phases (Figure 2). These splitting methods have been refined over time, and their strengths and weaknesses were explored and different pitfalls were pointed out. We distinguish between these different methods in our database (Table 1; Figure 2). The increasing availability of computing resources enables detailed assessments of existing methods to analyze deep mantle anisotropy as well as the development of new strategies (e.g., Komatitsch et al., 2010; Nowacki & Wookey, 2016; Parisi et al., 2018; Wolf et al., 2022a, 2022b, 2023b).

Many early studies measured differential SV-SH travel times from teleseismic S, ScS and $S_{diff}$ waves (Figure 2a), which are interpreted as being due to D′′ anisotropy (e.g., Kendall & Silver, 1998; Pulliam & Sen, 1998; Rokosky et al., 2004). Recent studies, however, have demonstrated that under some circumstances, differential SV-SH travel times can also be caused by isotropic structure (e.g., Borgeaud et al., 2016; Komatitsch et al., 2010; Parisi et al., 2018) for waves that are initially polarized to have both SV and SH energy. Therefore, it is unclear to what extent previously reported SV-SH differential times conclusively require deep mantle anisotropy.

Additionally, measurements of polarities of S phases that turn in the lowermost mantle (Figure 2b) have been used to infer deep mantle anisotropy (e.g., Garnero, Maupin, et al., 2004; Maupin et al., 2005). Later studies expanded polarity analyses to consider D′′-reflected SdS and PdP waves (Figure 2b; e.g., Pisconti et al., 2019; Thomas et al., 2011). Some of these studies show that changes in polarity are likely caused by the presence of seismic anisotropy (e.g., Garnero, Maupin, et al., 2004; Maupin et al., 2005), and others use polarities of reflected waves as an additional constraint on the nature of an anisotropic D′′ region along with a different method (Pisconti et al., 2019, 2023).

Wang and Wen (2004) and Niu and Perez (2004) were among the first studies to interpret differences in SKS and SKKS splitting in terms of deep mantle anisotropy. This technique became increasingly useful when applied to larger data sets (e.g., Deng et al., 2017; Long, 2009). The SKS-SKKS differential splitting technique relies on the argument that the raypaths of SKS and SKKS are similar in the upper mantle; therefore, large differences in splitting between these phases can generally be attributed to anisotropy in the lowermost mantle. This assumption is generally valid if the difference in splitting due to deep mantle anisotropy is sufficiently large (e.g., Tesoniero et al., 2020), although it has been shown that small differences in SKS-SKKS splitting can be due to upper mantle structure (e.g., Lin et al., 2014).

Wookey et al. (2005) developed the S-ScS differential splitting technique, which has been widely used since then (e.g., Asplet et al., 2023; Creasy et al., 2017; Nowacki et al., 2010; Pisconti et al., 2023). This method exploits the fact that S and ScS waves have very similar raypaths in the upper mantle beneath the source and receiver. However, only ScS potentially experiences shear wave splitting due to deep mantle anisotropy and this contribution can be extracted by comparison to S splitting. The validity and potential pitfalls of this method have been thoroughly investigated using full-wave simulations (Nowacki & Wookey, 2016; Wolf et al., 2022a, 2022b). It has been demonstrated that the initial implementation of the S-ScS differential splitting technique, which does not explicitly account for the radial component phase shift due to the CMB reflection, can introduce apparent splitting under certain circumstances even when D′′ anisotropy is not present (Wolf et al., 2022a). Specifically,

**Table 1**
*Studies (First Column) That Have Suggested the Presence of Deep Mantle Seismic Anisotropy Based on Body Wave Analysis*

