

# Modeling of Anisotropy in the Lithosphere and Asthenosphere for Real Earth Cases: A Critical Assessment of the Impact on SKS Measurements

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## Key Points:

- We analyze the effects of realistic Earth's lithospheric structures on SKS splitting parameters
- Highly anisotropic crustal materials can explain 40% of the SKS time delay
- In realistic cases, the observed average SKS splitting direction does not always represent the asthenospheric flow direction

## Supporting Information:

- Supporting Information S1

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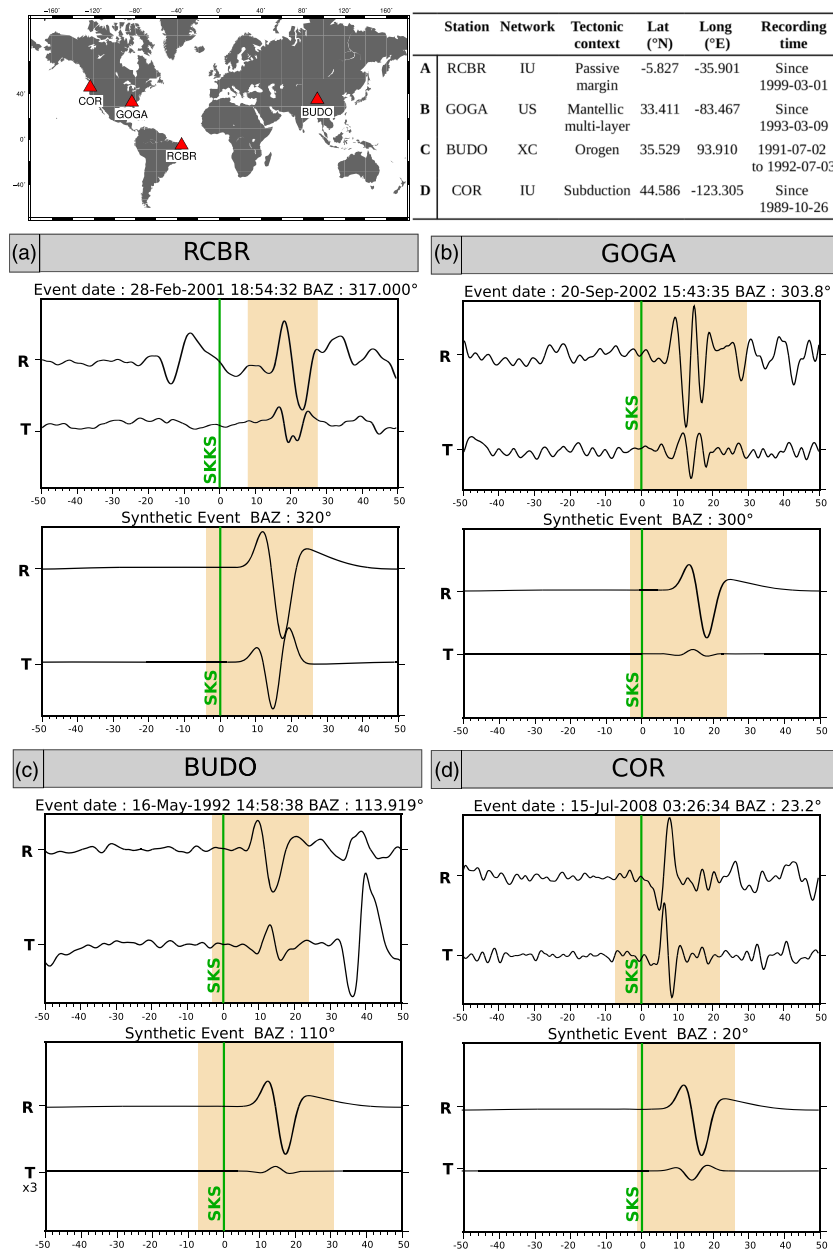
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**Abstract** We investigate effects of realistic Earth's lithospheric structures on measurements of SKS seismic waves birefringence, which could be perturbed by different factors. We present SKS measurements recorded in four different tectonic settings. For each case, a realistic lithospheric structure is assumed and synthetic SKS splitting measurements are compared with the field observations. Our results show that (a) in a simple case, where anisotropy is aligned in both the lithospheric mantle and the asthenosphere, the SKS measurements can be safely interpreted as dominantly related to asthenospheric mantle flow; (b) in case of multilayer anisotropy in the lithospheric mantle, SKS measurement can correspond to a combination of the different fast-axis orientations and intensities of the anisotropic layers, dominated by the layer with stronger anisotropy; (c) across orogens, where highly anisotropic ( $\geq 10\%$ ) crustal sections are present, a relevant percent (30–40%) of SKS measurement can be explained by crustal contributions, with additional challenge related to the different direction of retrieved and expected symmetry axis; and finally, (d) in subduction zones, even in the absence of mantle corner flow, subducted crust materials can interplay with the overriding plate to generate an interpretable SKS observation. We conclude that complex crustal and/or lithospheric anisotropy can lead to erroneous SKS splitting parameters interpretations in terms of mantle deformations. We show in particular that complex crustal anisotropy can produce both important time delay and back azimuthal pattern. We also confirm that SKS splitting parameters do not allow to identify the presence of more than two anisotropic layers in the mantle.

