



# ScS shear-wave splitting in the lowermost mantle: Practical challenges and new global measurements

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**Abstract** Many regions of the Earth's mantle are seismically anisotropic, including portions of the lowermost mantle, which may indicate deformation due to convective flow. The splitting of ScS phases, which reflect once off the core-mantle boundary (CMB), is commonly measured to identify lowermost mantle anisotropy, although some challenges exist. Here, we use global wavefield simulations to evaluate commonly used approaches to inferring a lowermost mantle contribution to ScS splitting. We show that due to effects of the CMB reflection, only the epicentral distance range between 60° and 70° is appropriate for ScS splitting measurements. For this distance range, splitting is diagnostic of deep mantle anisotropy if no upper mantle anisotropy is present; however, if ScS is also split due to upper mantle anisotropy, the reliable diagnosis of deep mantle anisotropy is challenging. Moreover, even in the case of a homogeneously anisotropic deep mantle region sampled from a single azimuth by multiple ScS waves with different source polarizations (in absence of upper mantle anisotropy), different apparent fast directions are produced. We suggest that ScS splitting should only be measured at “null” stations and conduct such an analysis worldwide. Our results indicate that seismic anisotropy is globally widespread in the deep mantle.

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## 1 Introduction

Convective flow in Earth can lead to the preferential alignment of minerals, causing waves to travel through the material with different speeds dependent on propagation and polarization directions, a property called seismic anisotropy (e.g., Silver and Chan, 1991; Long and Becker, 2010). Analogous to optical birefringence, shear waves split into a fast and a slow traveling component in seismically anisotropic materials (e.g., Silver and Chan, 1991). Seismic anisotropy has been found to be most prominent in the upper and lower layers of Earth's mantle, while it is almost absent in the bulk of the lower mantle (e.g., Panning and Romanowicz, 2006; Chang et al., 2015). For example, anisotropy has been measured in Earth's crust (e.g., Barruol and Kern, 1996; Haws et al., 2023), the upper mantle (e.g., Silver, 1996; Savage, 1999; Zhu et al., 2020), the mantle transition zone (e.g., Yuan and Beghein, 2014; Chang and Ferreira, 2019) and the uppermost lower mantle (e.g., Foley and Long, 2011; Mohiuddin et al., 2015). Moreover, the lowermost 200-300 km of the mantle, also called D'', is anisotropic in many places (e.g., Kendall and Silver, 1996; Garnero and Lay, 1997; Nowacki et al., 2010; Reiss et al., 2019; Nowacki and Cottaar, 2021; Wolf et al., 2024; see summary by Wolf et al., 2023c).

On average, seismic anisotropy in Earth's upper mantle is stronger than at the base of the mantle (e.g., Panning and Romanowicz, 2006; French and Romanow-

icz, 2014). It is thus challenging to measure seismic anisotropy in the lowermost mantle because the potential contribution of upper mantle anisotropy to every seismogram needs to be accounted for, as the seismic waves used to infer D'' anisotropy travel through the upper as well as the deepest mantle (e.g., Wolf et al., 2022b). To account for the upper mantle contribution, multiple techniques have been developed, most of which rely on comparisons of the shear wave splitting contribution to multiple seismic waves. A popular method to infer deep mantle anisotropy is from differential splitting of the SKS and SKKS phase (e.g., Wang and Wen, 2004; Niu and Perez, 2004; Long, 2009; Reiss et al., 2019; Wolf et al., 2024). SKS and SKKS have very similar raypaths through the upper mantle and a much larger spatial raypath separation in the lowermost mantle. Therefore, large differences in SKS and SKKS splitting for the same source-receiver pair must be due to lowermost mantle anisotropy (e.g., Niu and Perez, 2004; Wang and Wen, 2004). Alternatively, the splitting of SKS and S<sub>diff</sub> can be compared. If SKS is not influenced by seismic anisotropy but S<sub>diff</sub> clearly is, this is evidence for deep mantle anisotropy causing splitting of S<sub>diff</sub> (Cottaar and Romanowicz, 2013; Wolf et al., 2023b; Wolf and Long, 2023). The advantage of measurements using SKS, SKKS and S<sub>diff</sub> waves is that the source-side anisotropy contribution in the upper mantle is either erased by the P-to-SV conversion at the core-mantle boundary (CMB; SKS and SKKS) or, under certain conditions, negligible (S<sub>diff</sub>;

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Wolf et al., 2023b). A technique that explicitly accounts for source-side and receiver-side anisotropy is S-ScS differential splitting (Wookey et al., 2005). After applying explicit ray-theoretical corrections to S and ScS for known receiver-side anisotropy, source-side anisotropy can be measured from the corrected S phase. After correcting ScS for the source-side contribution, the remaining anisotropy contribution to ScS must be due to  $D''$  anisotropy (Wookey et al., 2005b; Nowacki et al., 2010; Creasy et al., 2017; Pisconti et al., 2023).

These differential splitting techniques make a number of assumptions, typically in the context of ray theory. These assumptions have been tested using global wavefield simulations. For example, the interpretation of differential  $SV_{\text{diff}}-SH_{\text{diff}}$  travel times as being uniquely indicative of  $D''$  anisotropy has been questioned (Komatitsch et al., 2010; Borgeaud et al., 2016; Parisi et al., 2018) as isotropic models can induce  $SV_{\text{diff}}-SH_{\text{diff}}$  travel time differences under certain circumstances. The SKS-SKKS differential splitting technique, on the other hand, has largely been shown to reliably detect anisotropy if certain caveats are considered (Tesoniero et al., 2020; Wolf et al., 2022b; see also, Lin et al., 2014). Nowacki and Wookey (2016) pointed out that some of the ray-theoretical assumptions do not always hold for the S-ScS differential splitting technique, especially in case of heterogeneous anisotropy. In particular the assumption of a horizontal ScS raypath through  $D''$  is a significant oversimplification. Additionally, Wolf et al. (2022b) showed that the phase shift of the radial component of ScS due to the reflection off the mantle-core interface needs to be explicitly considered to accurately measure ScS splitting. Also, Parisi et al. (2018) demonstrated that differential ScS SV-SH travel times can be produced by isotropic structure at distances  $> 90^\circ$ . Some of these challenges could successfully be resolved; for example, the horizontal raypath assumption has been avoided in recent S-ScS differential splitting studies (e.g., Pisconti et al., 2023; Asplet et al., 2023). However, there still are many open questions, the answers to which will help our ability to use ScS to measure deep mantle anisotropy.

In this work, we assess in detail how ScS waves can be used to measure  $D''$  anisotropy. To do so, we address several questions. First, we analyze the effects of the CMB reflection on the polarization of ScS, and how they influence the measured ScS splitting parameters. Second, we use global wavefield simulations to investigate whether and how apparent shear-wave splitting can be produced for isotropic input models. Here we use the term ‘shear-wave splitting measurements’ to refer to the measurement of splitting parameters (delay time, fast polarization direction, splitting intensity) and not simply to differential SV-SH delay times. (This distinction is important, because shear-wave splitting defined in this way includes requirements regarding the waveform’s shape.) Third, we analyze how well the source-side correction of the S-ScS splitting technique works in light of the polarization effects on ScS due to its CMB reflection and the slightly different raypaths of S and ScS in the source-side upper mantle. Fourth, we assess the accuracy of explicit ScS receiver-side anisotropy cor-

rections using a realistic forward modeling framework. Putting all these insights together, we suggest a strategy for inferring deep mantle anisotropy from the shear wave splitting of ScS waves. Fifth, we apply this strategy globally to analyze deep mantle anisotropy using suitable broadband seismic stations. We find evidence for seismic anisotropy in regions that have been analyzed in previous studies, such as beneath the northern Pacific Ocean, the Caribbean and northern Asia, but we also identify deep mantle anisotropy in previously unexplored regions such as beneath southern Russia and the southwestern Pacific Ocean. Finally, we discuss ways forward to improve the reliability of ScS splitting measurements and interpretations for  $D''$  anisotropy studies.

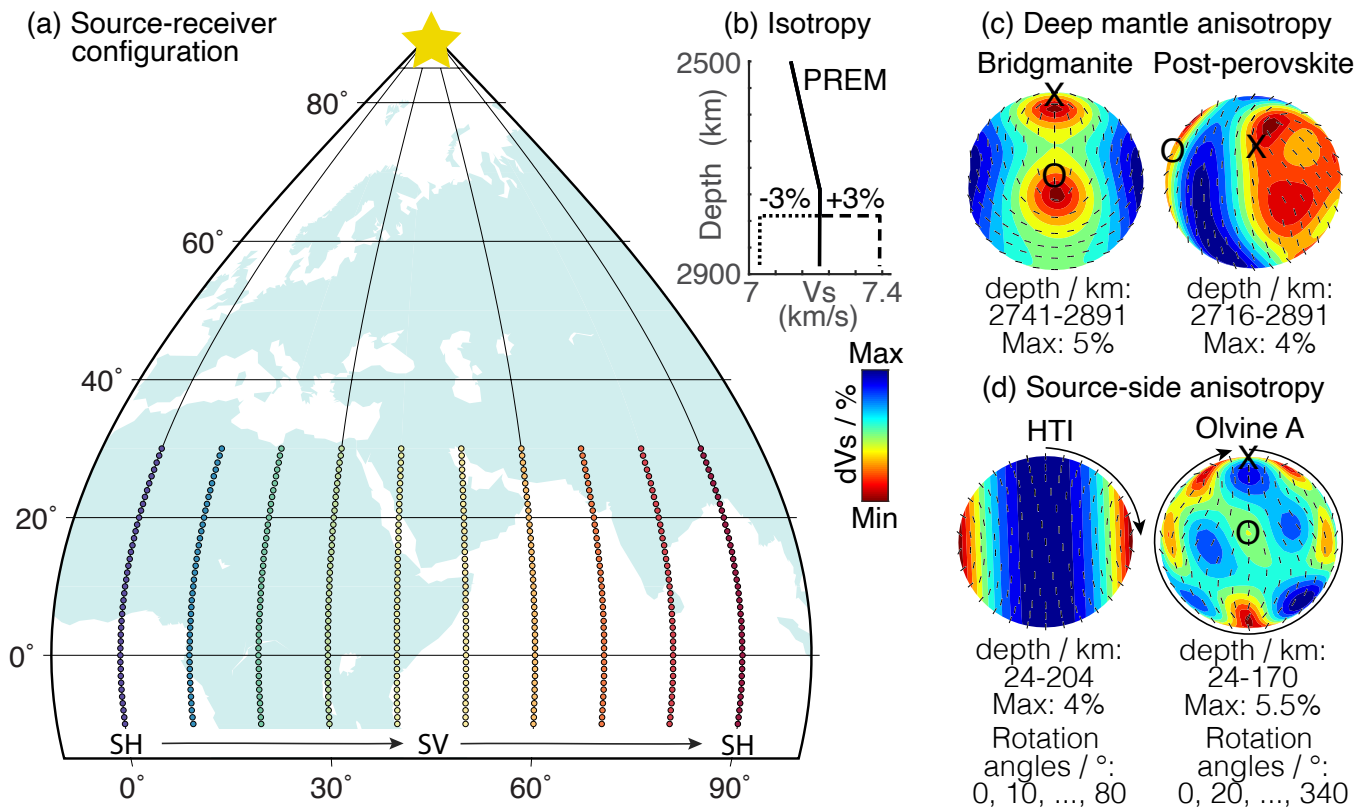
## 2 Methods

### 2.1 Global wavefield simulations

We use the global wavefield modeling code AxiSEM3D (Leng et al., 2016; 2019) in this work. While the code can handle arbitrary three dimensional input models, it calculates synthetic seismograms very efficiently in axisymmetric input models, at the same speed as the older AxiSEM code (Nissen-Meyer et al., 2014). We mostly conduct simulations using axisymmetric models such as isotropic PREM (Dziewonski and Anderson, 1981), which we always use as background model, following our previous work (e.g., Wolf et al., 2022a). We always consider PREM-attenuation and Earth’s ellipticity in our simulations. In some simulations (see below), we replace PREM’s mantle velocity structure with the tomographic model S40RTS (Ritsema et al., 2011). We carry out numerical experiments with and without seismic anisotropy in the lowermost and/or upper mantle. In all simulations presented in this work, we compute synthetic seismograms down to minimum periods of 5 s.