| Study | Region | Modeled flow directions |
|---|---|---|
| **1. Differential SV-SH travel times (S, $S_{diff}$, ScS)** | | |
| Lay and Helmberger (1983)$^{iso}$ | Caribbean | No |
| Lay and Young (1991) | Alaska | No |
| Vinnik et al. (1995) | Central Pacific | No |
| Kendall and Silver (1996) | Caribbean | No |
| Matzel et al. (1996) | Alaska | No |
| Ding and Helmberger (1997) | Caribbean | No |
| Garnero and Lay (1997) | Alaska | No |
| Vinnik et al. (1998) | Central Pacific | No |
| Ritsema et al. (1998) | Central Pacific | No |
| Pulliam and Sen (1998) | Central Pacific | No |
| Russell et al. (1998) | Central Pacific | No |
| Kendall and Silver (1998)$^{iso}$ | Central Pacific | No |
| Russell et al. (1999) | Central Pacific | No |
| Wysession et al. (1999) | Alaska | No |
| Ritsema (2000) | Indian Ocean | No |
| Fouch et al. (2001) | Alaska | No |
| Thomas and Kendall (2002) | North Asia | No |
| Garnero, Moore, et al. (2004)$^{iso}$ | Atlantic Ocean | No |
| Rokosky et al. (2004) | Caribbean | No |
| Rokosky et al. (2006) | Caribbean | No |
| S. R. Ford et al. (2006) | South Pacific | No |
| Thomas et al. (2007) | Southeast Asia | No |
| Usui et al. (2008) | Antarctic Ocean | No |
| Yang et al. (2008) | North Asia | No |
| **2. Polarities (S, SdS, PdP)** | | |
| Garnero, Maupin, et al. (2004) | Caribbean | No |
| Maupin et al. (2005) | Caribbean | No |
| Thomas et al. (2011) | North Asia; Caribbean | No |
| Pisconti et al. (2019) | Atlantic Ocean | Northeast |
| Pisconti et al. (2023) | Atlantic Ocean | East-Northeast |
| **3. SKS-SKKS-S3KS-PKS differential splitting** | | |
| Wang and Wen (2004) | West Africa | No |
| Niu and Perez (2004) | Single paths across globe | No |
| Long (2009) | Eastern Pacific | No |
| He and Long (2011) | Western Pacific | No |
| Vanacore and Niu (2011) | Northwest Pacific Ocean | Upwelling |
| Lynner and Long (2012) | Central Africa | No |
| Lynner and Long (2014) | Africa; South Europe | No |
| Roy et al. (2014) | Southeast Asia | No |
| Long and Lynner (2015) | East Europe | No |
| H. A. Ford et al. (2015) | West Africa | Horizontal and upwelling |

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**Table 1**
*Continued*

| Study | Region | Modeled flow directions |
|---|---|---|
| Creasy et al. (2017) | Indian Ocean; Antarctic Ocean | Inconclusive; North-northeast/South-southwest |
| Deng et al. (2017) | East Pacific Ocean | No |
| Wolf et al. (2019) | North Europe | Horizontal, upwelling |
| Grund and Ritter (2019) | Central, Northern Europe; North Asia | No |
| Reiss et al. (2019)*iso* | South Europe; Africa | Northwest/Southeast; Southwest, upwelling |
| Asplet et al. (2020) | Northeast Pacific Ocean | No |
| Lutz et al. (2020) | Western USA | ~West |
| Creasy et al. (2021) | North Asia | North-Northeast/South-southwest |
| Wolf and Long (2022) | Northeast Pacific Ocean | South |
| Wolf et al. (2023a) | Northeast Pacific Ocean; Western USA | No |
| Asplet et al. (2023) | Northeast Pacific Ocean | Northwest or Southwest/up-downwelling |
| Wolf and Long (2023) | Southeast Asia | Southwest |
| **4. S-ScS differential splitting** | | |
| Wookey et al. (2005) | Northwest Pacific | No |
| Wookey and Kendall (2008) | North Asia | South |
| Nowacki et al. (2010) | Western USA; Caribbean | No |
| H. A. Ford et al. (2015) | West Africa | Horizontal and upwelling |
| Creasy et al. (2017) | Indian Ocean; Antarctic Ocean | Inconclusive; North-northeast/South-southwest |
| Rao et al. (2017) | Indian Ocean | No |
| Pisconti et al. (2019)*iso* | Atlantic Ocean | Northeast |
| Wolf et al. (2019) | Northern Europe | Horizontal and upwelling |
| Creasy et al. (2021) | North Asia | North-Northeast/South-southwest |
| Wolf et al. (2022a) | East Asia | No |
| Pisconti et al. (2023)*iso* | Atlantic Ocean | East-Northeast |
| Asplet et al. (2023) | Northeast Pacific Ocean | Northwest or Southwest/up-downwelling |
| **5. Regional anisotropic inversions** | | |
| Kawai and Geller (2010) | Central Pacific Ocean | No |
| Suzuki et al. (2021) | North Pacific Ocean; Alaska | No |

*Note*. The table is primarily ordered by the method used to detect seismic anisotropy, and secondarily ordered by the year of publication. The second column indicates the region for which deep mantle anisotropy has been suggested, and the third column lists whether flow directions were modeled, and if so, which directions are considered to be most likely. If *iso* is appended to the study name in the first column, this indicates that the authors interpret at least some of their observations as likely indicative of the absence of D′′ anisotropy. These interpretations are difficult to account for objectively in the context of our compiled database, but we still report them in this table.

measurements are accurate when the source-side anisotropy contribution is absent or small, or when ScS is initially (nearly) completely SH-polarized due to the source mechanism. However, artifacts may be introduced in other circumstances (Wolf et al., 2022a). Furthermore, full-wave (i.e., non-ray theoretical) effects have been shown to be important for heterogeneous anisotropy (e.g., Nowacki & Wookey, 2016; Wolf et al., 2022b).

Anisotropic inversions that focus on a specific region represent another approach to investigate D′′ anisotropy (Kawai & Geller, 2010; Suzuki et al., 2021). Such studies have used full seismic waveforms around the S and ScS arrival times at teleseismic distances to invert for radial anisotropy. These studies, by construction, consider full-wave effects but are sometimes hard to compare to splitting studies due to the simplified assumption of radial anisotropy.