## 1. Introduction

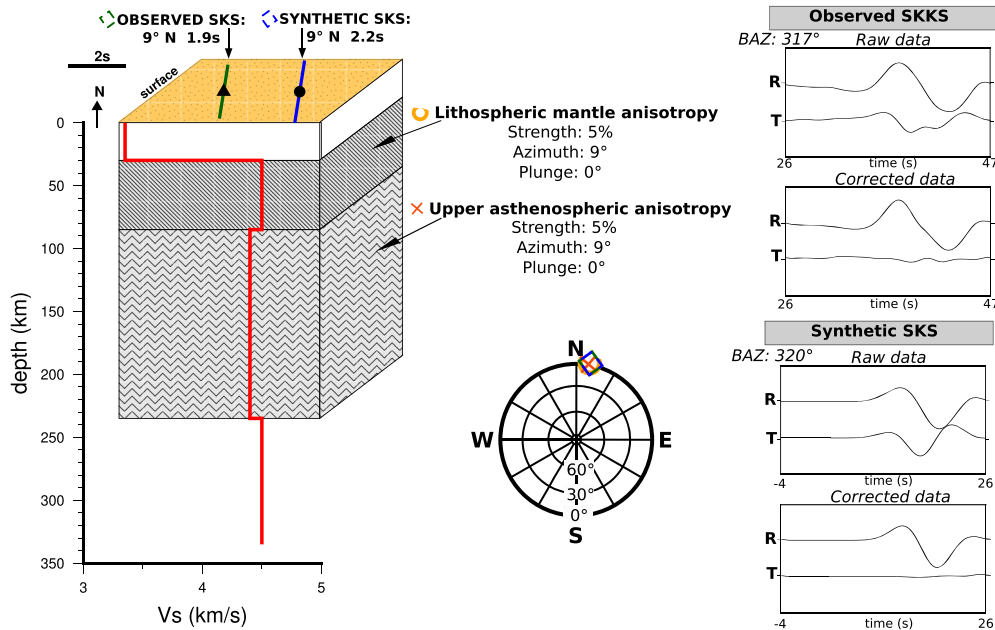
Measuring seismic anisotropy within the Earth is essential as it constitutes a proxy for inferring upper mantle deformation related to mantle flow that develops preferred orientations of the minerals in response to tectonic strain (Mainprice et al., 2000; Nicolas & Christensen, 2013; Silver et al., 1999). The most used and longest-standing method to detect anisotropy beneath a seismic station is the measurement of teleseismic core-refracted SKS, SKKS, PKS, and PKKS (hereinafter referred to as XKS) wave splitting on two horizontal recordings. This method consists on measuring the direction of fast polarization ( $\varphi$ ) and the delay time ( $\delta t$ ) between the two fast- and slow- polarized shear waves generated by the presence of anisotropic material. This technique allows an integrative measurement which estimates the average  $\varphi$  and  $\delta t$  along the entire XKS raypath. The nearly vertical propagation of XKS waves within the lithosphere and the asthenosphere beneath the seismic station provides high lateral but poor vertical resolution on the measurement of anisotropy.

This lack of depth-dependent resolution related to the presence of anisotropy at depth can result in misinterpretation regarding mantle deformation in several cases and, consequently, can lead to erroneous geodynamical implications. For example, discrimination between crustal and mantle anisotropy is essential to infer deformation processes in orogenic belts or continental rifting (Gueydan et al., 2008; Meissner et al., 2002). Questions regarding (de)coupling at the Moho boundary and implications for lithospheric deformations remain highly debated (Brun, 2002; Vauchez et al., 1998). Latifi et al. (2018) show with synthetic examples that even for simplistic models with only one moderate to weak anisotropic layer with horizontal axis of symmetry, the crust can have significant impact on the XKS splitting parameters. It is thus important to



**Figure 1.** Localization of selected stations and examples of observed and synthetic XKS phases at each station. The green line represents the arrival time as predicted by automatic traveltimes calculation. The yellow window corresponds to the manually selected window for XKS phase analyses. Note that amplitudes of the synthetic transverse components are multiplied by 3 for station BUDO.

understand the effect of crustal anisotropy for more realistic crustal models including several anisotropic layers with both horizontal and plunging axis of symmetry. In fact, XKS measurements are highly sensitive to anisotropic media with horizontal axis of symmetry, but they could be difficult to interpret in a region with plunging axis of symmetry (such as a subduction zone), unless combining them with other independent seismic data (Levin et al., 2007; Plomerová et al., 1996; Yuan & Levin, 2014). Finally, Silver and Savage (1994) and Rumpker and Silver (1998) highlighted that, in the case of two horizontal anisotropic layers, the resulting time delay recorded at the surface can be either decreased or increased and azimuthal variations on the polarization direction of the fast wave can be observed (or not) depending on the relative direction of the two layers. All these results question the complexity of interpreting XKS measurements in regions where several (more than two) anisotropic layers occur.



**Figure 2.** Summary of velocity model and splitting measurements for both real and synthetic data at station RCBR. The  $S$  wave velocity model is plotted in red with anisotropic layers drawn in gray. Synthetic splitting parameters obtained for this velocity model are represented by the blue line and real data by the green line. The length of the segments represent the amplitude of the delay time, and their direction the azimuth of the fast split shear wave. The caneva summarizes the input anisotropic orientations for synthetic computations (points and crosses), as well as the mean anisotropy orientations (diamonds) after analyses of observed (green diamond) and synthetic (blue diamond) data. Right panels represent examples of raw and corrected data for both observed and synthetic XKS phases with similar back azimuth as presented in Figure 1. The time window presented corresponds to the yellow window in Figure 1.