Our source-receiver configuration is shown in Figure 1a. We place a strike-slip earthquake at the north pole and stations at epicentral distances of  $60^\circ$  to  $100^\circ$  (spaced in  $1^\circ$  distance increments) between longitudes  $0^\circ$  to  $90^\circ$  (spaced in  $10^\circ$  increments). We choose event depths of either 100 m or 500 km. A strike-slip focal mechanism is selected such that the initial source polarization of S and ScS is purely SH for longitudes  $0^\circ$  and  $90^\circ$  and purely SV for longitude  $45^\circ$  (Figure 1). For each candidate event depth, we conduct three types of simulations:

1. Isotropic simulations:
  - (a) using isotropic PREM (Figure 1b) as input model;
  - (b) incorporating modified velocities in the lowermost 150 km of the mantle, replacing those of PREM (Figure 1b);
  - (c) incorporating a 3D tomography model (S40RTS) in the mantle, replacing PREM velocities.
2. Anisotropic simulations with lowermost mantle anisotropy:



**Figure 1** Source-receiver configuration and input models of synthetic simulations. (a) Source and receivers: The strike-slip event (see text) is shown as a yellow star; stations are represented as dots, colored by longitude (which corresponds to the initial polarization of the arriving wave). (b) Lowermost mantle velocity as a function of depth for the PREM model, PREM with 3% reduced (dotted line), and 3% increased velocities (dashed line). All these scenarios are used in our synthetic modeling. (c) Upper hemisphere representations of the elastic tensors (bridgmanite, post-perovskite) used in simulations in which we incorporate deep mantle anisotropy (at the depths shown below each elastic tensor plot). The elastic tensors were taken from the elastic tensor library of [Creasy et al. \(2020\)](#). The color scale shows the percentage of S-wave anisotropy as a function of direction. The maximum percentage is shown at the bottom and depends on the elastic tensor. The small black sticks indicate the fast polarization direction of the S wave for the corresponding propagation direction. The black ‘O’ represents the shear-plane normal and ‘X’ the shear direction. The lowermost mantle elastic tensors are oriented such that robust shear-wave splitting measurements can be obtained. (d) Similar to panel (c), for upper mantle source-side anisotropy. The elastic tensor rotation performed in this work is indicated by arrows. The HTI elastic tensor was calculated using MSAT ([Walker and Wookey, 2012](#)) and the olivine type-A elastic tensor was taken from [Karato \(2008\)](#).

- (a) incorporating bridgmanite (Br) anisotropy in the lowermost 150 km of the mantle;
- (b) incorporating post-perovskite (Ppv) anisotropy in the lowermost 175 km of the mantle.

These elastic tensors were taken from [Creasy et al. \(2020\)](#) and are displayed as upper hemisphere representations in Figure 1c. The use of these elastic tensors leads to slightly different lowermost mantle velocities than PREM. The main goal of these simulations is to evaluate the influence of realistic lowermost mantle anisotropy on ScS seismic waves; the isotropic effects are analyzed in the previous set of simulations.

3. Anisotropic simulations with upper mantle anisotropy:

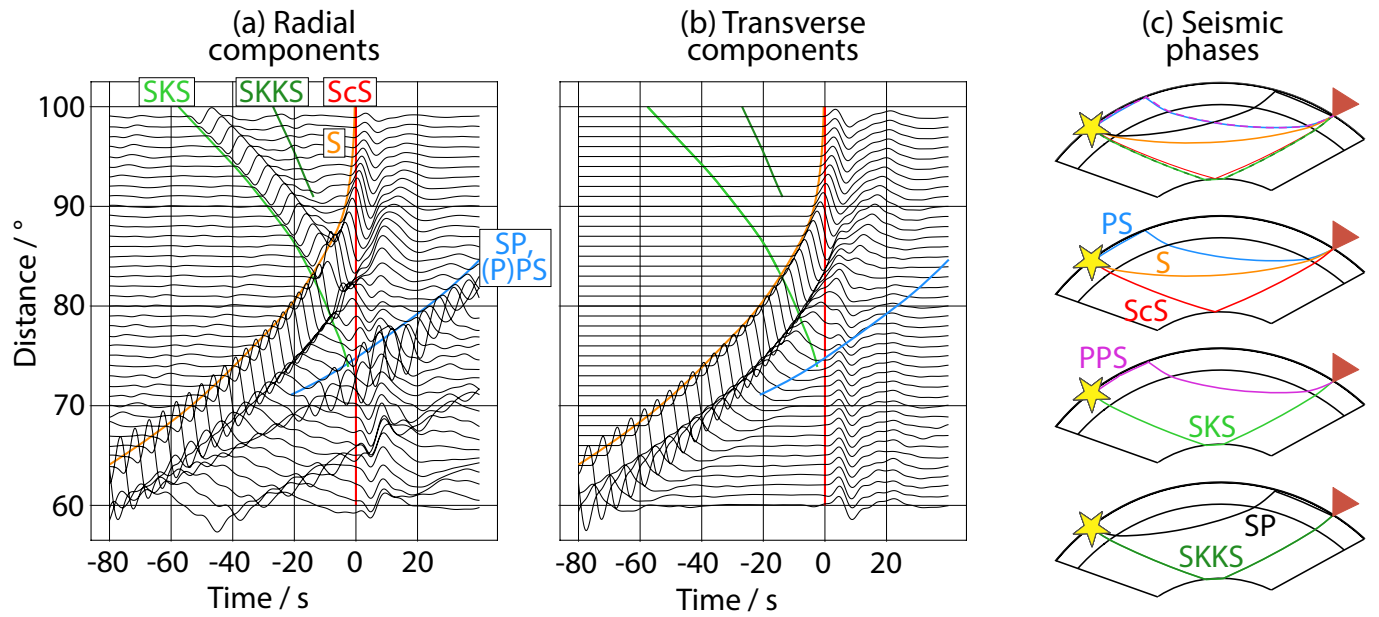
- (a) using horizontal transverse isotropy (HTI) in the upper mantle (Figure 1d). The HTI elastic

tensor is calculated using MSAT ([Walker and Wookey, 2012](#)) and incorporated at the depth range of 24 km to 204 km.

- (b) using olivine (A-type fabric) anisotropy in the upper mantle (Figure 1d). The elastic tensor is from [Karato \(2008\)](#) and the anisotropy is incorporated at the depth range of 24 km to 170 km.

In both cases, the anisotropy in the upper mantle leads to a maximum delay time of  $\sim 1.5$  s. In order to sample anisotropy from different directions, the elastic tensors are rotated around the vertical axis (with respect to their representations in Figure 1d) for different simulations. Due to its symmetry, the HTI elastic tensor is only rotated by angles of  $0^\circ$  to  $80^\circ$  (in  $10^\circ$  increments), while the olivine elastic tensor is rotated between  $0^\circ$  to  $340^\circ$  (in  $20^\circ$  increments).

Synthetic radial and transverse seismograms as a function of distance (for PREM as input model), aligned



**Figure 2** Synthetic waveforms as a function of distance for stations placed along longitude  $70^\circ$  (Figure 1), with sketch of relevant seismic phases. (a) Radial component displacement waveforms, plotted at every  $1^\circ$  distance increment. Incoming high-amplitude seismic phases are marked with colored lines. (b) Same as panel (a) for the transverse component. (c) Schematic diagrams of raypaths through Earth for the seismic phases marked in panels (a) and (b). The source is shown as a yellow star and the station, at an epicentral distance of  $70^\circ$ , as a red triangle.

on the predicted ScS arrival, are shown in Figure 2a,b. At an epicentral distance of around  $75^\circ$ , interference from the PS and PPS phases, which arrive very close together in time at these distances, can be observed. Additionally, some SP energy (which arrives contemporaneously to PS for a 0 km deep source) likely arrives on the radial component. While PS interference can be observed in the record section shown in Figure 2, the phase is not observable at this distance range for events with focal depths deeper than 200 km, although some PPS energy may still be relevant. For distances  $> 80^\circ$ , ScS starts to merge with S. For distances  $< 70^\circ$  and  $> 63^\circ$ , SKS and ScS arrive almost contemporaneously, although it is unclear whether SKS has a sufficiently large amplitude to noticeably influence ScS. (A partial answer to this question will be discussed in Section 4.) The raypaths of the seismic phases that may potentially interfere with ScS are shown in a cross-section in Figure 2c.

## 2.2 Shear wave splitting measurements

Shear wave splitting, which is analogous to optical birefringence, is a consequence of seismic anisotropy. A shear wave that travels through an anisotropic medium splits into a fast and a slow component. The time lag between these components is called  $\delta t$  and the polarization direction of the fast traveling wave is usually referred to as  $\phi$  when measured clockwise from the north, or  $\phi'$  (Nowacki et al., 2010) when measured with respect to the incoming wave's backazimuth. Another quantity that is frequently used is the splitting intensity (Chevrot, 2000),  $SI$ , which yields a scalar value indicating the splitting strength on an individual seismogram. The

splitting intensity is defined as:

$$SI = -2 \frac{Pol_{90}(t)Pol'_0(t)}{|Pol'_0(t)|^2} \approx \delta t \sin(-2\phi'), \quad (1)$$

with  $Pol'_0(t)$  denoting the time derivative of the component in the direction of initial polarization, whereas  $Pol_{90}(t)$  is the horizontal seismogram component oriented  $90^\circ$  away from the incoming wave's primary polarization.

We determine the splitting parameters ( $\phi$ ,  $\delta t$ ) using a modified version of the SplitRacer software (Reiss and Rumpker, 2017), which is the same version previously used by Wolf et al. (2022b). This version estimates the initial polarization of the incoming wave, through particle motion analysis, as ScS waves are not typically initially SV-polarized. SplitRacer calculates the splitting parameters ( $\phi$ ,  $\delta t$ ) using the transverse energy minimization technique (Silver and Chan, 1991), incorporating a corrected calculation of the 95% confidence intervals (Walsh et al., 2013). Whenever we apply source-side anisotropy corrections for the S-ScS differential splitting technique, we measure source-side anisotropy splitting parameters with SplitRacer. Then, we use a code to correct the ScS phase for these source-side splitting parameters, following the algorithm described in Wolf et al. (2022b), which is based on work from Wookey et al. (2005). In this algorithm, we also calculate splitting parameters using the transverse energy minimization technique, building upon an implementation from Creasy et al. (2017). For all these measurements, we consider ( $\phi$ ,  $\delta t$ ) measurements well-constrained if the 95% confidence intervals are smaller than  $\pm 25^\circ$  for  $\phi$ ,  $\pm 0.8$  s for  $\delta t$  and  $\pm 0.5$  for  $SI$ . Before measuring splitting parameters, we filter our seismograms retaining periods between 5 s and 15 s (unless specified differently).

Polarizations are determined from the seismograms at longer periods (8-25 s) from the long axis of the particle motion ellipse.

### 3 SV reflection coefficients of ScS at the CMB

In order to understand the potential effects of the CMB reflection on ScS phases, we solve the equations of Chapman (2004) to calculate SV reflection coefficients of ScS at the CMB for PREM velocity structure in the whole mantle, as well as for 3% reduced and increased velocities with respect to PREM in the lowermost 150 km of the mantle (Figure 3). Such velocity variations are realistic for Earth's faster and slower lowermost mantle regions (e.g., Ritsema et al., 2011). We also explore variations of the reflection coefficients as a function of source depth and do not find any substantial differences compared to the 0 km case shown in Figure 3. We do not compute SH reflection coefficients as the shear wave velocity in the outer core is zero and SH does not couple with P; therefore, all SH energy will be reflected without a phase or amplitude change. Several observations can be made from Figure 3:

- For distances  $< \sim 60^\circ$ , SV amplitudes are strongly reduced after the reflection. For example, at an epicentral distance of  $\sim 30^\circ$  SV loses  $\sim 70\%$  of its amplitude. This pattern depends on the lowermost mantle velocity and is therefore only possible to account for exactly if the velocity structure at the reflection point is well known. While the SV amplitude effects are complicated, for most distances  $< \sim 60^\circ$  the SV phase shift is simple and close to  $180^\circ$  (Figure 3).
- For epicentral distances  $< 10^\circ$ , SV will simply undergo a sign-flip with amplitudes almost unaffected by the reflection.
- For epicentral distances  $> \sim 60^\circ$ , SV amplitudes are largely unchanged by the reflection and the SV phase shift is between  $160^\circ$  and  $180^\circ$ , depending on distance and deep mantle velocity structure (Figure 3). Because of this, Wolf et al. (2022b) suggested that the description of SV behavior at distances  $> \sim 60^\circ$  as a simple sign-flip is accurate enough for the purpose of ScS splitting measurements.

Our analysis of distance-dependent SV reflection coefficients for ScS shows that it is difficult to infer the presence of deep mantle anisotropy for ScS waves at epicentral distances  $< \sim 60^\circ$ . For these epicentral distances, relative SV-SH amplitudes will be strongly influenced by the deep mantle velocity structure of the region under study, which needs to be precisely accounted for. However, this appears challenging, as the deep mantle velocity structure in any particular deep mantle region is often poorly known. We therefore focus our following analysis on epicentral distances  $> 60^\circ$ , which is the most frequently used distance range. For example, the S-ScS differential splitting technique has been suggested to be applicable at a distance range between  $60^\circ$  and  $85^\circ$  (Wookey et al., 2005). There are

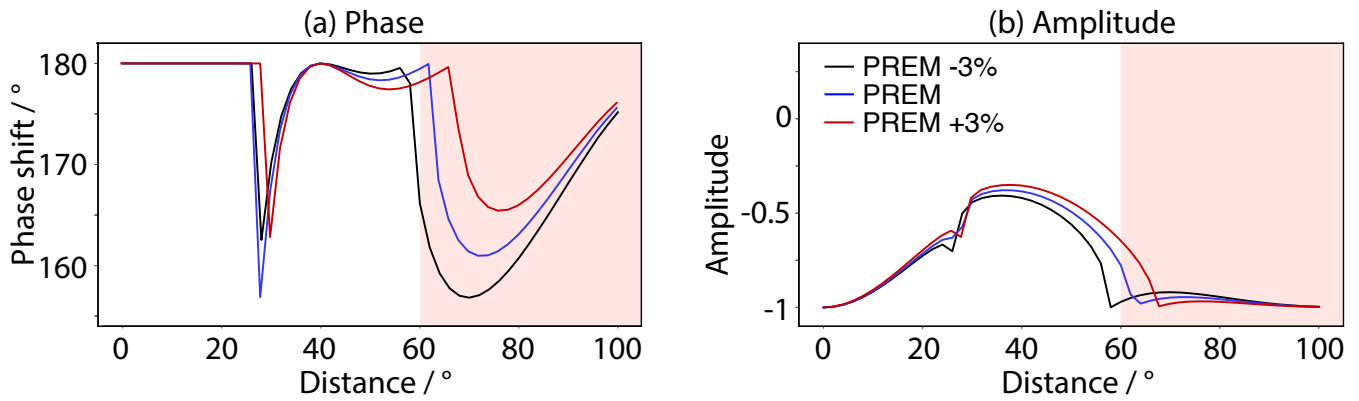
also multiple previous studies that have analyzed the behavior of S and ScS waves at distances  $> \sim 85^\circ$  (e.g., Kendall and Silver, 1996; Pulliam and Sen, 1998; Fouch et al., 2001) to infer deep mantle anisotropy.