A relatively recent development is the implementation of $S_{diff}$ splitting measurements that explicitly consider the initial source polarization of $S_{diff}$ (e.g., Cottaar & Romanowicz, 2013; Wolf & Long, 2022) (in the following abbreviated as $S_{diff,pol}$ splitting measurements). These measurements are compatible with the results of previous

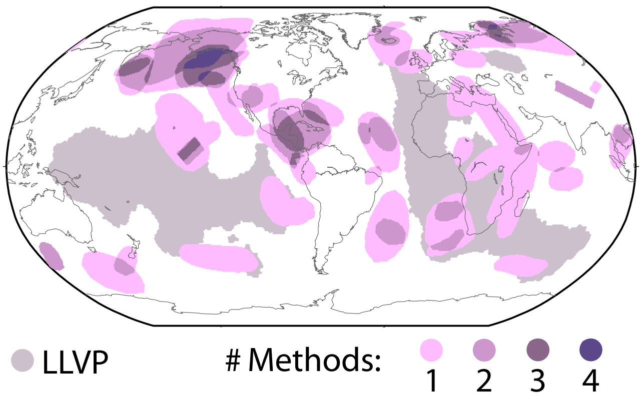


**Figure 1.** Locations for which the presence of deep mantle seismic anisotropy has been suggested in previous studies. The number of methods used to analyze deep mantle anisotropy in these regions is shown with violet shading (see legend), using the method categorization from Table 1. Low velocity features are shown in gray as determined by regions where at least 3 out of 5 tomography models assigned a particular point to a slow cluster at a depth of 2,700 km in the cluster analysis performed by Lekic et al. (2012).

studies that have shown that differential SV-SH times can be accumulated in an isotropic structure (e.g., Borgeaud et al., 2016; Komatitsch et al., 2010; Parisi et al., 2018) and have been tested in detail using global wavefield simulations (Wolf et al., 2023b).

This suite of body wave methods to observe D′′ anisotropy is sensitive to different aspects of anisotropic geometry. For example, the regional anisotropic inversions for D′′ anisotropy that have been conducted to date, by construction, resolve radial anisotropy. Splitting studies, often resolve more complex anisotropy with an azimuthal component; however, the sensitivity to different types of anisotropy depends on the raypath geometry. For example, SKS, SKKS, and ScS waves generally sample D′′ obliquely, but SKS is often closer to vertical and ScS closer to the horizontal (Figure 2), although the details depend on the raypath configurations. Similarly, $S_{diff}$ splitting results have often been interpreted in terms of radial anisotropy. However, using a single measurement, it is impossible to distinguish whether seismic anisotropy is sampled while $S_{diff}$ travels horizontally along the CMB or obliquely through D′′. Therefore, for a single $S_{diff}$ measurement, it is hard to distinguish between radial anisotropy, sampled at the CMB and more complex seismic anisotropy sampled on the upgoing (or downgoing) leg through D′′.

## 3. Compilation of D′′ Anisotropy Locations

We compile and digitize the full set of lowermost mantle locations for which previous studies have suggested the presence of D′′ anisotropy, as presented in the original publications. These locations are hand-digitized based mostly on the figures provided in the studies, but also based on information given in text and corresponding supplementary materials. We present a global map of these previously suggested deep mantle anisotropy locations in Figure 1 and different sub-data sets for different analysis methods in Figures 2a–2f. The reason for distinguishing between different splitting strategies is that each of them has distinct strengths and weaknesses, as described in Section 2. Despite these differences, we chose to incorporate all previous studies in our analysis. Users of the database can choose themselves which studies they consider relevant for their research purpose. The full list of studies, grouped using the method used to analyze deep mantle anisotropy, and further grouped by year of publication, is shown in Table 1. Overall, seismic anisotropy has been found for ∼26% of D′′.

## 4. Statistical Analysis: Is There a Spatial Correlation Between Anisotropy Locations and LLVP Edges?

We conduct a statistical analysis on the global data set, with the specific goal of testing whether deep mantle seismic anisotropy is more likely to be found near the edges of LLVPs than elsewhere. For this analysis, we create a regular, equally spaced, spherical grid with 10,242 grid points, leading to a spacing of 2.5° between grid points (and thus using equal area bins). For each grid point, we check whether it marks a location at which D′′ mantle anisotropy has been suggested previously or not. We then calculate the shortest distance of each grid point that indicates deep mantle anisotropy to the border of the nearest LLVPs in the deep mantle. We determine these borders by defining LLVP locations as regions where at least 3 out of 5 tomography models show low velocity structures at 2,700 km depth in the cluster analysis of Lekic et al. (2012). Finally, we calculate the average distance of all grid points marking deep mantle seismic anisotropy to the nearest edge of an LLVP. The precise LLVP edge locations are used in these calculations, as defined above, without interpolation to the grid. For comparison, we generate a set of 1,000 random distributions of deep mantle anisotropy by applying 1,000 uniform random spherical rotations of the actual anisotropy distribution (i.e., maintaining the relative orientation of regions). We then repeat our minimum distance calculations for each distribution. Finally, we compare our results using the actual distribution with the results using the distribution of average distances obtained through the random rotations. Unfortunately, reports of null detections of deep mantle anisotropy are rare in the literature and cannot be usefully incorporated into our analysis.