The aim of this study is to investigate the effect of complex crustal and/or lithospheric structures on XKS splitting parameters considering “realistic cases.” For that purpose, we select four representative tectonic environments sampled by four seismic stations, where velocity models and anisotropic layers are well defined within the lithosphere from geo-observables other than XKS, in order to evaluate the impact of such features on XKS measurements. In particular, we focus our study on (1) a divergent passive margin region, where coherent anisotropic layers within the lithospheric mantle and the asthenosphere (station RCBR, Brazil) are expected; (2) a region where subsequent stages of deformation generated multiple anisotropic layers within the mantle (station GOGA, eastern United States); (3) a collisional orogen, where different geo-observables pointed out a complex crustal structure including multiple anisotropic layers with both horizontal and dipping axis of symmetry (station BUDO, Tibet); and (4) a subduction zone where anisotropic lithosphere is dominated by several anisotropic layers with a steeply dipping axis of symmetry (station COR, western United States). For each region, we compute an observed XKS data set (and/or we collected results from previous XKS studies, if available) to use as a benchmark for our synthetic SKS measurements. Then, we compose an anisotropic model of the lithosphere based on literature, and we perform forward simulation of SKS wave through such model, to obtain a synthetic SKS data set of SKS splitting measurements. The goal of our modeling approach is not to precisely fit the data but to compute synthetic SKS out of previously established anisotropic models (i.e., without trying to modify the single model for improving the fit to SKS observations). Additionally, for having a uniform approach, where a single study reporting the entire lithosphere and asthenosphere anisotropic model is not existent, we compose the model integrating more than one source of constraints on anisotropic structure. Comparison between observed XKS and synthetic SKS data set allows us to discuss the effect of simple-to-complex lithospheric anisotropy on such observable.

## 2. Data and Method

For this study we selected four seismic stations, which are listed together with their coordinates, locations, networks, and recording times in Figure 1. In order to evaluate the impact of complex structures to XKS splitting parameters, we performed synthetic SKS waves propagating through crustal or lithospheric velocity models defined from previous studies (see the following sections for details about velocity models). Such

studies generally involved other seismic observables (e.g., receiver function and/or surface waves) and exclude XKS measurements, for defining the anisotropic layering. Synthetic SKS waves are obtained from Frederiksen and Bostock (2000) software. We then measured splitting parameters from synthetic SKS waves and compare them to real XKS data at the corresponding station. Note that synthetic data were computed for a set of back azimuths which correspond to the real back azimuthal coverage recorded at the station for XKS measurements.

Both synthetic and real data splitting measurements were performed using SplitRacer software (Reiss & Rumpker, 2017). For real data, we selected events with epicentral distance between 85° and 140° from the seismic station and with magnitude higher than or equal to 6. At station BUDO, which recorded only 1 year data, we extended our analysis to earthquakes with magnitude higher than or equal to 5. Single splitting analysis is based on the minimum eigenvalue method (Silver & Chan, 1991), which performs a grid search over  $\varphi$  and  $\delta t$  that best linearizes the particle motion and thus best corrects the anisotropy within the selected measurement window. Data were filtered between 4 and 50 s, and signals with signal-to-noise ratio below 2.5 were automatically discarded. Measurements are repeated for a number of time windows to enable statistical error analysis. We determined the quality (good, fair, poor, or null) of each individual measurement by applying manual evaluation according to a set of criteria defined as the signal-to-noise ratio of the initial waveform (only for real data), the correlation between the fast and slow shear waves, the linearity of the particle motion in the horizontal plane after correction, and of the size of the 95% confidence area (Barruol et al., 1997).

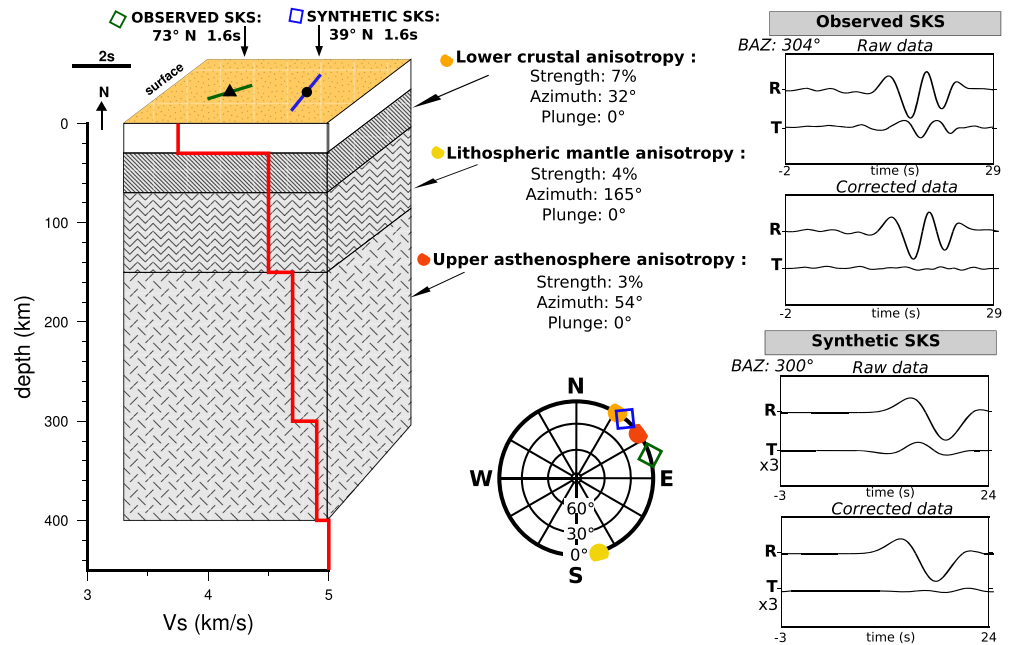
The average values of splitting parameters  $\varphi$  and  $\delta t$  per station are obtained from SplitRacer software, which calculates an average layer model assuming an average period of 10 s for the phases with standard deviations for the splitting parameters of 20° and 1 s. This calculation includes “good,” “fair,” and “null” quality measurements but do not take into account “poor” quality measurements.