### 4 S and ScS polarizations in isotropic input models

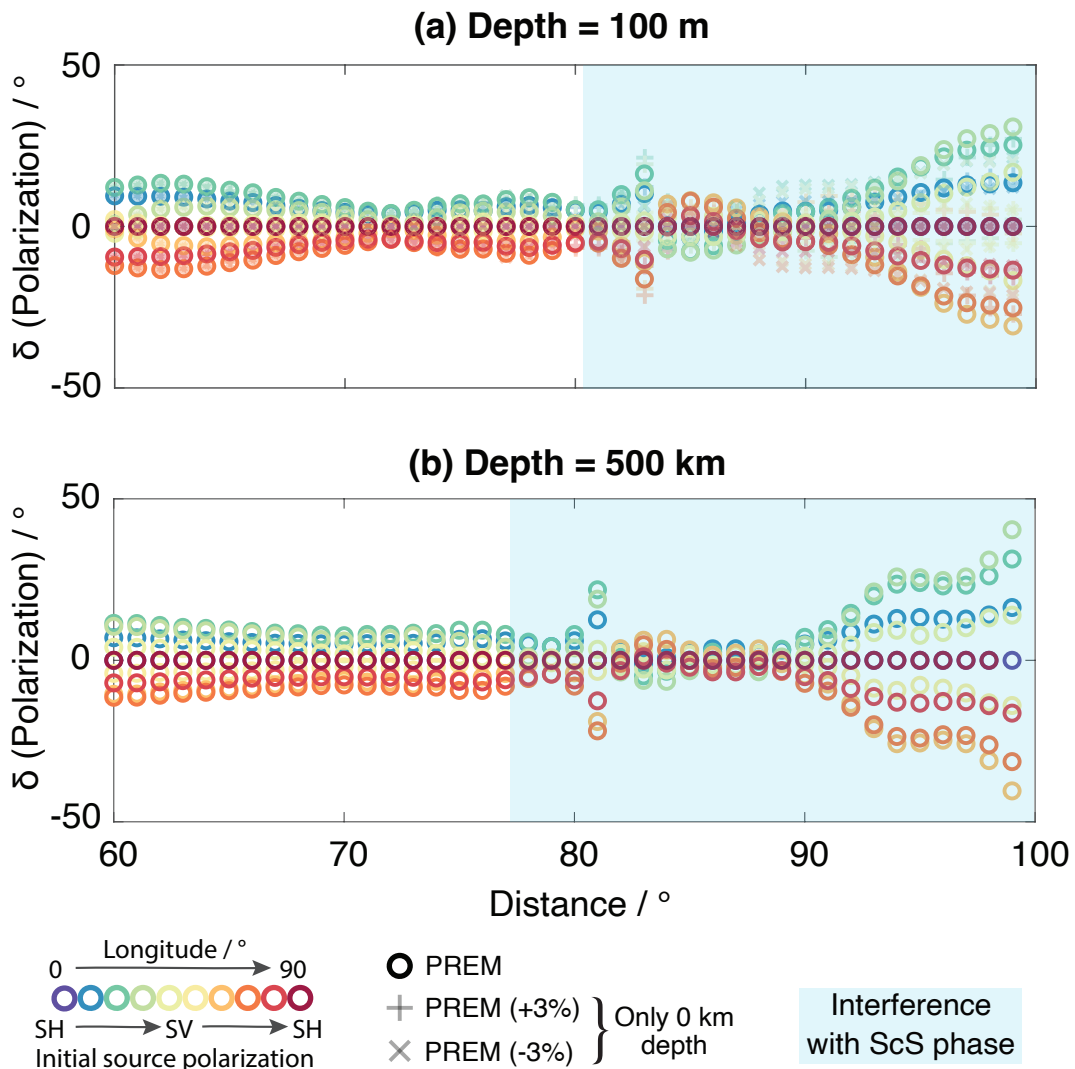
Next, we analyze S and ScS polarizations at epicentral distances between  $60^\circ$  and  $100^\circ$  using global wavefield simulations. We conduct synthetic simulations for PREM velocity structure in the whole mantle as well as for 3% increased and reduced velocities above the CMB (Figure 1a). In Figure 4, we show measured S polarizations for different initial source polarizations of the wave and source depths of 100 m and 500 km. The results are only weakly influenced by the lowermost mantle velocity, but do depend on source depth for distances  $> 90^\circ$ . Figure 2 shows that the S wave polarizations are relatively unaffected by interference from other seismic phases at distances  $< 80^\circ$ , but start to be influenced by ScS at greater distances. Accordingly, measured S polarizations agree very well with the initial source polarizations for distances  $< 80^\circ$  (Figure 4). For larger distances, S polarizations are influenced by ScS but still largely agree with the initial source polarization (Figure 4).

For ScS, the pattern of measured polarizations as a function of distance is more complicated (Figure 3). At epicentral distances between  $60^\circ$  and  $70^\circ$ , ScS initial polarizations are approximately opposite the S wave polarization as controlled by the source (Figure 5) due to the approximate SV sign-flip (Figure 3). However, because the sign-flip of SV is not exact (Figure 3), and because of the potential interference with SKS in some of the epicentral distance range (Figure 2), this pattern is by no means perfect. These two effects are hard to distinguish; however, analyzing them in isolation is not required to understand the conditions under which ScS can be used for analyses of lowermost mantle anisotropy, which is the main goal of this study. For distances between  $73^\circ$  and  $79^\circ$ , interference with PS can lead to estimated polarizations close to SV (Figure 5a). For deep sources (Figure 5b), no PS energy arrives; however, PPS and SP may still influence ScS waveforms around this distance range. Exceptions are observed at the stations at azimuths for which the initial polarization is purely SH, as the (P)PS amplitude is zero for them (Figure 5). For distances  $> 80^\circ$ , S and ScS merge, with S dominating, leading to polarizations that are close to the S initial source polarization (Figure 5). These overall patterns hold for all the different lowermost mantle velocities that we tested (Figure 5).

Considering these results, it appears challenging to measure deep mantle anisotropy reliably from ScS for distances at which the PPS or PS phase potentially interferes with ScS. This corresponds to a distance range between  $73^\circ$  and  $79^\circ$  for shallow events (e.g., Figure 5) and to distances down as close as  $70^\circ$  for an event depth of 150 km. For events deeper than  $\sim 200$  km no PS phase arrives at these distances, but PPS may have an influence



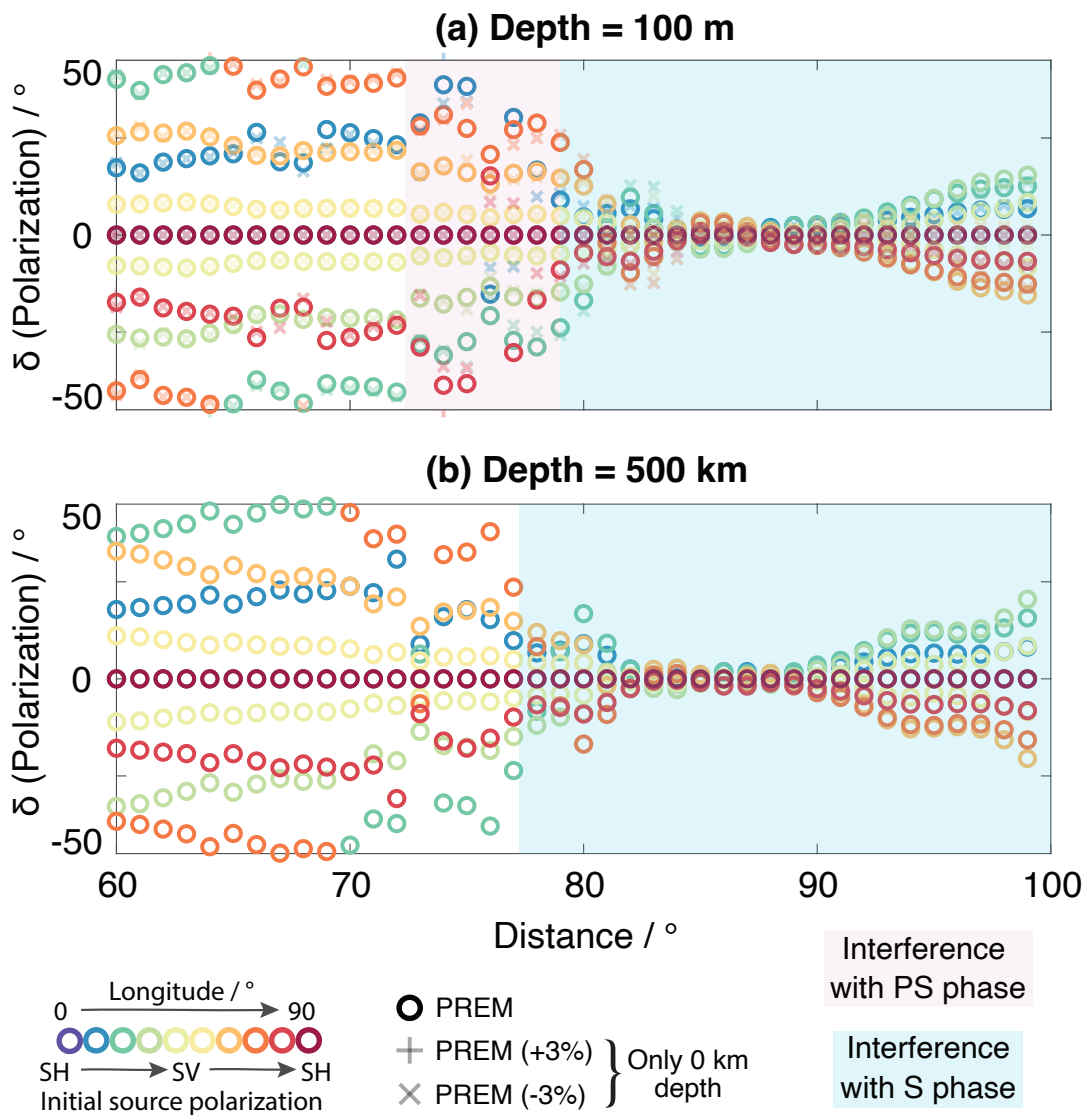
**Figure 3** Influence of the CMB reflection on the SV portion of the ScS phase. We calculate reflection coefficients for PREM (blue line), PREM -3% (black line), and PREM +3% (red line) shear velocities in the lowermost 150 km of the mantle (Figure 1b). The source depth for this calculation is 0 km, but we note that no significant variation can be observed as a function of source depth. Red shading marks epicentral distances > 60°, which are typically used for measurements of shear-wave splitting due to lowermost mantle anisotropy. (a) Phase shift of the radial component of the ScS as a function of epicentral distance. (b) Amplitudes (real part of the reflection coefficient) as a function of epicentral distance.



**Figure 4** Measured S polarizations relative to the initial source polarization as a function of epicentral distance, for different deep mantle velocity profiles (legend), initial source polarizations (legend), and source depths. Potential interference with ScS is indicated by blue shading. Measurements are conducted for source depths of (a) 100 m and (b) 500 km.

on seismic waveforms down to 70° epicentral distance. Similarly, if shear wave splitting is measured from S/ScS

for distances ~ > 80°, it should be considered that the S initial polarization likely dominates, but ScS influences



**Figure 5** Same as Figure 4 for ScS. Potential PS interference is indicated by pink shading and potential S interference by blue shading.

the waveforms and horizontal component amplitude ratios.