Our statistical analysis shows that the mean distance of D′′ anisotropy locations to the nearest LLVP regions approximately agrees with the mean value obtained from the 1,000 random rotations (Figure 3a), suggesting that there is no global spatial correlation of D′′ anisotropy with the edges of LLVPs. We also conducted separate

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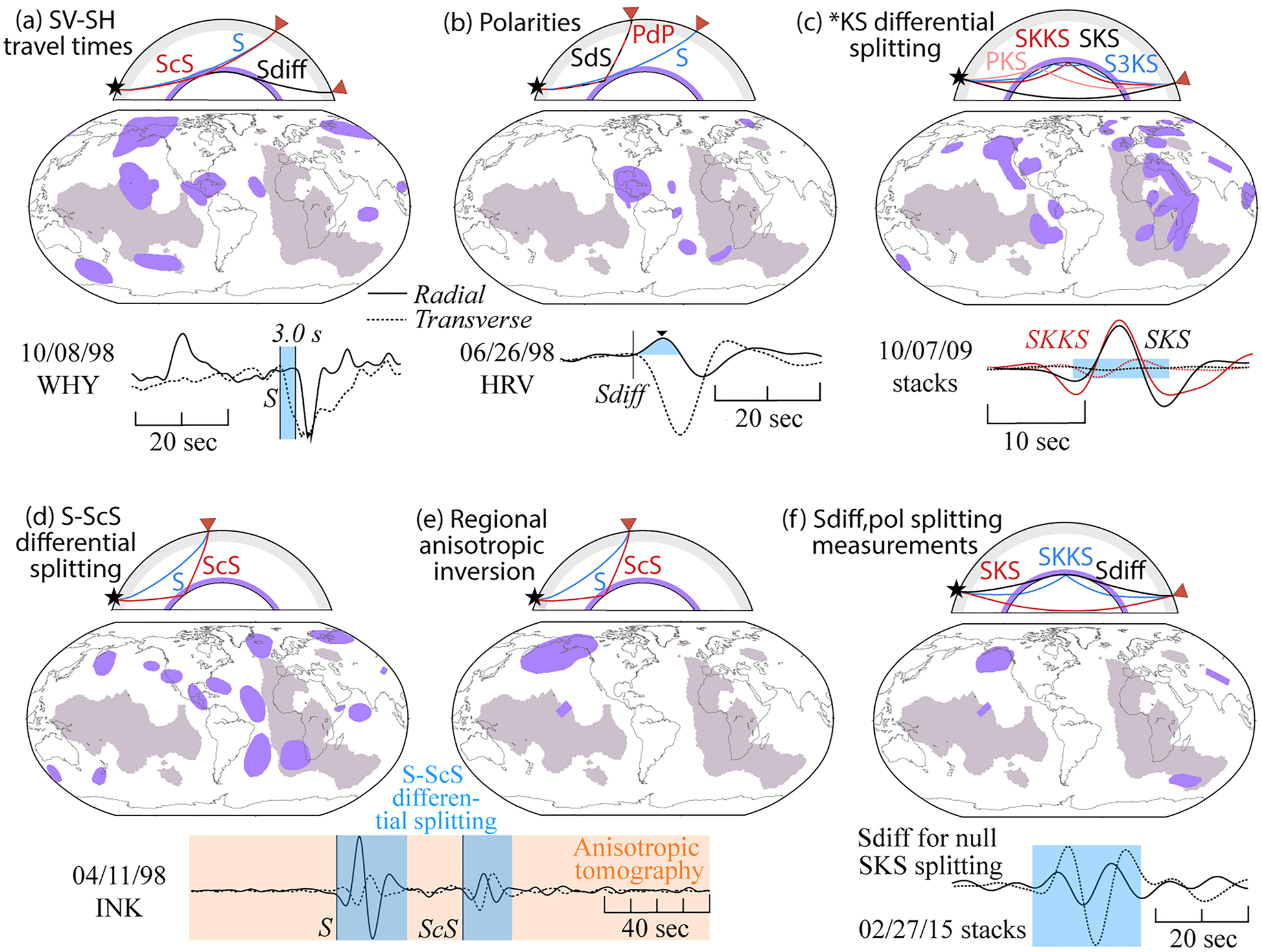