### **3. A Simple Case: Multiple Anisotropic Layers in the Lithosphere, With Subhorizontal and Parallel Symmetry Axes**

At station RCBR we study the case where only horizontal anisotropic layers with parallel fast axis of symmetry occur. We use this simple case as a standard in order to validate the methodology. Left panel of Figure 2 represents the velocity model used to generate SKS synthetic waves. The model has been compiled using the results from Bastow et al. (2011), Heit et al. (2007), Liu et al. (2019), and Lamarque and Juliá (2019), where the authors analyzed fast-polarization direction from SKS splitting analysis, Moho and lithosphere-asthenosphere boundary depths from *S* wave receiver functions, intensity of anisotropy from EBSD measurements, and direction of anisotropy within the lithospheric mantle from harmonic stripping of *P* wave receiver functions, respectively, for making inferences on the lithospheric seismic structure. Details for this model are presented in Table A1. Average splitting parameters for real data are reported in Figure 2, appendix Table B1, and section C.1). Both Assumpção et al. (2011) and this study retrieved similar fast-polarization direction but different time delay. The two studies performed similar calculation to retrieve the splitting parameters by using both Silver and Chan (1991) algorithm. Different values for  $\delta t$  must be related to manual selection and quality classification of events. We choose to use time delay computed by Assumpção et al. (2011) because (i) uncertainties are much more lower in his study, (ii) 1.9 s is much more realistic than 3 s in passive margin context, and (iii) 1.9 s is included in the 95% confidence level in our study, and it is thus as probable as 3 s. Coherent fast-polarization directions in the two anisotropic layers is proposed to explain the large time delay measured from real data (Assumpção et al., 2011). Results from synthetic SKS waves provide splitting parameters  $\varphi = 9^\circ\text{N}$  and  $\delta t = 2.2$  s which explains well the real measurements done at this station. In that case, time delays produced within each individual layer are summed up to finally give the large time delay measured at the surface. This sum is only possible in the case of parallel fast axis of symmetry in the two layers.

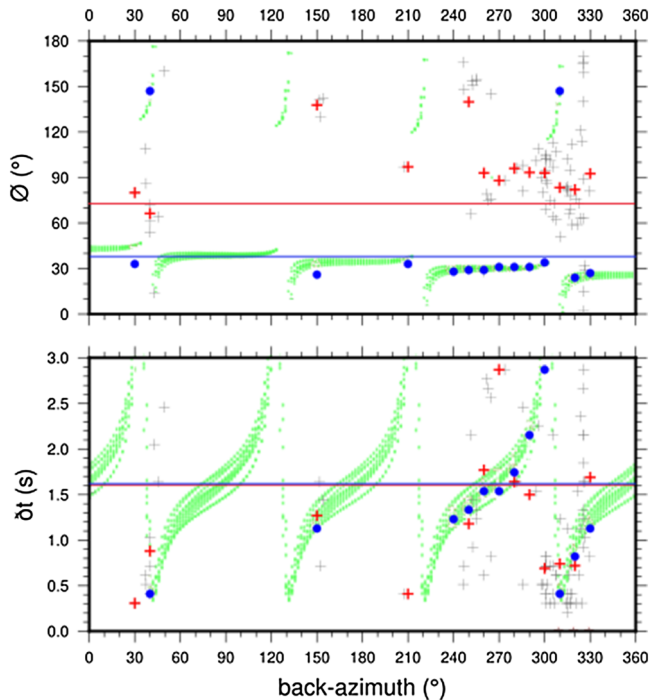
### **4. Getting Complex: Multiple Anisotropic Layers in the Lithosphere With Differently Oriented Symmetry Axis**

GOGA station is located in the eastern Appalachian region in the United States, where three anisotropic layers with different fabrics have been identified by surface wave tomography (Deschamps et al., 2008).



**Figure 3.** Same as Figure 2 but for station GOGA. Velocity model parameters are based on Deschamps et al. (2008). Amplitudes of the synthetic transverse components (raw and corrected data) are multiplied by 3.

These authors inverted phase velocity maps and pairs of selected measured dispersion curves, highlighting the presence of two anisotropic layers within the lithosphere (30–70 and 70–150 km depths) and one anisotropic layer within the asthenosphere (deeper than 150 km) with fast axis of hexagonal symmetry from top to bottom oriented 32°N, 165°N, and 54° N, respectively (see Figures 3 and 5 of Deschamps et al., 2008). All these layers are supposed to have horizontal axis of symmetry. Figure 3 represents the velocity model used to generate SKS synthetic waves, which is also presented in detail in Table A2. Average splitting parameters for real and synthetic data are reported in Figure 3, appendix Table B1, and section C.2). Synthetic SKS provide results with [R1.11] different trend but similar time delay to the observed XKS parameters at the surface. XKS splitting at station GOGA has been analyzed many times, from different research groups (Barruol et al., 1997; Liu, 2009; Long et al., 2010; Yang et al., 2017). In some studies, the authors only found null measurements (Long et al., 2010), while others were able to compute splitting parameters from SKS waves (Barruol et al., 1997; Yang et al., 2017). This discrepancy was already discussed in Yang et al. (2017). From our side, we computed 92 good/average SKS splitting measurements that have been used in our study and which are consistent with results from Yang et al. (2017). In Figure 4, splitting parameters for both observed (gray crosses) and synthetic (blue circles) data are represented in functions of back azimuth. Red crosses correspond to the average value per back azimuth for observed data, which are calculated by a simple average formula taking only into account the values (not the standard deviation) of splitting parameters from “good” and “average” events (not null measurements). The red (observed data) and blue (synthetic data) lines correspond to the splitting parameters of the average layer as calculated by Splitracer software. This calculation takes into account “good,” “fair,” and “null” measurements. We notice that both average observed (red crosses) and synthetic (blue circles) data display similar back azimuthal patterns for both fast-polarization direction ( $\Phi$ ) and time delay ( $\delta t$ ). By inverting the synthetic results, we found that a two-layer model composed of (i) a top layer with splitting parameters 30°N and 1.6 s and (ii) a bottom layer with splitting parameters 100°N and 0.4 s perfectly fits the data. Splitting results for such model are presented in green in Figure 4. The fact that a two-layer model fits our synthetic results made from a three-layer model indicates that inversion of SKS waves cannot identify the presence of more than two anisotropic layers. We also notice that the average values of the  $\phi$  direction for the synthetic data (blue line in Figure 4) is closely related to the most anisotropic layer (the top one in our case). Moreover, results from synthetics perfectly fit