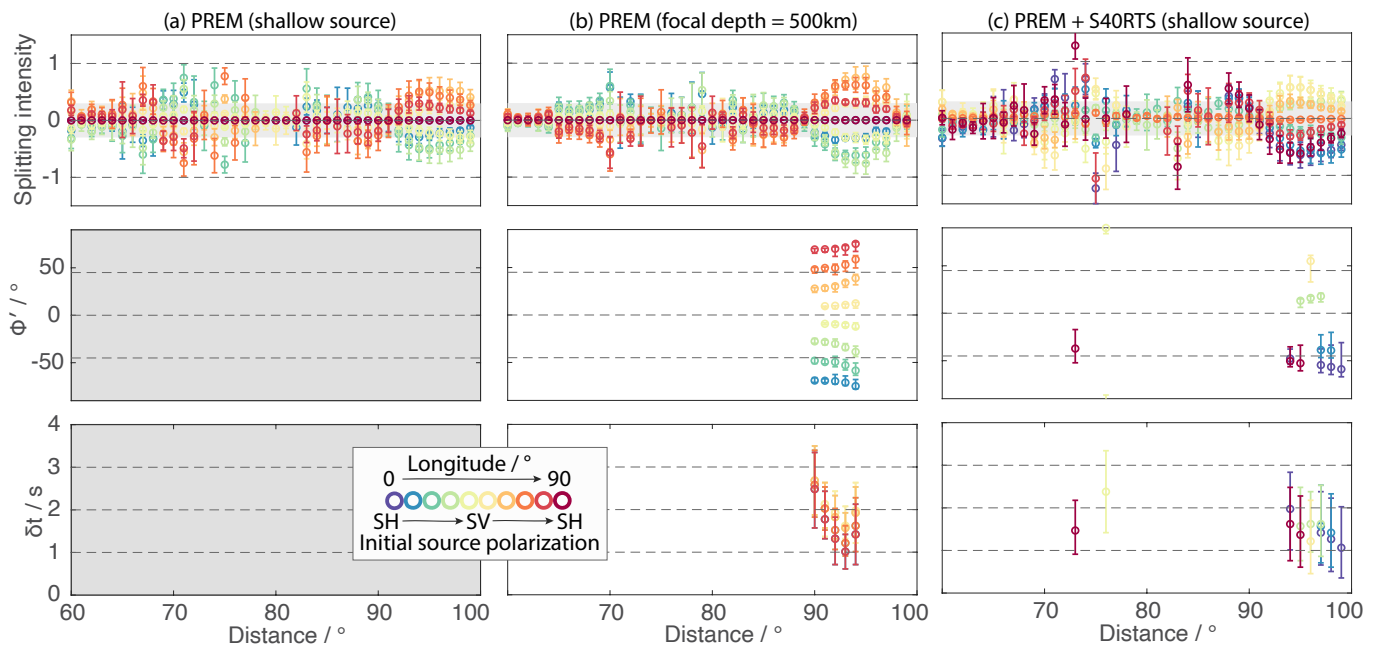
### 5 Apparent shear-wave splitting in isotropic input models

We have shown how the CMB reflection and phase interferences can influence the polarization of ScS. However, it remains unclear whether such effects can result in apparent shear wave splitting. To test this, we conduct synthetic simulations in isotropic input models as introduced in Section 2.1.

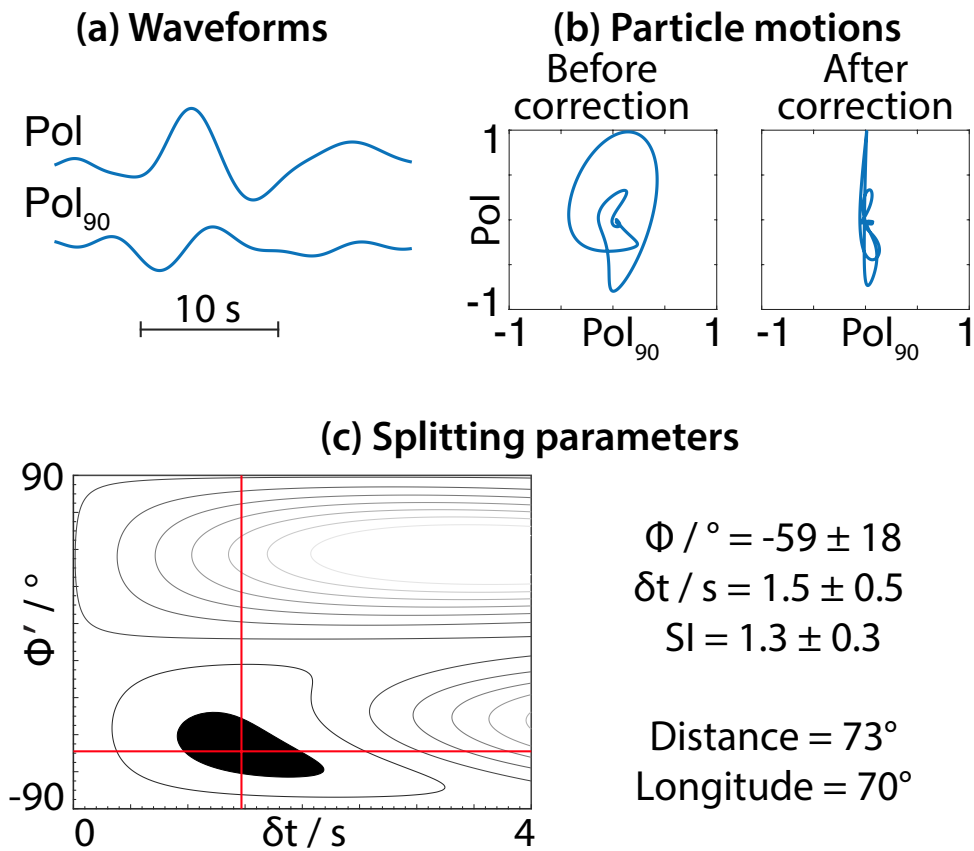
For PREM synthetics, calculated for a focal depth of 100 m, non-null splitting intensities can be reproduced, although we do not measure well-constrained splitting parameters ( $\phi$ ,  $\delta t$ ) (Figure 6a). If the source is placed in a depth of 500 km, however, apparently well-constrained ( $\phi$ ,  $\delta t$ ) values can be measured at distances between 90° and 94° (Figure 6b). Some of these measurements may be identified as null splitting, but not all of them. For PREM+S40RTS, on the other hand, apparently well-constrained ( $\phi$ ,  $\delta t$ ) values are mainly obtained for dis-

tances > 94° (although there is also some apparent splitting at smaller distances). The reason for the apparent splitting is phase interference; for example, the interaction between S and ScS (Figure 2), which arrive at approximately the same time for distances > 90°. The transverse components of S and ScS are generally very similar at these distances, as the transverse ScS component is largely unaffected by the reflection. However, the radial ScS component will be approximately sign-flipped compared to S (Figure 3) and potentially have a slightly different amplitude; the details of the phase’s behavior depend on lowermost mantle velocity structure and the event depth (Figure 3). If these waveform distortions affect transverse and radial components in a way that the energy on the *Pol* component has the shape of the time derivative of the *Pol*<sub>90</sub> component, apparent splitting results.

We show an example of apparent shear-wave splitting from simulations using isotropic PREM+S40RTS with a source at 100 m depth in Figure 7. The *Pol*<sub>90</sub> component has approximately the shape of the *Pol*<sub>0</sub> component time derivative (Figure 7a) and the particle motion



**Figure 6** Shear wave splitting parameters  $SI$  (top),  $\phi'$  (middle),  $\delta t$  (bottom) as a function of distance, dependent on initial source polarization (legend), for isotropic input models. Error bars indicate 95 % confidence intervals of the measurements (see Section 2.2). Only well-constrained splitting measurements are shown (see text). (a) For PREM input model and a focal depth of 100 m. (b) For PREM input model and a focal depth of 500 km. (c) For PREM input model, for which the mantle was replaced with the tomographic model S40RTS, and a focal depth of 100 m. Apparent shear-wave splitting can be produced at distances  $> 90^\circ$ , but also sometimes at smaller distances.



**Figure 7** Example apparent shear wave splitting for the (isotropic) PREM+S40RTS input model and a source depth of 0 km. (a)  $Pol$  and  $Pol_{90}$  waveforms for the combined ScS phase. (b) Particle motions before (left) and after (right) correction for the best-fitting splitting parameters. (c) Best-fitting splitting parameters in the  $\phi'$ - $\delta t$  plane. The 95% confidence interval is shown in black.



looks elliptical (Figure 7b), mimicking shear wave splitting due to seismic anisotropy. Accordingly, the apparent estimated splitting parameters are well-constrained (Figure 7c).

Our results so far indicate that measurements of shear-wave splitting for epicentral distances  $< 60^\circ$  need to carefully consider the SV reflection coefficient at the CMB for ScS, which will depend on the deep mantle velocity structure of the region under study. Additionally, distances between  $70^\circ$  and  $80^\circ$  cannot be used for ScS splitting measurements if (P)PS or SP may be interfering. For distances  $> 80^\circ$ , S and ScS merge (Figure 2), making it challenging to distinguish between these phases in seismograms. Apparent splitting of the combined S/ScS phase can be produced in isotropic structure (Figures 6 and 7). Therefore, the most promising distance range to measure ScS splitting due to deep mantle anisotropy is between  $60^\circ$  and  $70^\circ$ .

## 6 Shear wave splitting in models that incorporate deep mantle anisotropy

We next test the effects of deep mantle anisotropy on measured ScS splitting in absence of upper mantle anisotropy, incorporating Br (Figure 8a) and Ppv (Figure 8b) anisotropy in the lowermost mantle, replacing PREM velocity structure (see Section 2.1). In Figure 8 we show measured shear wave splitting parameters ( $SI$ ;  $\phi'$ ,  $\delta t$ ) from ScS as a function of epicentral distance and initial source polarization. Due to the aforementioned challenges at many epicentral distances, we focus on shear wave splitting measured at distances between  $60^\circ$  and  $70^\circ$ . In this distance range, we measure many well-constrained ( $\phi'$ ,  $\delta t$ ) values for our anisotropic input models (Figure 8). The seismic anisotropy in the input model is incorporated such that it is sampled from the same direction independent of azimuth. However, we can observe a large spread of measured  $\phi'$  values for both elastic tensors we tested. The reason for this is that the measured splitting is a combination of the splitting accumulated on both legs of the ScS raypath through  $D''$  (Figure 8c). The initial polarization of ScS depends on its azimuth in our simulations, and this initial polarization affects how the wave is split on both legs of the raypath. This situation is analogous to splitting from multiple layers of anisotropy in the upper mantle, which produces apparent splitting that depends on azimuth (Silver and Savage, 1994; Silver and Long, 2011). Therefore, it is logical that measured fast polarizations are not the same, even though the same deep mantle anisotropy is sampled. As a consequence, if ScS splitting due to  $D''$  anisotropy is measured from a certain sampling direction for any given lowermost mantle region, ScS splitting parameters ( $\phi$ ,  $\delta t$ ) cannot be expected to be the same for different events, unless the events all have similar initial polarizations. Therefore, the mean splitting measurement as often determined in ScS splitting studies (e.g., Nowacki et al., 2010; Wolf et al., 2019; Pisconti et al., 2023) does not have a clear meaning for the interpretation of mantle flow directions, since the same measurement can be obtained for a variety

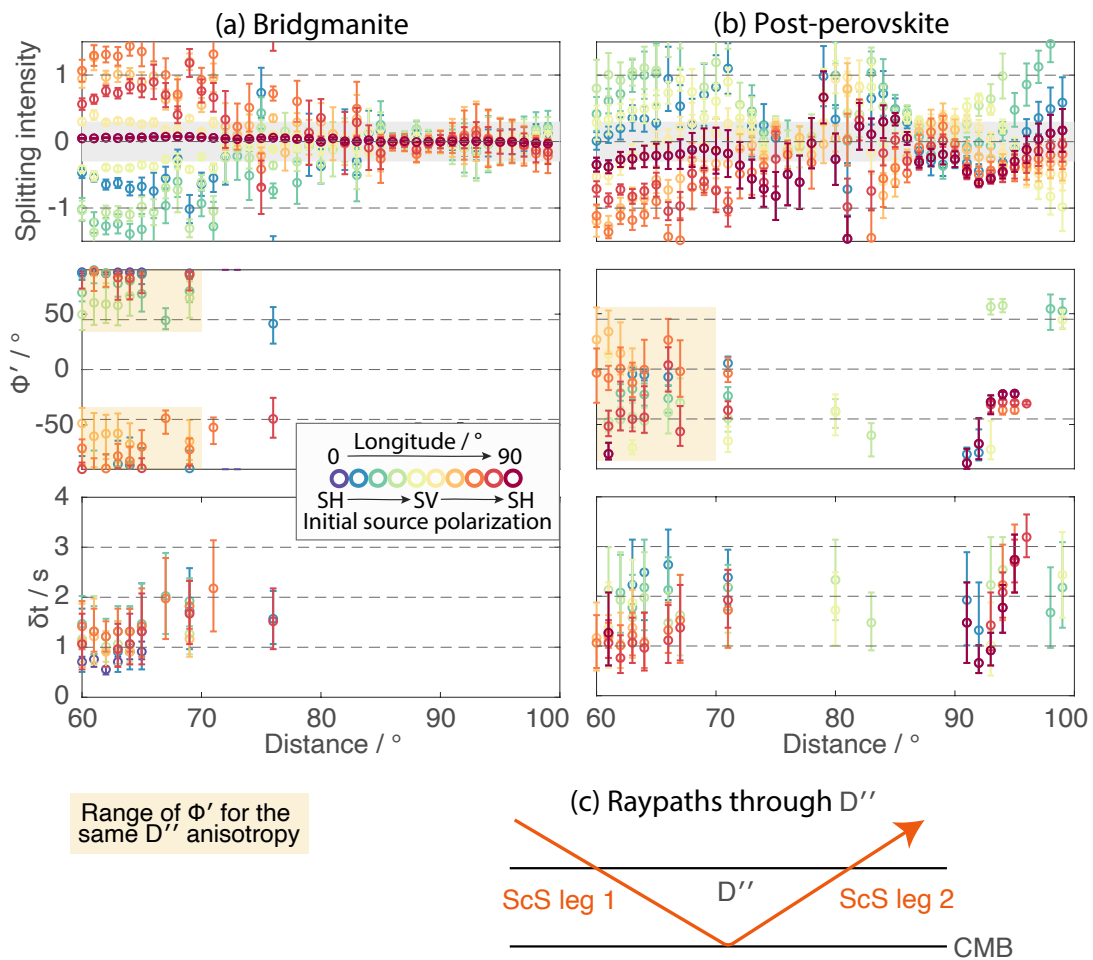
of anisotropy scenarios and initial polarizations of the wave.