**Figure 2.** Summary of D′′ anisotropy distribution, based on different measurement methods and ordered as in Table 1. (a) Top: Cross-section of seismic phases used to determine differential SV-SH travel times. The source is represented as a black star and stations as red triangles. Middle: Seismic anisotropy locations identified using differential SV-SH travel times. The plotting conventions are as in Figure 1. Bottom: Real data example after Garnero, Maupin, et al. (2004), showing a differential arrival time for the S seismic phase in radial and transverse component seismograms (blue shading). The waveforms were recorded at station WHY for an event that occurred on 8 October 1998. (b) Polarity studies; the real data example is after Garnero and Lay (2003) and shows an anomalous radial component $S_{diff}$ polarity (blue shading). Otherwise, as in all other panels, plotting conventions are the same as in panel (a). (c) *KS differential splitting measurements; the real data example is after Wolf and Long (2022) and shows differential splitting of SKS and SKKS (blue shading). (d) S-ScS differential splitting; the real data example of S and ScS waveforms is after Wolf et al. (2019) (blue shading). (e) Regional anisotropic inversions; real data example of a seismogram around S and ScS arrivals (orange shading) is as in panel (d). (f) $S_{diff}$ splitting measurements that explicitly consider the wave's initial polarization; the real data example is after Wolf and Long (2023), showing an example radial and transverse $S_{diff}$ waveforms that exhibit splitting for a case in which SKS splitting is null (blue shading).

analyses for D′′ anisotropy locations detected using three particularly commonly used methods, including SKS-SKKS differential splitting, S-ScS differential splitting and $S_{diff}$ observations (differential travel times and/or $S_{diff,pol}$ splitting measurements). This consideration separately allows us to explicitly consider the global ray coverage for each method (Section 5), as different epicentral distances are used for each. The results show that D′′ anisotropy is, on average, slightly farther away from the LLVP edges than for a set of 1,000 random rotations of D′′ anisotropy for $S_{diff}$ and S-ScS. For SKS-SKKS differential splitting, D′′ anisotropy is slightly closer to an LLVP edge than expected for the random distribution. However, these differences are slight and we do not view them as statistically significant.

## 5. Discussion

While our straightforward statistical analysis is informative, it does not consider several potential factors influencing the distribution of previously detected deep mantle anisotropy locations. For example, it is immedi-

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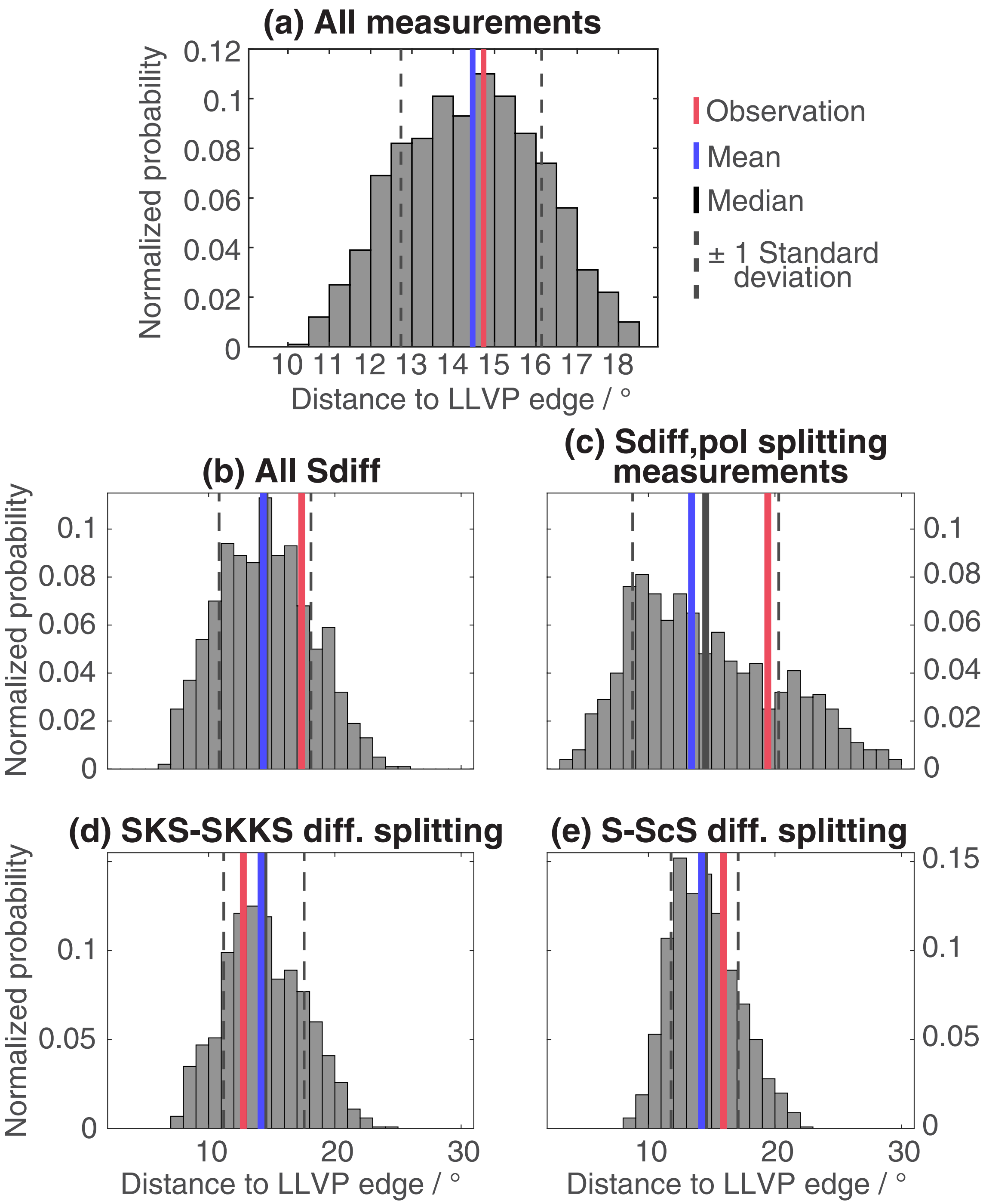