**Figure 4.** Results at station GOGA for synthetic SKS (blue circles) and XKS observed data (gray crosses) splitting parameters in functions of back azimuth. Red crosses represent the average value for observed data for a  $10^\circ$  back azimuth interval. Upper panel represents the polarization direction of the fast  $S$  wave, and lower panel corresponds to the time delay between the fast and the slow  $S$  waves. As an indication, splitting parameters of the average layer model for synthetics (blue line) and observed data (red line) are represented. The light green circles represent the best model after inversion of the synthetic SKS.

this model fits the observed data. We also notice that synthetic SKS waves propagating only through the crustal model produce an apparent fast-polarization direction which is also subparallel to the observed XKS waves. This observation indicates that the crust significantly contributes to the observed SKS splitting. In fact, synthetic SKS waves for the crustal contribution display time delay  $\delta t$  equal to 0.8 s, which accounts for 33% (or 44%) of the time delay recording at the surface,  $\delta t = 2$  s, this study (or  $\delta t = 2.4$  s McNamara et al., 1994). Moreover, it is worth noticing that the apparent  $\phi$  direction computed from synthetic data using only crustal anisotropic layers is almost  $90^\circ$  from the direction of the symmetry axis of such two layers. This fact is probably due to the concurrent effects of plunging axis (lower crustal layer) and change from anisotropy with slow (due to aligned cracks) to fast axis of symmetry (generated by the alignment of elongated mineral grains, Sherrington et al., 2004). Summing/subtracting  $t$  delays in case of complex anisotropy could give misleading insights.

### 5.2. With Plunging Subslab Anisotropy Into the Mantle

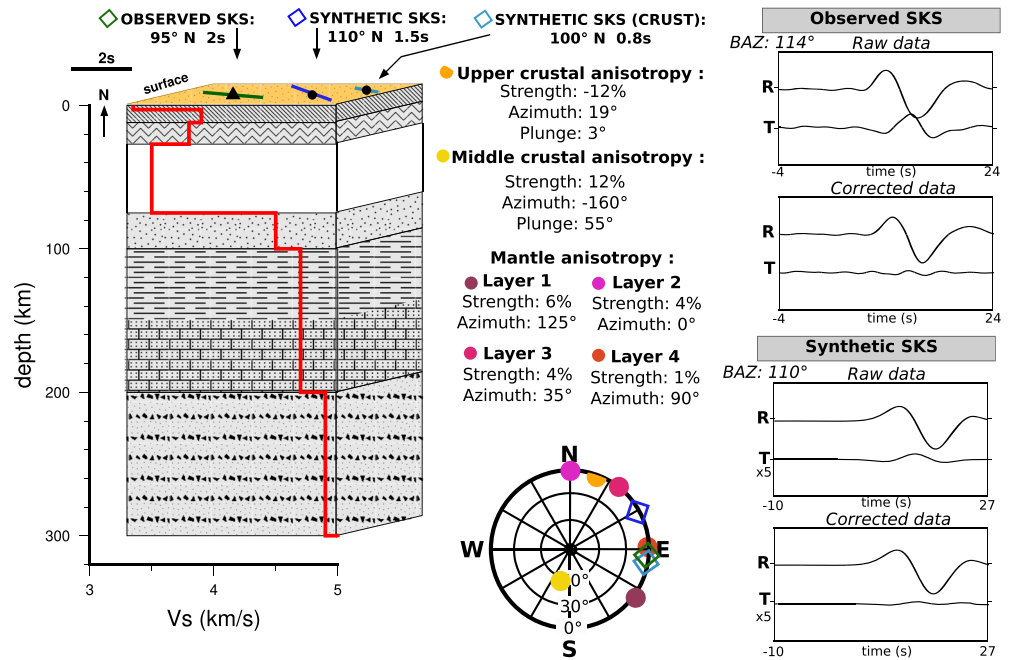
Corvallis (COR) station is located above the Cascadia subduction zone. Park et al. (2004) have shown that no corner mantle flow is observed beneath that station because they identified a low-velocity ( $V_p = 6.0$  km/s) layer made up of materials with strong slow axis of symmetry ( $-7\%$ ) which is unlikely to represent olivine material. The proposed model includes the superposition of a complex continental lithosphere above the plunging oceanic plate and the subslab mantle, including metamorphosed mafic crust (Piana Agostinetti & Miller, 2014). Following the receiver function analysis presented in Park et al. (2004), the shallow structure ( $<50$  km depth) is characterized by the presence of four crustal anisotropic layers with varying anisotropy intensity and axis of symmetry direction and plunging. The slab and subslab directions are taken from Roth et al. (2008), which are both deduced from XKS data, and slab geometry from Fowler (1990). Figure 6 represents the velocity model used to generate SKS synthetic waves, which is also presented in

observed time delay and are shifted by  $\sim 40^\circ$  for fast-polarization direction. We assume that this shift could be related to crustal anisotropy, which we investigate in the two following examples.