## 7 Correction of ScS for source-side anisotropy contribution inferred from S

The S-ScS differential splitting technique isolates the lowermost mantle anisotropy contribution to ScS by correcting the ScS waveform for the influence of receiver-side and source-side anisotropy in the upper mantle (Wookey et al., 2005). The source-side anisotropy contribution is inferred from the S waveform, which has been first corrected for the influence of receiver-side anisotropy. The assumptions made in this process are that S and ScS raypaths through the upper mantle are sufficiently similar that both phases experience the same splitting due to upper mantle anisotropy, and that their initial source polarizations are also similar. In the most extreme case, for a source-receiver distance of  $60^\circ$  and a surface event, S and ScS raypaths are up to 250 km apart at the bottom of the transition zone, so that the assumption that S and ScS raypaths are sufficiently close together may only be valid in cases of relatively generally homogeneous upper mantle anisotropy. To account for the CMB reflection, Wolf et al. (2022b) suggested approximating the phase shift of  $ScS_{SV}$  as a simple sign-flip of the radial component. More accurate corrections would be challenging, given that the precise phase shift depends on the deep mantle velocity structure near the ScS reflection point (Figure 3). Additionally, our results for a distance range close to  $60^\circ$ , at which the PREM-predicted phase shift corresponds to a precise sign-flip (Figure 3), do not indicate that ScS splitting measurements could be substantially improved by implementing the PREM-predicted phase shift. Using this assumption, Wolf et al. (2022b) showed that approximate source-side splitting parameters for ScS can indeed be inferred from S. These splitting parameters can then be used to correct ScS waveforms after a correction for receiver side anisotropy has been applied (Wookey et al., 2005).

Measurements of the polarization of the S phase can be used to predict ScS polarization in the epicentral distance interval between  $60^\circ$  and  $70^\circ$ . Since the backazimuth is always zero for our source-receiver configuration (Figure 1a) and the radial ScS component is approximately a sign-flipped version of the S radial component (Figure 2), the sum of the S and the ScS polarizations must be approximately zero.

Figure 9 explores how accurately, under the assumptions described above, ScS splitting due to source-side anisotropy can be predicted from the splitting of the corresponding S phase. We do not incorporate any receiver-side or deep mantle anisotropy in these simulations. We measure S and ScS polarizations and splitting parameters ( $\phi$ ,  $\delta t$ ). Then, we determine the difference between the ScS splitting parameters and those predicted from the S phase. Figure 9a shows an example for olivine anisotropy in the source-side upper mantle, with the elastic tensor rotated by  $60^\circ$  around the vertical axis (Section 2.1). The measured polariza-



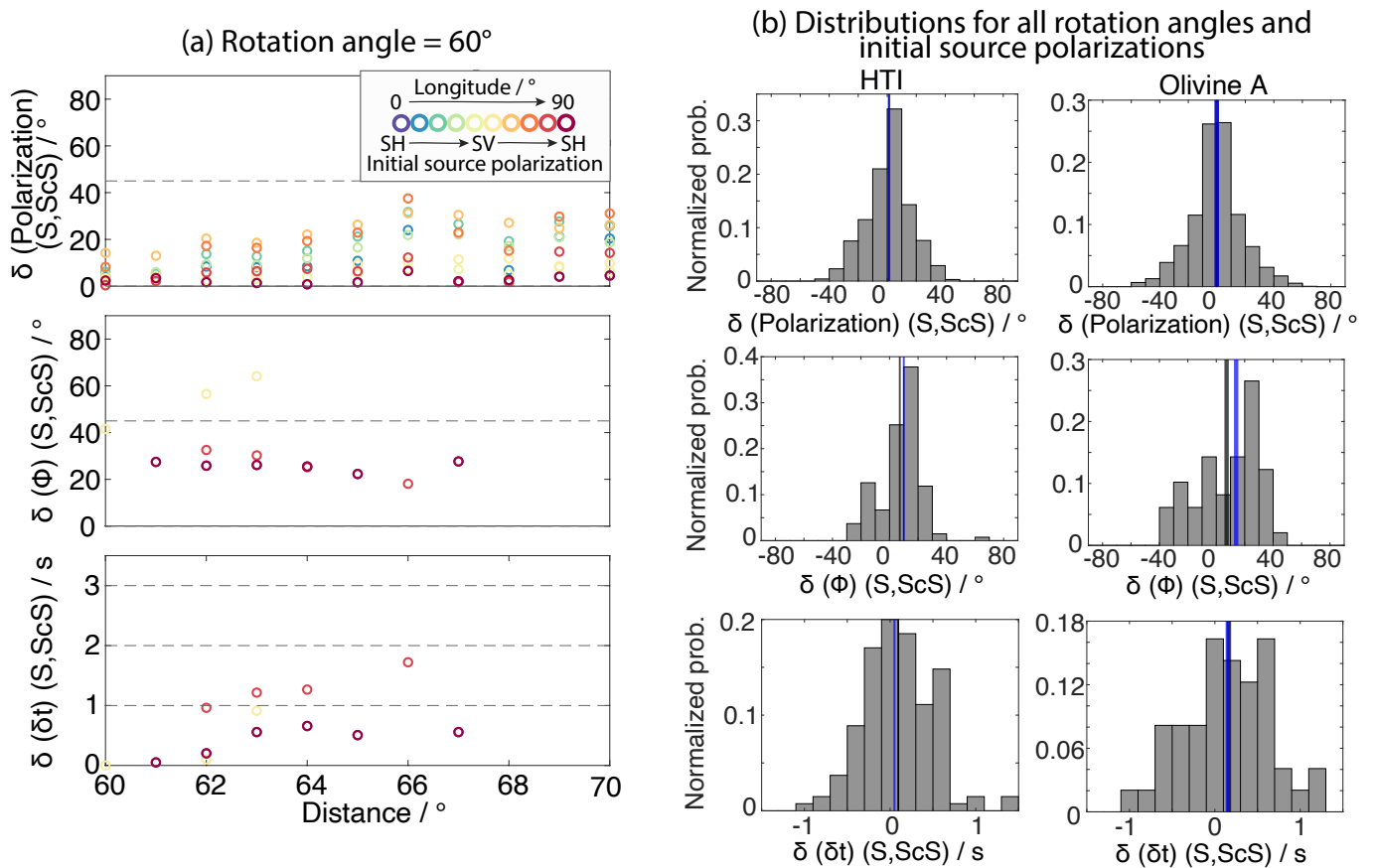
**Figure 8** Shear wave splitting parameters for input models that include global layers of lowermost mantle anisotropy and no seismic anisotropy in the upper mantle. (a) Results for a 150 km thick layer of Br anisotropy at the base of the mantle and PREM-velocities otherwise. Same plotting conventions as in Figure 6a. The range of  $\phi'$  values for the same deep mantle anisotropy, sampled from the same direction, but for different ScS initial source polarizations (see legend), is indicated by orange shading. (b) Results for a 175 km thick layer of Ppv anisotropy at the base of the mantle and PREM-velocities otherwise. Same plotting conventions as in panel (a). (c) Schematic illustration of the two ScS raypath legs through  $D''$ . Because the measured shear wave splitting is a combination of the sampled seismic anisotropy on both legs of the raypath and the initial source polarization, a range of  $\phi'$  values is obtained when sampling the same seismic anisotropy from the same direction for differently polarized ScS waves.

tions and fast polarization directions of ScS are different than those predicted from S by up to  $\sim 35^\circ$  and  $\delta t$  differs by up to 2 s. Summary histograms for all the results obtained using a range of different rotation angles for the anisotropy geometry (Section 2.1) are shown in Figure 9b. These results indicate that substantial differences between predicted source-side anisotropy associated splitting parameters from S and measured splitting parameters for ScS are common. Also, the assumption of a radial component sign-flip of ScS caused by the reflection is imperfect, sometimes leading to polarization differences of up to  $50^\circ$ .

Next, we systematically apply the source-side anisotropy splitting parameters, as inferred from S, to the ScS phase and then measure ScS splitting. If the source-side anisotropy correction was accurate, we would expect to measure null residual splitting from ScS as we did not incorporate deep mantle anisotropy in our simulations. (Recall that these simulations only include upper mantle anisotropy near the source.)

We define null measurements here as splitting measurements which have  $\delta t$ -values smaller than 0.3 s, or a 95% confidence interval that overlaps with values  $< 0.3$  s. This definition leads to few well-constrained  $(\phi, \delta t)$ -measurements with  $\delta t < 0.5$  s in Figure 10. We find that for the HTI elastic tensor, only  $\sim 63\%$  of the measured ScS splitting parameters are null after applying the source-side correction (Figure 10a). For olivine, this value is only  $\sim 23\%$ , meaning that in  $\sim 77\%$  of the cases apparent  $D''$  splitting is introduced by applying the source-side correction (Figure 10b).

The reason that the source-side anisotropy correction is not generally accurate is that the source-side contribution for ScS cannot accurately be inferred from S. In Figure 11 we show retrieved  $\delta t$  values for well-constrained ScS splitting measurements after accounting for source-side anisotropy inferred from S. If ScS source-side splitting parameters are used to correct ScS, in 98% of the cases no apparent  $D''$  splitting is introduced (Figure 11a), showing that our correction pro-



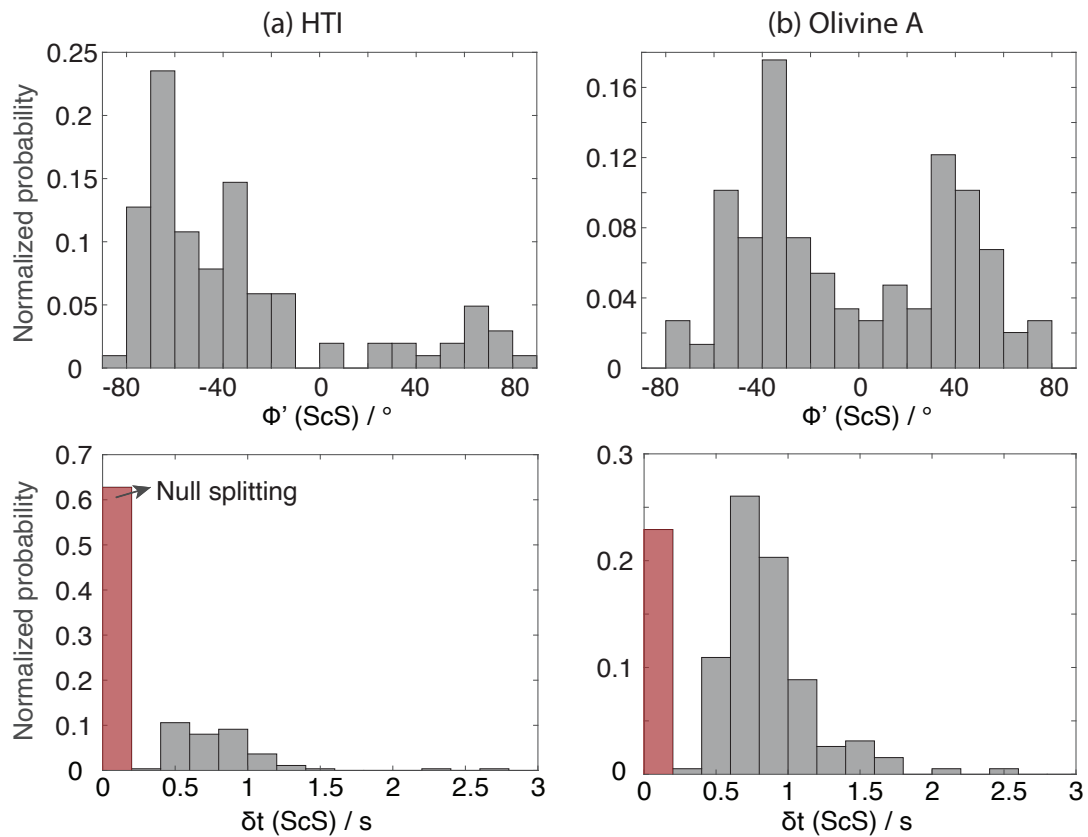
**Figure 9** Differences between estimated ScS polarizations, measured fast polarization directions  $\phi$ , and delay times  $\delta t$ , compared to the values that would be expected after S analysis if the radial ScS component was a perfectly sign-flipped version of the S radial component. Values are measured from synthetic waveforms generated for a model that includes source-side anisotropy only and PREM velocity structure elsewhere. Only well-constrained splitting results are shown (as defined in Section 5). (a) Example for the olivine elastic tensor shown in Figure 1c with a horizontal rotation angle of 60° (Section 2), and for different initial source polarizations (legend). Top: Absolute differences in predicted and measured ScS polarizations  $\delta(\text{Polarization})$ . Middle: Absolute differences in predicted and measured ScS fast polarization directions  $\delta(\phi)$ . Bottom: Absolute differences in predicted and measured ScS delay times  $\delta(\delta t)$ . (b) Histograms showing the distributions of  $\delta(\text{Polarization})$  (top),  $\delta(\phi)$  (middle) and  $\delta(\delta t)$  (bottom) for HTI (left) and olivine (right) anisotropy (Figure 1c) for all initial initial polarizations and elastic tensor rotation angles (Section 2.1). Distribution means are shown as solid black lines and medians as solid blue lines.

cedure works well if splitting is perfectly known. We can use these insights to suggest three different strategies for accounting for source-side anisotropy. First, we can restrict measurements of ScS splitting to cases for which S source-side splitting is null (Figure 11b). Second, we can minimize the influence of source-side upper mantle anisotropy by only measuring ScS splitting from deep seismic events. However, the presence of seismic anisotropy has been suggested in the uppermost lower mantle, particularly in subduction zones has been suggested by several studies (e.g., Foley and Long, 2011; Lynner and Long, 2015; Mohiuddin et al., 2015). Therefore, such an approach would not necessarily (always) be reliable. Third, we can apply a source-side anisotropy correction if we measure a ScS polarization that is within 10° of the expected initial polarization for a sign-flip of the ScS radial component Figure 11c). In 90% of these cases, null D'' splitting is correctly predicted from ScS if measured S source-side splitting is null (Figure 11b), suggesting that these strategies allow for the accurate consideration of source-side split-

ting in certain cases. In contrast, explicit source-side anisotropy corrections are inaccurate when these conditions are not met, even when ensuring that the ScS polarization is as expected from S (Figure 11c).