**Figure 3.** Statistical assessment of the spatial correlation between large-low velocity province edges and seismic anisotropy. (a) Histogram (gray) for 1,000 random spherical rotations of all deep mantle anisotropy locations (Section 4). The mean of the distribution is shown by a solid blue vertical line and the median as a black line (see legend). (Mean and median are identical for this distribution). One standard deviation of the random distribution is shown on both sides as vertical dashed black lines. The result of the actual deep mantle anisotropy distribution (Figure 1) is shown as a vertical solid red line. (b) Same as panel (a), for all studies that use $S_{diff}$ to measure deep mantle anisotropy. (c) Same as panel (a), for $S_{diff}$ splitting measurements that explicitly consider the wave's initial polarization. (The deviation from a normal distribution is due to the small number of measurements made with this method, as shown in Figure 2f.) (d) Same as panel (a), for SKS-SKKS differential splitting. (e) Same as panel (a), for S-ScS differential splitting.

ately apparent in Figure 1 that fewer D′′ anisotropy locations have been identified in the southern than in the northern hemisphere. This observation is unlikely to be linked to mantle dynamics but is rather caused by the unequal global ray coverage. To interrogate whether and how ray coverage influences the results of our statistical

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correlation, we consider the ray coverage in the D′′ layer for the different data subsets shown in Figure 3. Expanding upon previous work (e.g., Creasy et al., 2019), we report ray coverage individually for each method that can be used to diagnose D′′ anisotropy, including $S_{diff}$ splitting, using realistic source-receiver configurations. Because our aim is to illustrate which regions are well-sampled by commonly used splitting methods and where seismic anisotropy has and has not (yet) been detected, we do not include PdP and SdS polarity measurements here. Such measurements are usually used as an additional constraint along with complementary splitting data (e.g., Pisconti et al., 2019, 2023) rather than being interpreted as uniquely indicative of deep mantle anisotropy. We estimate this ray coverage by considering all events with moment magnitudes 6 or larger (according to the International Seismological Center Bulletin, International Seismological Centre (2023)) that occurred between January 1990 and March 2023, and the station distribution covered by most common data request clients (see Acknowledgments). We use ObsPy (Beyreuther et al., 2010) to calculate the lowermost mantle ray coverage of $S_{diff}$ (epicentral distance 103°–125°; Figure 4a), SKS-SKKS (epicentral distance 108°–122°; Figure 4b), and S-ScS (epicentral distance 60°–85°; Figure 4c) at the epicentral distances used in splitting studies. We combine these results in Figure 4d for a map of global ray coverage using any of these methods. For each splitting method, we assign every grid point a number between 1 and 0, based on the number of rays that sample it, normalized to the maximum number of rays globally for any grid point (Figure 4). Figure 4 shows that D′′ seismic anisotropy has been suggested in many well-sampled regions, but not in all of them.

This exercise demonstrates that it is essential to consider ray coverage when assessing the spatial distribution of deep mantle seismic anisotropy. However, ray coverage is difficult to quantitatively account for a statistical analysis such as that discussed in Section 4. One approach to understanding how well-sampled LLVP edges are compared to the global average is to compare the mean and median ray coverage of bins that mark LLVP edges with the global mean and median ray coverage. For the methods investigated in Figure 4, both the mean and medium ray coverage tends to be ∼20% lower at the LLVP edges than for the global average. This discrepancy may influence the results of our statistical analysis, which implicitly assumes equal ray coverage throughout the deep mantle. The raypath sampling maps (Figure 4) can be used to determine new target regions with dense raypath coverage for which seismic anisotropy has not yet been analyzed in past studies.