## 5. Complex Crustal Anisotropy Including Dipping Symmetry Axis

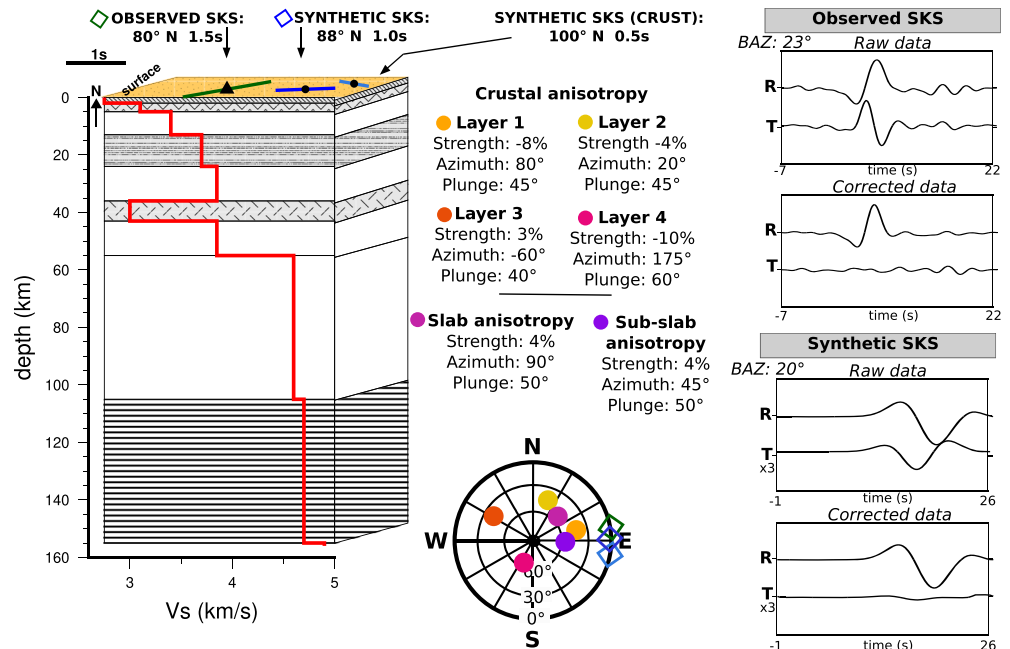
### 5.1. With Horizontal Fast Axis of Symmetry Into the Mantle

In order to study the influence of complex shallow crustal anisotropy (0–20 km depth range) on XKS splitting, we choose BUDO station in Tibet. The selection of this station has been made by the availability of a detailed crustal model which is constrained by four different studies (see below) which mostly agree on the velocity and anisotropy structure of the crust beneath this station. Figure 5 represents the velocity model used to generate SKS synthetic waves, which is also presented in detail in Table A3. This model is made by summing crustal structure extracted from receiver functions and mantle anisotropy inferred from surface waves. Anisotropic structure within the crust is based on Licciardi and Piana Agostinetti's (2016) work, which matches pretty well previous studies on crustal anisotropic layers at the same station (Frederiksen et al., 2003; Sherrington et al., 2004; Vergne et al., 2003). Main outlines of this model are the presence of two anisotropic layers with opposite axis of symmetry directions ( $\phi = 19$  and  $-160$  for top and bottom layers, respectively). Moreover, the top anisotropic layer has a horizontal axis of symmetry, whereas the bottom one is characterized by  $55^\circ$  plunging axis of symmetry. Anisotropy within the mantle is based on surface waves analysis of Pandey et al. (2015), who identified four layers with horizontal fast axis of symmetry oriented  $125^\circ\text{N}$ ,  $0^\circ\text{N}$ ,  $35^\circ\text{N}$ , and  $90^\circ\text{N}$ , respectively. Average splitting parameters for real and synthetic data are reported in Figure 5, appendix Table B1, and section C.3. Average polarization direction for synthetic XKS waves (dark blue in Figure 5) propagating through

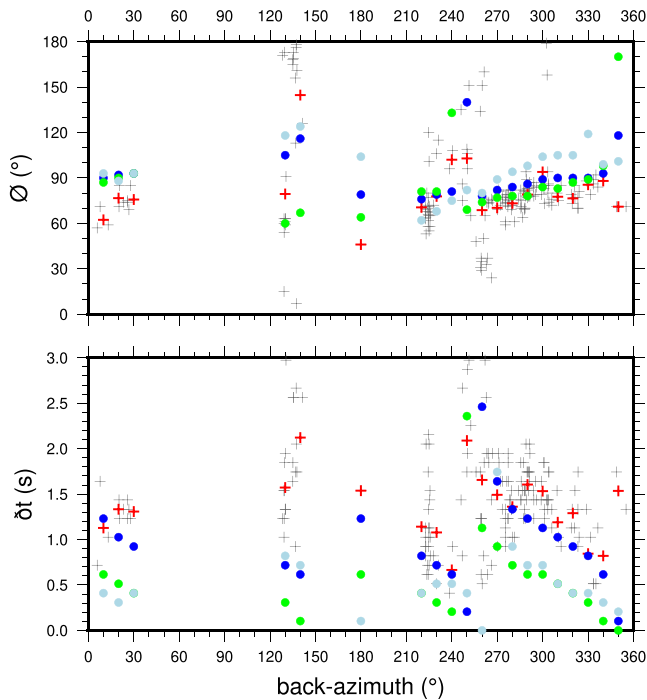


**Figure 5.** Same as Figure 2 but for station BUDO. Velocity model parameters are based on Licciardi and Piana Agostinetti (2016). Amplitudes of the synthetic transverse components (raw and corrected data) are multiplied by 5.

detail in Table A4. Average splitting parameters for real and synthetic data are reported in Figure 6, appendix Table B1, and section C.4). The average XKS splitting parameter measured at the surface is ENE-SWS, in agreement with previous studies (Eakin et al., 2010; Martin-Shortet et al., 2015).



**Figure 6.** Same as Figure 2 but for station COR. Velocity model parameters are based on Park et al. (2004). Amplitudes of the synthetic transverse components (raw and corrected data) are multiplied by 3.



**Figure 7.** Results at station COR for observed (gray crosses), mean value per  $10^\circ$  back azimuth intervals (red crosses), synthetics for the complete model presented in Figure 6 (dark blue circles), synthetics for the crust only (light blue circles), and synthetics for the slab and subslab only (green circles) XKS splitting parameters in functions of back azimuth. Upper panel represents the polarization direction of the fast  $S$  wave, and lower panel corresponds to the time delay between the fast and the slow  $S$  waves.