## 8 Correction of ScS for receiver-side anisotropy contribution inferred from SKS

As discussed in Section 7, we now better understand the strengths and weaknesses of the source-side correction for shear wave splitting; however, the receiver-side corrections remain to be explored. We next use a realistic synthetic setup to test the accuracy of receiver-side corrections. We again incorporate olivine A-type (Figure 1c) anisotropy in the upper mantle and infer upper mantle shear wave splitting parameters from the SKS seismic phase recorded at an epicentral distance of 100°. We fit a  $\sin(2\theta)$ -curve to the SKS  $SI$  values as a function of backazimuth, as commonly done for real



**Figure 10** Distributions of measured  $\phi'$  and  $\delta t$  for all initial polarizations and elastic tensor rotation angles after correcting for source-side anisotropy measured from S, only showing well-constrained results (as defined in Section 5). (a) Results for a model including HTI source-side anisotropy and PREM-velocities elsewhere. Top:  $\phi'$  histograms; bottom:  $\delta t$  histograms.  $\phi'$  values are only plotted for non-null measurements. Measurements are defined as null if the 95% confidence interval of  $\delta t$  overlaps with the interval  $[0 \text{ s}, 0.3 \text{ s}]$ . Null measurements are indicated in orange color. (b) Same as panel (a) for olivine A source-side anisotropy.

data (e.g., Chevrot, 2000; Monteiller and Chevrot, 2010). These results are shown in Figure 12a. The determined best-fitting splitting parameters are then used to correct ScS for the effect of anisotropy beneath the receiver for simulations that only include upper mantle receiver-side anisotropy. For approximately 40% of robust ScS measurements (for the setup shown in Figure 1) the measured splitting is null (Figure 12b), as expected. For the remaining 60% of robust measurements, a variety of  $\phi'$  and  $\delta t$  values are obtained (Figure 12b). This exercise demonstrates that explicit receiver-side corrections for upper mantle anisotropy beneath the receiver are likely unreliable in real data. The challenges are likely to be particularly given that splitting patterns as a function of backazimuth are often substantially more complicated than in this simple synthetic scenario.

An example of a robust (but artificial) ScS splitting measurement obtained after correcting for receiver-side anisotropy determined using SKS phases is shown in Figure 13. This particular case corresponds to a scenario in which the olivine A-type elastic tensor is sampled from a backazimuth of  $80^\circ$  in Figure 12a. It is apparent that the  $\sin(2\theta)$ -fit is imperfect for this backazimuth (Figure 12a), which is why the corrected waveform (Figure 13a) appears substantially split, the particle motion (Figure 13b) mimics splitting, and splitting parameters are well-constrained with very tight

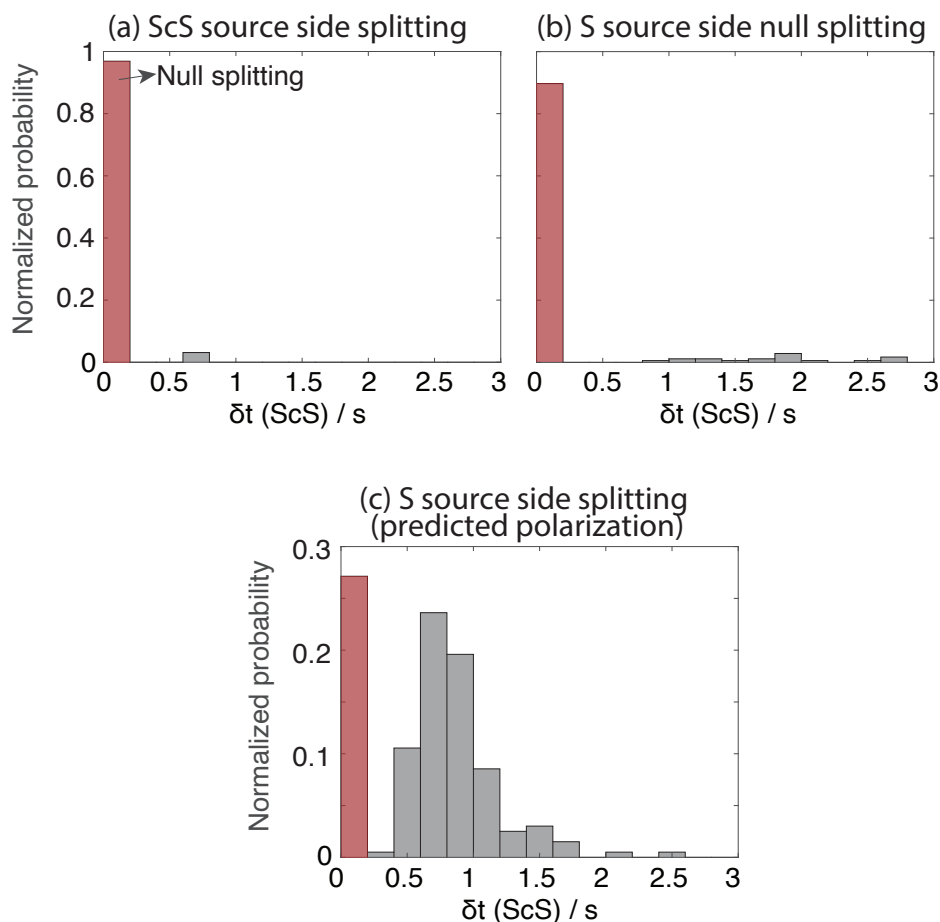
uncertainty intervals (Figure 13c), despite the lack of  $D''$  anisotropy in this simulation.

While we conduct these measurements for ScS in this work, our calculations are similarly applicable for the measurement of S splitting after correcting for receiver-side anisotropy inferred from SKS, which is commonly done to infer seismic anisotropy in the transition zone in subduction zones (e.g., Russo et al., 2010; Mohiuddin et al., 2015; Eakin et al., 2018). One potential way to deal with this challenge may be to correct for upper mantle splitting beneath the receiver determined using other phases measured at the same backazimuth, preferably for the same source-receiver configuration. However, this appears challenging for ScS distance between  $60^\circ$  and  $70^\circ$ , as there is no obvious additional phase that could be used for such an approach.

## 9 Discussion

### 9.1 How to infer $D''$ anisotropy from ScS splitting measurements

We have shown that  $D''$  anisotropy is challenging to infer from ScS waves that arrive at epicentral distances  $< 60^\circ$ , because CMB reflection coefficients for the SV component will strongly depend on the deep mantle velocity structure close to the ScS reflection point (Fig-



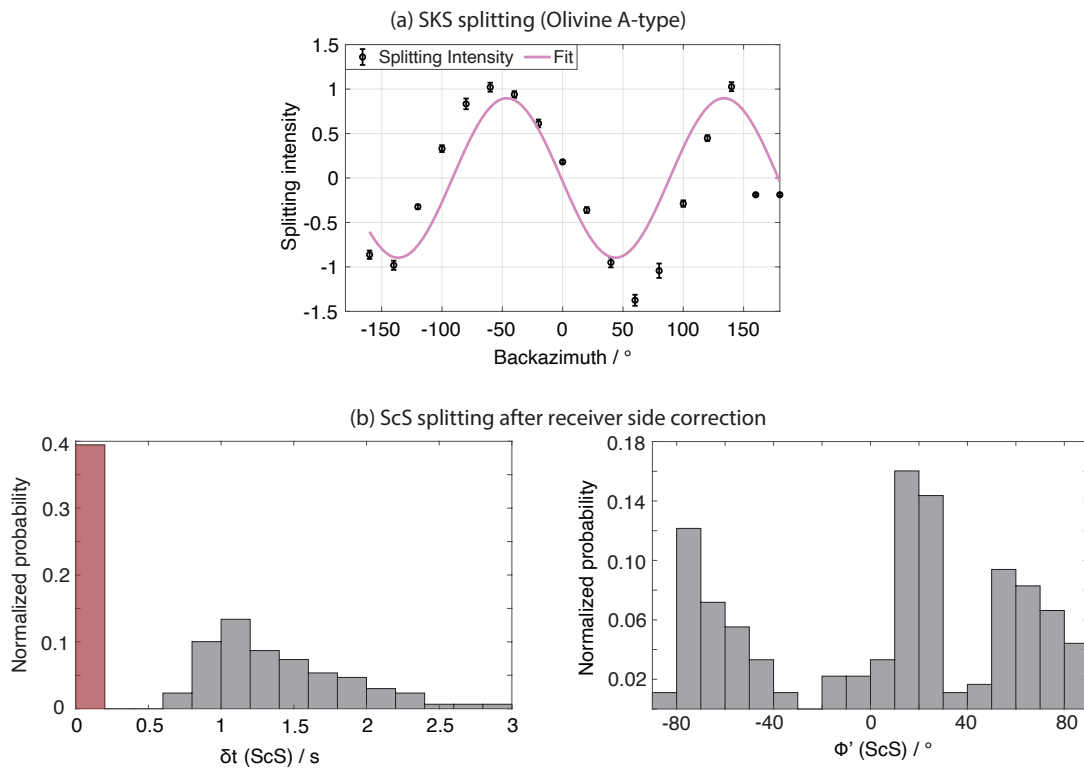
**Figure 11** Retrieved  $\delta t$  values for well-constrained ScS splitting measurements after accounting for olivine source-side anisotropy, for the same set of simulations used in Figure 10. Only well-constrained splitting results are shown (as defined in Section 5). (a) Histograms of results obtained after correcting ScS waveforms for source-side anisotropy measured from the same ScS waveform. Plotting conventions are the same as in the bottom panel of Figure 10a. (b) ScS  $\delta t$  measurements for those S-ScS pairs for which S source-side splitting is null. Plotting conventions are as in panel (a). (c) Histogram of ScS  $\delta t$  measurements obtained after correcting for source-side anisotropy inferred from S for those S-ScS pairs for which ScS polarizations are as predicted from S (under the assumption of a sign-flip of the radial component of ScS through the CMB reflection). Plotting conventions are as in panel (a).

ure 3). Therefore, polarization directions of ScS, as well as apparent  $Pol/Pol_{90}$  amplitude ratios, will be influenced by effects other than seismic anisotropy. For epicentral distances between  $70^\circ$  and  $80^\circ$ , the ScS arrival may potentially be contaminated by (P)PS or SP (Figures 2 and 5), which strongly influences ScS polarizations (Figure 5). This can, in some cases, cause apparent ScS splitting in absence of seismic anisotropy (Figure 6c). For even larger distances, S and ScS merge (Figures 2, 4 and 5), which can lead to effects that mimic splitting, even for simple isotropic models such as isotropic PREM (Figure 6). Apparent splitting caused by isotropic effects at these distances can be indistinguishable from shear wave splitting caused by lowermost mantle anisotropy, with the waveform shape of the  $Pol_{90}$  component approximately agreeing with the time derivative of the  $Pol_0$  component (Figure 7). Therefore, we suggest that ScS shear wave splitting measurements are difficult to reliably perform for epicentral distances  $> 70^\circ$  and for most epicentral distances  $< 60^\circ$  (with the exception, perhaps, of almost vertical incidence angles for small distances).