Another factor potentially influencing our analysis is the difficulty of conclusively identifying the absence of anisotropy in D′′. While null splitting measurements for deep mantle anisotropy are regularly reported for specific raypaths (e.g., Asplet et al., 2020; H. A. Ford et al., 2015; Garnero, Maupin, et al., 2004; Reiss et al., 2019), they are only sometimes interpreted as being indicative of an isotropic D′′ (Table 1). The reason is that a null measurement along a single raypath cannot, by itself, rule out the presence of seismic anisotropy, and confirmation of the absence of seismic anisotropy in the region under study requires raypath sampling from multiple directions. Previous studies have handled this issue in different ways: Some explicitly invoke isotropy as a likely explanation if no splitting is observed from a single direction (e.g., Kendall & Silver, 1998; Pisconti et al., 2019; Reiss et al., 2019), while other studies are more cautious (e.g., H. A. Ford et al., 2015; Wolf & Long, 2023) in their interpretation. Some studies that measure null splitting for certain sampling directions explicitly consider the possibility that they have sampled a null direction of the anisotropy (Asplet et al., 2023; H. A. Ford et al., 2015). While investigators may be aware of this ambiguity, whether they find their observations sufficiently indicative of isotropy is a matter of interpretation. Therefore, it is very challenging to consider null measurements of D′′ anisotropy in a global analysis.

Apart from uneven ray coverage, there are other potential factors that may influence the results of our statistical analysis. For example, our results are potentially influenced by the fact that after it had been suggested that D′′ seismic anisotropy may be stronger along LLVP edges based on regional studies (e.g., Cottaar & Romanowicz, 2013; Wang & Wen, 2004), subsequent studies may have tended to preferentially search for D′′ anisotropy at these edges. Again, this factor is difficult to quantify. Investigations of correlations that include estimates of anisotropy strength, rather than a binary finding of anisotropy detected/not detected, would be highly desirable, but are currently extremely challenging. Anisotropy strengths determined using different methods are not necessarily comparable, as raypaths are different, methods are sensitive to different types of anisotropy (e.g., radial or azimuthal anisotropy; see Section 2), and the apparent anisotropic strengths depend on the sampling direction. Additional uncertainty is added by the subjective definition of exactly where the LLVP edge is located. Estimates of LLVP edge locations can vary between different tomography models, in some places by as much as 1,000 km (e.g., Garnero et al., 2016; Lekic et al., 2012).