Once again, as for station BUDO, the average polarization direction for synthetic SKS waves propagating through the entire model seems, interestingly, not related with any direction (even not to the subslab mantle flow), but it is relatively aligned to the polarization direction measured at the surface. Moreover, by modeling SKS waves propagating only through the upper plate, we make similar observations that the apparent polarization direction ( $\varphi = 100^\circ\text{N}$ ) is relatively aligned to the polarization direction measured at the surface. The concordance between these three results highlights the contribution of the upper plate shallow structure to the XKS splitting measured at the surface, which accounts for 33% of the total  $\delta t$  (i.e., 0.5 s estimated for the synthetics and 1.5 s measured at the surface).

The localization and long-time recording at this station allow us to observe the dependency of splitting parameters on the back azimuth of the incoming XKS wave. Figure 7 represents splitting parameters in functions of back azimuth for (i) synthetic waves for the entire model (dark blue circles), (ii) synthetic waves for the upper anisotropic lithosphere only (light blue circles), (iii) synthetic waves for the slab and subslab only (green circles), and (iv) recorded waves at the surface (gray and red crosses). This figure highlights that complex anisotropic lithosphere can produce back azimuthal patterns on splitting parameters  $\varphi$  and  $\delta t$ . We also notice that synthetic and measured splitting parameters display similar patterns, including for synthetics produced only from the upper lithosphere model. This observation suggests that at COR station the back azimuthal pattern can be explained by the complex anisotropic lithosphere depicted in Park et al. (2004) and that the contribution of deeper anisotropic material (slab and subslab) do not contribute to the relevant back azimuthal pattern. Moreover, apparent splitting direction at the surface is absolutely not related to the subslab fast axis of symmetry but results from a combination of complex crustal and mantle anisotropy.

## 6. Potential Pitfalls in XKS Measurement Interpretations

In this study, we focus on pitfalls related to incorrect parametrization of the Earth (i.e., not considering crustal anisotropy), dipping symmetry axis for anisotropic layers, and/or the presence of more than two anisotropic layers. A broader description of potential pitfalls in real data can be also found in Vecsey et al. (2008). The examples presented in this study highlight several potential pitfalls while interpreting XKS measurements. These pitfalls would come as no surprise to most shear wave splitting analysts as these are well-known issues of SKS splitting interpretation and they are well established in literature. Our examples move the discussion a step forward to a broader audience of geoscientists because interpretations of SKS splitting measurements in terms of mantle flow are widespread in geophysical literature, but those pitfalls are not always carefully considered as we show they should be.

The analysis for obtaining XKS measurements is actually robust because it does not need heavy processing, but the near-vertical geometry of their raypath prohibits any vertical resolution. We show with station RCBR (northeast Brazil—divergent passive margin) that in a simple case with one or several mantle anisotropic layer(s) with parallel fast axis of symmetry (and no or negligible crustal anisotropy), it is relatively straightforward to interpret XKS measurements. In that case, the measured fast axis of symmetry is directly related to fast axis of symmetry at depth, and the entire time delay can be attributed to mantle deformation (both lithospheric and asthenospheric mantle).

At station GOGA, we investigate the effect of an anisotropic structure that comprises more than two horizontal anisotropic layers within the mantle, with nonparallel symmetry axis. First, we notice that synthetic SKS waves computed with this velocity model do not fully reproduce XKS splitting parameters observed at



the surface. Such observation argues in favor of joint inversion/interpretation of several seismic data set in order to propose a comprehensive velocity model that explains at best independent data (Babuška et al., 1993, 2008; Plomerová et al., 1996; Plomerová & Babuška, 2010; Romanowicz & Yuan, 2012). The back azimuthal variations of synthetic SKS parameters is very limited and could be missed in the presence of back azimuthal gaps larger than  $90^\circ$  (as in the case of GOGA station). Our synthetic test using a realistic multi-layer structure of the upper mantle indicates that by looking at XKS splitting parameters only one could miss information about the presence of several anisotropic layers (Savage, 1999). Once again, the use of others methods such as surface waves tomography or receiver functions is fundamental to constrain the upper structure along the raypath of the XKS waves and, by coupling these models to XKS data, better estimate depth-dependent anisotropy within the lithosphere and the asthenosphere.

Along the Himalayan collisional orogen, we show that in the presence of complex crustal anisotropy, expected in most of the tectonically active area worldwide (here, station BUDO, but also at station COR above the Cascadia subduction zone), the crust can account for a large (up to 30–40%) amount of the observed time delay. In these two cases, the shallow Earth structure (<50 km) is composed of several anisotropic layers with dipping fast or slow axis of symmetry directions, not oriented parallel to each other. But the resulting apparent SKS wave is subparallel to the observed XKS. We can thus conclude that here, the time delay must be 30–40% reduced in order to interpret the XKS measurements in terms of mantle deformation.

Contrary to what happens at station GOGA, our analysis of station COR station highlighted that complex crustal anisotropy can produce back azimuthal pattern which could be misinterpreted in terms of multiple anisotropic layers within the mantle. In this specific example, we suggest that anisotropy within the subducted Juan de Fuca mantle could simply increase the observed delay time, without affecting the back azimuthal pattern related to crustal anisotropy. Thus, it is necessary to estimate velocity and anisotropy models for the crust (and the entire lithosphere) in order to evaluate the impact of shallow structures on splitting parameters.

## 7. Conclusions

By studying four examples of anisotropy complexity beneath selected stations, we highlight potential pitfalls in XKS splitting parameters interpretations.