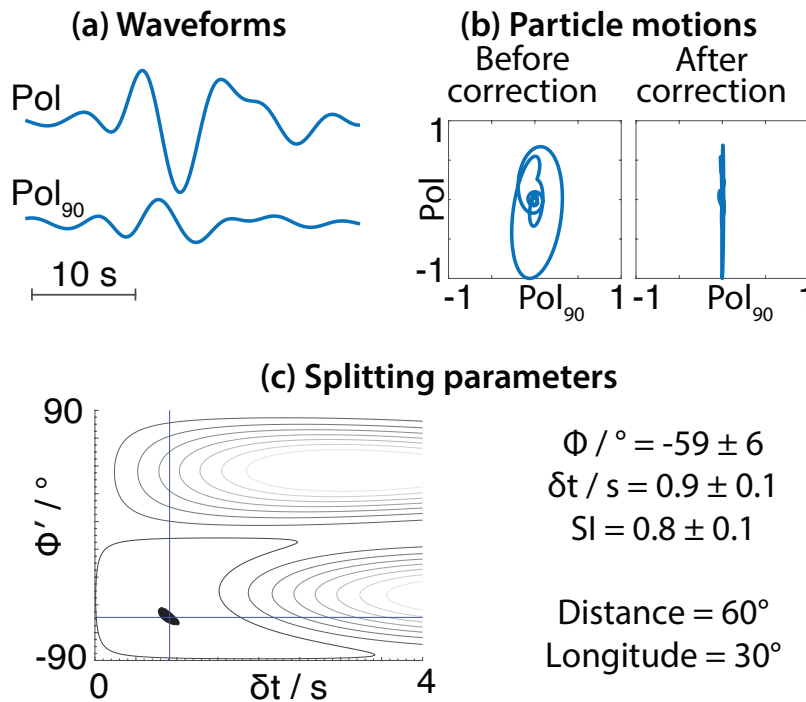
In the candidate epicentral distance range between  $60^\circ$  and  $70^\circ$  for ScS splitting measurements, the receiver- and source-side anisotropy influence is often explicitly corrected to extract the lowermost mantle contribution. However, we have shown that explicit upper mantle anisotropy corrections can be unreliable (Figures 10 to 13) and therefore recommend only using ScS waves for which both source-side and receiver-side anisotropy are null. Practically, this means that ScS splitting measurements should only be applied at null stations for S-ScS pairs for which S source-side splitting is null. While these precautions mean that a much smaller number of S-ScS pairs are available for D'' splitting studies, they are likely to result in significantly higher-quality estimates of ScS splitting due to lowermost mantle anisotropy.

## 9.2 Global measurements of ScS splitting due to deep mantle anisotropy

We apply our strategy for estimating D''-associated ScS splitting measurements worldwide at the null stations reported by Lynner and Long (2013) and Walpole et al.



**Figure 12** Apparent shear-wave splitting from ScS waveforms that were corrected for upper mantle anisotropy. (a) SKS *SI* values (black circles) and 95% confidence intervals (error bar) as a function of backazimuth. The fitted  $\sin(2\theta)$ -curve to determine best-fitting splitting parameters is shown in pink. The best-fitting values are ( $\phi = -1.2^\circ, \delta t = 0.9$  s). (b)  $\phi'$  and  $\delta t$  histograms using the same plotting conventions as in Figure 10a.

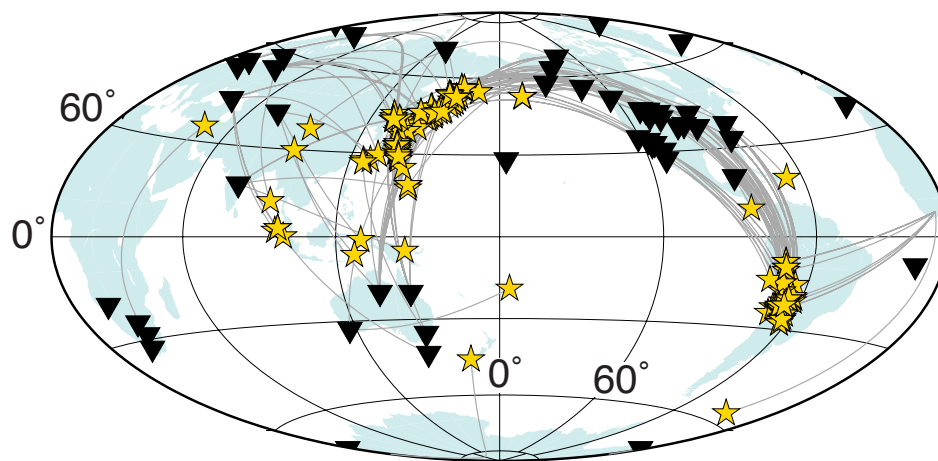


**Figure 13** Measured shear wave splitting from waveforms corrected for upper mantle anisotropy inferred from SKS (Figure 12). Plotting conventions are identical to Figure 7.

(2014). We use all seismic events with moment magnitude  $> 5.7$  in an epicentral distance range between  $60^\circ$  and  $70^\circ$  that occurred after January 1, 1990. The raypath coverage for all source-receiver pairs for which we could obtain well-constrained ScS splitting measurements is shown in Figure 14. Following the recommen-

dations developed here, we only interpret ScS splitting as being indicative of deep mantle anisotropy if the S phase for the same source-receiver pair is not split. An example splitting measurement for such a S-ScS pair is presented in Figure 15.

We follow our suggested procedure to calculate split-



**Figure 14** Source (yellow stars)-receiver (black triangles) configuration for global deep mantle anisotropy analysis using ScS. The selected stations are the null stations reported by [Lynner and Long \(2013\)](#) and [Walpole et al. \(2014\)](#). We only show sources for which well-constrained  $D''$  anisotropy associated  $SI$  values could be obtained. Great circle raypaths are shown as gray lines.

ting parameters to all our seismic data for null stations. All ScS splitting measurements due to lowermost mantle anisotropy are shown in map view in Figure 16. In some cases only well-constrained splitting intensities can be obtained. In other cases, splitting parameters ( $\phi'$ ,  $\delta t$ ) can also be reliably measured. We can identify four different deep mantle regions A-D that show at least some evidence for anisotropy (Figure 16). Overall, we find evidence for seismic anisotropy in all regions in which ray coverage is good, suggesting that lowermost mantle anisotropy is likely widespread. These regions include central Asia (A), southeast Asia (B), northeast Russia/Alaska (C), and the Caribbean (D). North of region A, multiple studies have previously reported seismic anisotropy in  $D''$  (e.g., [Wookey and Kendall, 2008](#); [Creasy et al., 2021](#)). Our results for this raypath corridor approximately agree with the  $\phi'$  values of  $35^\circ$  reported by [Creasy et al. \(2021\)](#) but are different than those from [Wookey and Kendall \(2008\)](#), who reported  $\phi' \approx -7^\circ$ . However, as mentioned above,  $\phi'$  values depend on the initial polarization of the ScS wave, which is why we cannot necessarily expect to obtain the same  $\phi'$  values for a particular region if the ScS initial polarizations in the dataset vary. [Grund and Ritter \(2018\)](#), [Thomas and Kendall \(2002\)](#) and [Wolf et al. \(2022b\)](#) also identified lowermost mantle anisotropy in some parts of region A using a different methodology. These measurements are hard to directly compare with ours; however, these studies are consistent with our finding of  $D''$  anisotropy here.

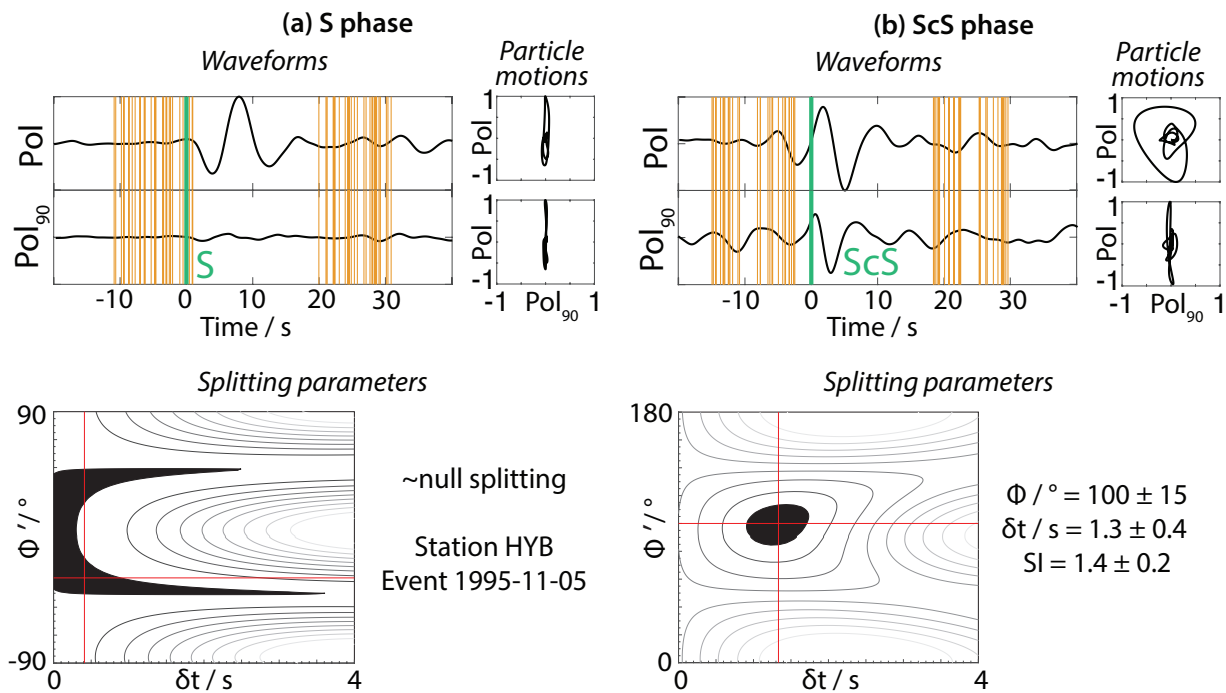
Deep mantle anisotropy in region B has not been previously studied. We find the lowermost mantle in this region to be generally anisotropic; however, the strength of splitting due to seismic anisotropy varies (Figure 16).  $\phi'$ -values tend to be close to  $0^\circ$  in most cases, but this – on its own – is an insufficient constraint on the geometry of anisotropy without taking into account the wave's initial polarization. The ScS raypaths through  $D''$ , shown in the inset for region B (Figure 16), are close to the edge of the Pacific LLVP and show evidence for seismic anisotropy. This agrees with

the finding of other studies that seismic anisotropy is often strong close to such edges (e.g., [Wang and Wen, 2004](#); [Lynner and Long, 2014](#); [Deng et al., 2017](#), [Reiss et al., 2019](#); [Wolf and Long, 2023](#)).

Much of region C has been found to be anisotropic in previous studies (e.g., [Wookey et al., 2005](#); [Asplet et al., 2020, 2023](#); [Suzuki et al., 2021](#); [Wolf and Long, 2022](#); [Wolf et al., 2023a; 2024](#)). Direct comparisons to many of these studies are difficult because they used different methods to infer the presence of seismic anisotropy. [Wookey et al. \(2005\)](#) used S-ScS differential splitting to investigate the west portion of region C. Additionally, seismic anisotropy has been detected in the western part of region C using multiple different methods (e.g., [Wolf and Long, 2022](#); [Asplet et al., 2023](#)), which include S-ScS and SKS-SKKS differential splitting as well as  $S_{\text{diff}}$  splitting. Notably, we also detect particularly strong seismic anisotropy in this region.

Seismic anisotropy in region D has been identified by a large number of previous studies (e.g., [Kendall and Silver, 1996](#); [Rokosky et al., 2004, 2006](#); [Garnero et al., 2004](#); [Maupin et al., 2005](#); [Nowacki et al., 2010](#)). The study by [Nowacki et al. \(2010\)](#) also used S-ScS differential splitting measurements. Interestingly, we find splitting due to seismic anisotropy to be strong beneath central America and almost absent further to the east (Figure 16). In the northwest part of region D, shear wave splitting is weak as well, while it is substantially stronger in the southwest (Figure 16). To the east of region D we obtain five measurements that consistently show no evidence for splitting due to deep mantle anisotropy, and whose initial polarizations differ by up to  $40^\circ$ . Therefore, we find the deep mantle in this region to likely be isotropic, in disagreement with the findings of [Pisconti et al. \(2023\)](#).

Due to the constraints that we impose in our approach to the measurement of ScS splitting, a large majority of seismograms cannot be used to reliably measure ScS splitting due to lowermost mantle anisotropy. A back-of-the-envelope calculation suggests that approximately 15 million three-component seismograms are currently



**Figure 15** Example of an S and ScS splitting pair used to infer deep mantle anisotropy at station HYB for an event of 1995-11-05. (a) S *Pol* and *Pol*<sub>90</sub> component velocity waveforms (top left). The PREM-predicted phase arrival time is shown by a light green line and the start/end of the automatically selected measurement windows are shown as orange lines. At the right we show S particle motions before (top) and after (bottom) correcting for the best fitting splitting parameters. At bottom, we show the best fitting splitting parameters for S in the  $\phi$ - $\delta t$  plane. The 95% confidence interval is shown in black. Splitting for this S arrival is null. (b) Same as panel (a) for the corresponding ScS phase. ScS splitting parameters are shown in the bottom right.

publicly available for seismic events with moment magnitudes over 6.0. In this work, we obtain  $\sim 130$  robust ScS splitting measurements for seismic events with such moment magnitudes, using all null stations known to us (which may not be all that exist). Following this line of reasoning, under the constraints used in this study, only one out of every 100,000 seismograms is expected to yield a robust ScS splitting measurement of lowermost mantle anisotropy – a very small minority of available data. However, with the suggestions we put forward in Section 10, it may be possible increase this number.