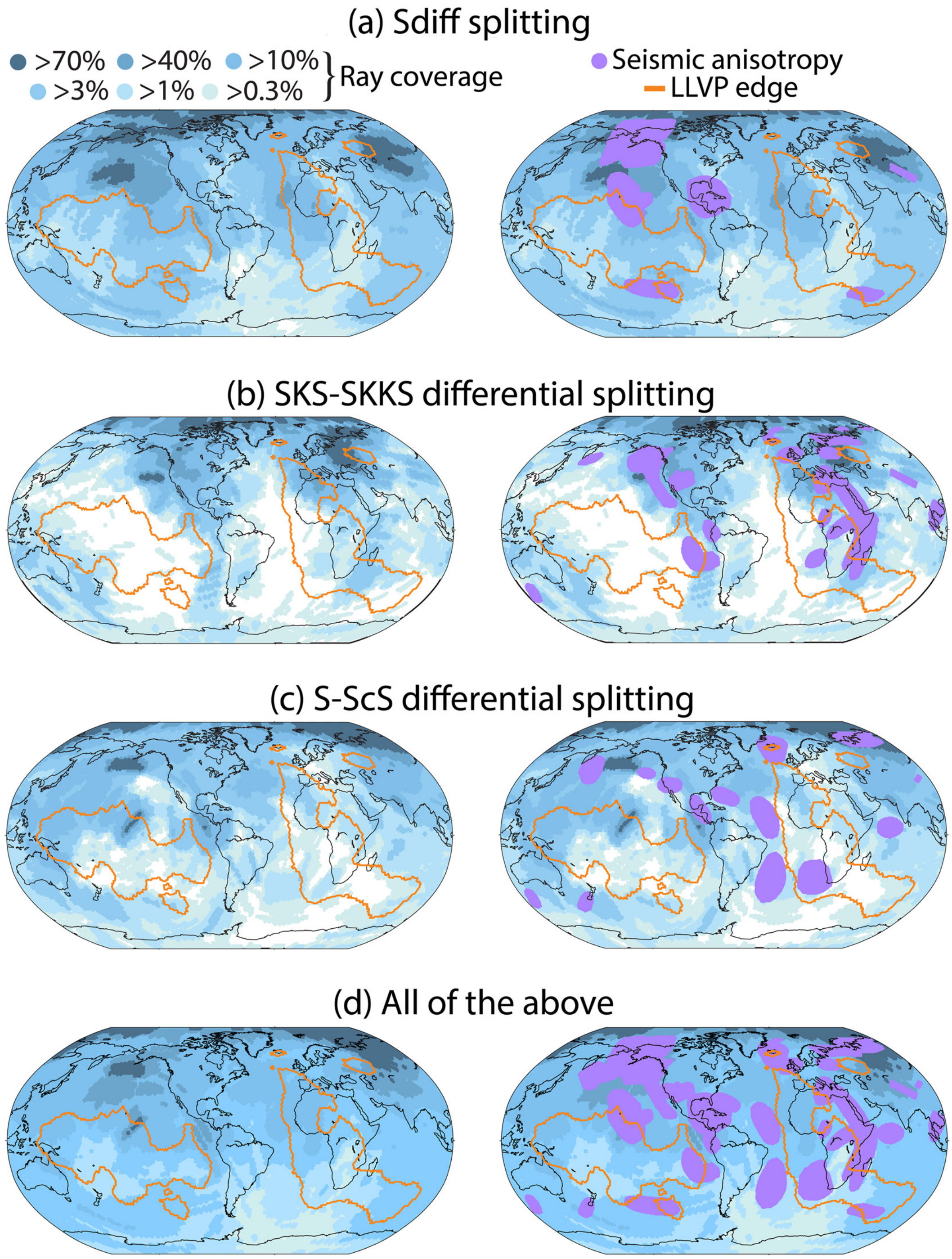


**Figure 4.** Global raypath coverage for (a) $S_{diff}$, (b) SKS-SKKS differential splitting, (c) S-ScS differential splitting measurements, and (d) all these methods together, calculated for all events with moment magnitudes greater than 6 between January 1990 and March 2023. Ray coverage is reported relative to the maximum bin (100%, see legend). Large-low velocity province edges are indicated by orange lines. The right column additionally shows locations for which the presence of seismic anisotropy has been previously suggested (violet color), hinting at which regions with good coverage the different techniques can be applied to in future studies.

One simple question that we can answer with our compiled database is whether previously suggested locations of deep mantle anisotropy are primarily located within or outside of LLVPs. Overall, 33% of the sampled area of D′′ outside LLVPs has been found to be anisotropic, while this value is only 21% inside the LLVPs. The significance of this observation, however, is influenced by the same caveats as the potential correlation with LLVP edges. In particular, ray coverage within LLVPs tends to be poorer than outside them (Figure 4); therefore, it is less likely that seismic anisotropy is detected within LLVPs than elsewhere.

Because of the caveats discussed above, whether D′′ anisotropy preferentially occurs near LLVP edges on a global scale remains inconclusive. With the increasing availability of D′′ seismic anisotropy studies, however, this question can be more confidently pursued in future work. One way to do this is to apply a uniform methodology to investigate deep mantle anisotropy globally, exploiting all available seismic data (Figure 4). Seismic anisotropy can also be predicted through geodynamic modeling calculations (Chandler et al., 2021; Cottaar et al., 2014; Walker et al., 2011). Therefore, our understanding of the global distribution of seismic anisotropy in the D′′ layer and its relation with the lowermost mantle structures and dynamics can also be improved by comparing seismically determined anisotropy models with results of geodynamic modeling experiments.

## 6. Conclusion

We create and make available a global digital database of locations at which seismic anisotropy in the D′′ layer has been detected using a variety of body wave phases. We encourage researchers to reach out to the corresponding author to add new data sets and results to the database and plan to regularly update it as new studies are published. Using this database at the time of writing, we show that on a global scale, deep mantle seismic anisotropy is not more likely to be found at the edges of the LLVPs than a random distribution would suggest. One factor influencing our statistical assessment is ray coverage, which tends to be poorer than the global average at LLVP edges, although this factor is difficult to explicitly account for our analysis.

## Data Availability Statement

The compiled database of deep mantle anisotropy locations is available at a data repository (Wolf et al., 2023c) and https://github.com/wolfjonathan/Deep_Mantle_Anisotropy_Database.

**Acknowledgments**

This work was funded by Yale University and by the U.S. National Science Foundation via Grant EAR-2026917 to MDL, Grant EAR-2054926 to ML, and Grant EAR-1855624 to EG. We thank the Yale Center for Research Computing for providing the necessary research computing infrastructure for this study. The Generic Mapping Tools (Wessel & Smith, 1998), ObsPy (Beyreuther et al., 2010), and functions from MATLAB Central (von Laven, 2019a, 2019b) were used in this study. To compute global data coverage for different seismic phases, the following common data request clients were used: AUSPASS, BGR, EIDA, EMSC, ETH, GFZ, ICGC, INGV, IPGP, IRIS, KNMI, KOERI, LMU, NCEDC, NIEP, NOA, ORFEUS, RESIF, SCEDC, TEXNET, UIB-NORSAR, USGS, and USP. We thank Annie Haws, Will Frazer, and Tobias Wand for helpful discussions. We are grateful to two anonymous reviewers for constructive comments.

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