1. We show that the crust can account for a large (up to 40%) amount of the recorded time delay in different tectonic systems (orogenesis and subduction zone).
2. Moreover, complex anisotropic crustal structures can produce XKS back azimuthal pattern, which needs to be identified before interpreting XKS measurements in terms of mantle structure constituted by multiple layers.
3. In case of multilayer anisotropic mantle, with horizontal and/or dipping symmetry axis, the observed average SKS splitting direction,  $\phi$ , is not always representative of the direction of flow in the asthenospheric mantle.

To avoid such interpretation bias, XKS measurements need to be carefully coupled with other seismological studies (e.g., surface waves, receiver function, and local  $S$  wave splitting). Our results suggest that, in most of the tectonically active areas, the joint use of these methods should be “a must” for determining a fine-scaled velocity and anisotropy model for the upper part of the XKS raypath in order to correctly input such information for geodynamic modeling.

## Appendix A: Velocity Models

Velocity models are defined by a superposition of layers with a thickness, density,  $P$  wave velocity,  $S$  wave velocity, intensity of  $P$  wave anisotropy, intensity of  $S$  wave anisotropy, and direction and plunge of  $P$  and  $S$  waves anisotropy. The velocity models are detailed for RCBR station in Table A1, for GOGA in Table A2, for BUDO in Table A3, and for COR in Table A4.

**Table A1**  
*Velocity Model for Station RCBR*

Thickness (km)	Density (kg/cm <sup>3</sup> )	Vp (km/s)	Vs (km/s)	AVp (%)	AVs (%)	[R2.4] direction (°N)	Plunge (°)
30	2.6	5.8	3.35	0	0	0	0
55	3.3	8.1	4.5	5	5	9	0
150	3.3	8.0	4.4	5	5	9	0
1	3.3	8.1	4.5	0	0	0	0

*Note.* From right to left are represented the thickness of the layer, density, velocity of *P* wave, velocity of *S* wave, anisotropy of *P* wave, anisotropy of *S* wave, [R2.4] direction of the fast axis of symmetry, and plunge of the fast axis of symmetry.

**Table A2**  
*Same as Table A1 but for Station GOGA*

Thickness (km)	Density (kg/cm <sup>3</sup> )	Vp (km/s)	Vs (km/s)	AVp (%)	AVs (%)	[R2.4] direction (° N)	Plunge (°)
30	2.7	6.0	3.75	0	0	0	0
40	3.3	8.1	4.5	7	7	32	0
80	3.3	8.1	4.5	4	4	165	0
150	3.3	8.5	4.7	3	3	54	0
100	3.3	8.8	4.9	2	2	54	0
1	3.3	9.0	5.0	0	0	0	0

**Table A3**  
*Same as Table A1 but for Station BUDO*

Thickness (km)	Density (kg/cm <sup>3</sup> )	Vp (km/s)	Vs (km/s)	AVp (%)	AVs (%)	[R2.4] direction (° N)	Plunge (°)
0.001	2.6	5.8	3.35	0	0	0	0
3	2.6	5.8	3.35	-12	-12	19	3
9	2.6	6.7	3.9	-12	-12	19	3
15	2.6	6.6	3.8	12	12	-160	55
48	2.6	6.0	3.5	0	0	0	0
25	3.3	8.1	4.5	6	6	125	0
50	3.3	8.5	4.7	4	4	0	0
50	3.3	8.5	4.7	4	4	35	0
100	3.3	8.8	4.9	1	1	90	0
1	3.3	8.1	4.5	0	0	0	0

**Table A4**  
*Same as Table A1 but for Station COR*

Thickness (km)	Density (kg/cm <sup>3</sup> )	Vp (km/s)	Vs (km/s)	AVp (%)	AVs (%)	[R2.4] direction (° N)	Plunge (°)
0.001	2.6	4.6	2.75	0	0	0	0
2	2.6	4.6	2.75	-8	-8	80	45
3	2.6	5.4	3.1	-8	-8	20	45
8	2.6	6.1	3.4	0	0	0	0
11	2.6	6.7	3.7	3	3	300	40
12	2.6	7.1	3.85	0	0	0	0
7	2.6	6.4	3.0	-10	-10	175	60
12	2.6	7.1	3.85	0	0	0	0
50	3.3	8.1	4.6	4	4	90	50
50	3.3	8.5	4.7	4	4	45	50
1	3.3	8.1	4.6	0	0	0	0

## Appendix B: Average Layer Splitting Measurements

Average of both observed and modeled splitting parameter for each station are summarized in Table B1.

**Table B1**  
Summary of Average Layer Splitting Parameters Obtained From This Study

Station	Network	Average observed		Average synthetics	
		$\varphi$ (°)	$\delta t$ (s)	$\varphi$ (°)	$\delta t$ (s)
RCBR	IU	9	3	9	2.2
GOGA	US	73	1.6	39	1.6
BUDO	XC	95	2	110	1.5
COR	IU	80	1.5	88	1.0

Note. Both observed and synthetics results are presented.

## Appendix C: Single Splitting Measurements

Every individual measurement for observed SKS splitting parameters are presented in sections C1 for station RCBR, C2 for station GOGA, C3 for station BUDO, and C4 for station COR.

### C1. Station RCBR

This is a summary of individual splitting measurements results for station RCBR. From right to left are presented the date, time, phase, back azimuth, sensor correction, phi, dt, phi err min, phi err max, dt err min, dt err max, quality, and confidence level. Note that only events with “good,” “fair,” and “null measurements” are presented (“poor” quality events are excluded).

### C2. Station GOGA

Same as section C1 but for station GOGA.

### C3. Station BUDO

Same as section C1 but for station BUDO.

### C4. Station COR

Same as section C1 but for station COR.

## Data Availability Statement

Data used for this study are available from IRIS data center with FDSN network code IU (stations RCBR and COR—ASL/USGS, 1988), US (station GOGA—ASL/USGS, 1988), and XC (station BUDO—Owens & Wu, 1991).

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