### 9.3 Interpretations of ScS splitting measurements due to deep mantle anisotropy

Our work demonstrates that when multiple sets of splitting parameters ( $\phi$ ,  $\delta t$ ) due to lowermost mantle anisotropy can be estimated in a particular region, a significant spread of these values can be expected (Figure 8). The reason is that the measured ( $\phi$ ,  $\delta t$ )-values do not only depend on the nature of deep mantle anisotropy but also on the initial polarization of ScS. Therefore, the measurement scatter shown in Figure 16 does not imply that measurements are unreliable because displaying measurements in map projection does not account for the wave's initial polarization. In fact, all *SI* measurements that are plotted on top of each other in Figure 16 and whose *SI* values differ have at least somewhat different initial polarizations. In order to thoroughly characterize the geometry of deep man-

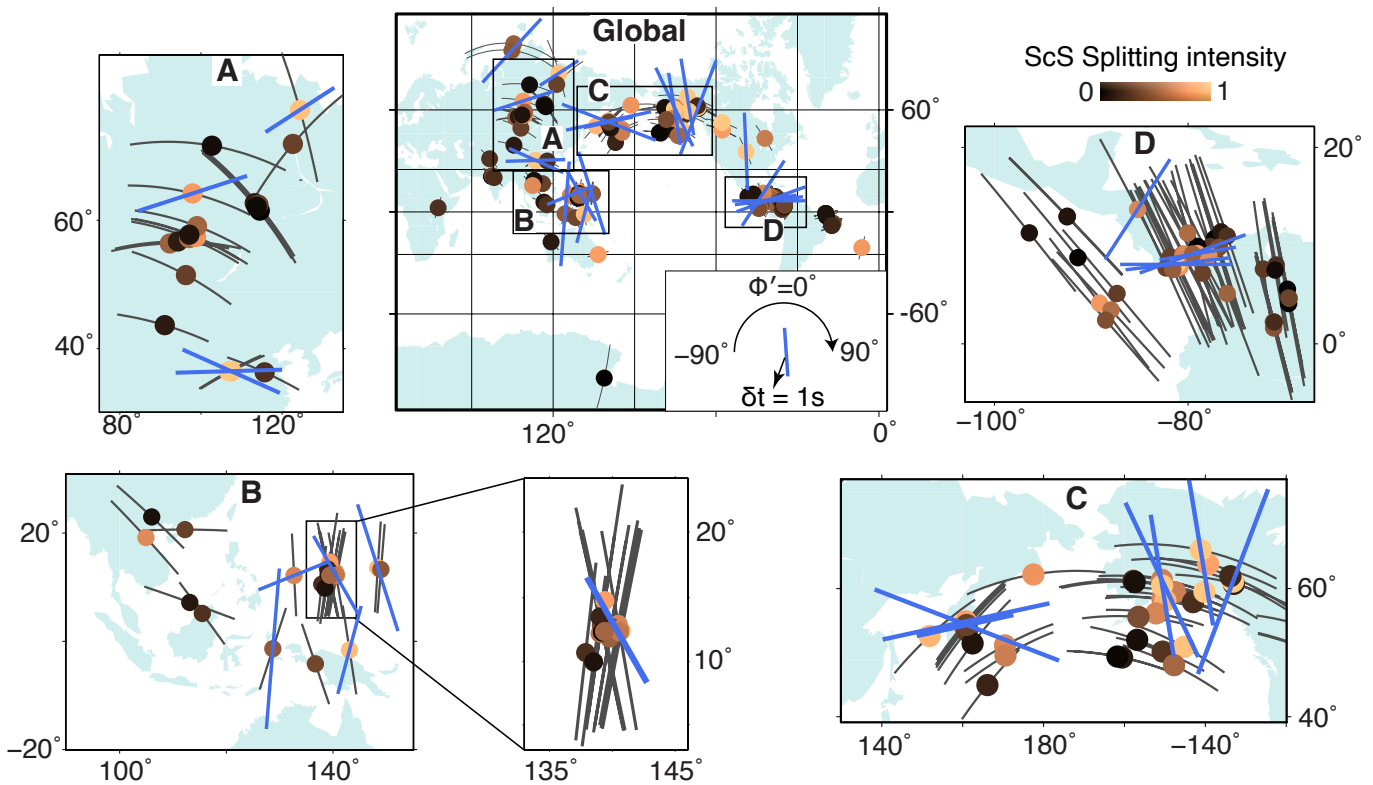
tle seismic anisotropy measured from ScS waves, a sufficient number of splitting measurements is needed to allow for forward modeling or inversions that explicitly consider the initial polarization of each wave. Practically, a sufficient number of measurements may be difficult to obtain in many regions, given the substantial restrictions imposed to correctly account for potential upper mantle contributions.

One potential way to make use of ScS splitting measurements to constrain the geometry of anisotropy as opposed to merely using them as an anisotropy detector is to interpret them along with other independent constraints, such as SKS-SKKS differential splitting (e.g., Asplet et al., 2023), *D'* reflection polarities (e.g., Piscinti et al., 2023), or *S*<sub>diff</sub> splitting (e.g., Wolf et al., 2023b). When multiple constraints are available, ray-theoretical forward modeling (e.g., Wolf et al., 2019; Piscinti et al., 2023), full-wave simulations (e.g., Wolf et al., 2022a; 2022b), or inversions of ScS waveforms (Asplet et al., 2023) can potentially shed light on deformation in the deep mantle.

## 10 Ways forward

We have shown that it can be difficult to infer deep mantle anisotropy from ScS splitting measurements due to potential contamination from upper mantle anisotropy, which is difficult to account for. We have suggested a strategy of avoiding explicit upper mantle anisotropy corrections going forward by focusing on null stations and S-ScS pairs for which S is not split due to source-side





**Figure 16** ScS splitting results for S-ScS pairs measured for station-event pairs shown in Figure 15, for which S splitting is null. Top center: Global results. ScS great circle raypaths through the lowermost 250 km of the mantle are shown as dark gray lines. Well-constrained ScS splitting intensity values are shown as colored circles (legend) at the ScS reflection point at the CMB. Splitting parameters ( $\phi'$ ,  $\delta t$ ; see legend) are shown as blue sticks and centered at the ScS reflection location. Different regions A-D with many well-constrained measurements are identified and labeled. Zoom-ins to these regions are shown in panels A-D surrounding the central plot.

upper mantle anisotropy. Crucial for this approach will be the identification of more null stations worldwide. In this work, we have used the null stations identified by Lynner and Long (2013) and Walpole et al. (2014); however, more null stations likely exist. Given the increased availability of seismic data since these two studies were published, it appears worthwhile to automatically and uniformly analyze all available broadband data to search for null stations, for example using an approach similar to Walpole et al. (2014).

Another possibility to increase the number of ScS splitting measurements due to deep mantle anisotropy is to use beamforming, which has only recently been applied in shear wave splitting studies (Wolf et al., 2023a). It has been shown that a beamforming approach effectively averages the upper mantle anisotropy contribution across the individual stations used to construct the beam (Wolf et al., 2023a). Therefore, it is possible to intentionally select stations such that the upper mantle anisotropy contribution to the beam beneath the array on the receiver side is effectively null. For such a station configuration, ScS splitting can be measured if the corresponding S beam splitting for the same source-array combination is null, indicating the absence of source-side anisotropy.

Interpretations of ScS splitting results in terms of anisotropic geometry will continue to be challenging. For such interpretations, the initial polarization of ScS will have to be explicitly considered. This has effectively

been done by Asplet et al. (2023) by ensuring that ScS polarizations (approximately) agree with the backazimuth (through analysis of particle motions), although they used explicit upper mantle anisotropy corrections in their approach. At least in theory one could even go further: Seismic anisotropy in the lowermost mantle could be characterized by analyzing splitting intensities as a function of initial polarization for waves that sample the same lowermost mantle portion. However, given that we are dealing with two-layer splitting, this requires a much larger number of measurements than we have obtained for any particular region in this study (Figure 16). Most previous studies have not explicitly taken into account the ScS polarization and operated under the assumption that splitting due to  $D''$  anisotropy should lead to the same ( $\phi'$ ,  $\delta t$ ) values for the same region and sampling direction (e.g., Creasy et al., 2017; Wolf et al., 2019; Pisconti et al., 2023).

If a sufficient number of ScS splitting measurements from earthquakes with different initial source polarizations can be obtained for a given set of raypaths sampling  $D''$ , a two-layer inversion for splitting parameters on the down- and upgoing leg of the raypath appears promising. Such an approach can be applied analogously to two-layer splitting analysis for the upper mantle (e.g., Silver and Savage, 1994; Wolfe and Silver, 1998; Aragon et al., 2017; Link et al., 2022). In our study, unfortunately, the number of well-constrained ( $\phi$ ,  $\delta t$ ) measurements in any particular region is insufficient for the

implementation of such an approach. As mentioned above, *SI* scattering is often straightforward to explain by different initial polarizations; in contrast, a precise characterization of the seismic anisotropy is challenging unless a large number of *SI* values for the same region can be obtained. Much easier is the detection of isotropic regions through initial polarization analysis, such as the isotropic region east of region D. The reason is that no more than a handful of null measurements with mutually different initial polarizations need to be obtained for the reliable characterization of an isotropic lowermost mantle region.

Going forward, it will also be important to combine ScS constraints with constraints from other seismic phases, whether waveform inversions (e.g., Asplet et al., 2023) or ray-theoretical forward modeling (e.g., Ford et al., 2015; Wolf et al., 2019; Pisconti et al., 2023) approaches are used. Given the issues that have been pointed out with the use of ray-theoretical assumptions (Nowacki and Wookey, 2016; Wolf et al., 2022a), it will be preferable to move away from ray-theory in future studies and make use of available full-wave modeling tools, including AxiSEM3D.

## 11 Conclusions

Using global wavefield simulations and calculations of ScS reflection coefficients, we have explored how ScS polarizations are affected by the CMB reflection. We find that measured ScS polarizations at the receiver, depend not only on the initial source polarization, but also on the deep mantle velocity structure at the reflection point and on the epicentral distance under consideration. In particular, in the epicentral distance between  $60^\circ$  and  $70^\circ$ , the CMB reflection can be well approximated as a sign-flip of SV, while SH is unaltered. For distances close than  $60^\circ$ , SV amplitudes are affected by the reflection, and for distances above  $70^\circ$ , apparent shear wave splitting can be introduced for isotropic input models due to phase interference, for example with S. Therefore, the distance range suitable for ScS splitting measurements is  $60^\circ$  to  $70^\circ$ .

If ScS shear wave splitting is caused by lowermost mantle anisotropy, the measured apparent splitting parameters are substantially influenced by the initial source polarization of the wave. The reason is that each leg of the ScS raypath through  $D''$  (downgoing and upgoing) experience splitting separately. Therefore, for any  $D''$  region that is sampled from the same direction by multiple ScS waves, we would expect to measure a range of apparent splitting parameters that depend on the initial polarizations of the ScS waves. We have shown that if an anisotropy contribution on the source side is inferred from S splitting and then used to correct the ScS waveform, in many cases apparent  $D''$  splitting can be introduced. Similar issues exist for explicit receiver-side corrections. Therefore, we suggest a strategy that only uses null stations to infer deep mantle anisotropy from ScS. Measurements of ScS splitting at null stations should only be attributed to deep mantle anisotropy if the measured S splitting for the same source-receiver pair is null. We have applied this analysis strategy glob-

ally and detected deep mantle seismic anisotropy in multiple regions around the Earth, including regions that have not been shown to be anisotropic before, for example, southern Russia and the southwestern Pacific Ocean.

Going forward, to improve  $D''$  anisotropy sampling using ScS, the identification of more null stations and the implementation of beamforming approaches in terms of the geometry of anisotropy will be helpful. Interpretations of ScS splitting going beyond using ScS as a simple anisotropy detector will need to consider the initial polarization of each ScS wave as well as potentially different splitting on the two ScS raypath legs through  $D''$ . While this approach is not typically incorporated in ScS splitting studies at present, it holds promise for gaining insight into the geometry of the anisotropy, and thus flow at the base of the mantle.

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## Data and code availability

All data used in this study are publicly available through Earthscope (<http://service.iris.edu>), SCEDC (<http://service.-scedc.caltech.edu>), RESIF (<http://ws.resif.fr>) and GEOFON (<http://geofon.gfz-potsdam.de>) data centers. We used data from USArray (IRIS Transportable Array, 2003) and data from networks AK (Alaska Earthquake Center, Univ. of Alaska Fairbanks, 1987), AT (NOAA National Oceanic and Atmospheric Administration (USA), 1967), CI (California Institute of Technology and United States Geological Survey Pasadena, 1926), CN (Canada, 1975), G (Institut de physique du globe de Paris (IPGP) and École et Observatoire des Sciences de la Terre de Strasbourg (EOST), 1982), GE (GEOFON Data Centre, 1993), GT (Albuquerque Seismological Laboratory (ASL)/USGS, 1993), II (Scripps Institution of Oceanography, 1986), IU (Albuquerque Seismological Laboratory/USGS, 2014), NL (KNMI, 1993), NR (Utrecht University (UU Netherlands), 1983), PM (Instituto Português do Mar e da Atmosfera, I.P., 2006), IU (Albuquerque Seismological Laboratory/USGS, 2014). The synthetic seismograms for this study were computed using AxiSEM3D, which is publicly available at <https://github.com/AxiSEMunity> (Fernando et al., 2024). The Generic Mapping Tools (Wessel and Smith, 1998), ObsPy (Beyreuther et al., 2010), MSAT (Walker and Wookey, 2012), SplitRacer (Reiss and Rumpker, 2017) and AxiSEM3D (Leng et al., 2016) were used in this research.

## Competing interests

The authors declare no competing interests with respect to this manuscript.

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