

1 **Upper-mantle anisotropy in the southeastern margin of the Tibetan Plateau revealed by fullwave**

2 **SKS splitting intensity tomography**

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13 **Key Points:**

- 14 • A 3D shear-wave anisotropy model for the SE margin of the Tibetan Plateau is obtained  
15 by fullwave SKS splitting intensity tomography
  - 16 • Anisotropy distribution shows a decoupling of the deformations in the lithosphere and  
17 asthenosphere
  - 18 • Lithospheric anisotropy has a complex pattern, whereas asthenospheric anisotropy  
19 follows the APM
- 20

21 **Abstract**

22 The southeastern margin of the Tibetan Plateau has experienced complex deformation since the  
23 Cenozoic, resulting in a high level of seismicity and seismic hazard. Knowledge about the seismic  
24 anisotropy provides important insight into the deformation mechanism and the regional  
25 seismotectonics beneath this tectonically active region. In this study, we conduct a fullwave multi-  
26 scale tomography to investigate the seismic anisotropy in the southeastern margin of the Tibetan  
27 Plateau. Broadband records from 470 teleseismic events at 111 permanent stations in the region are  
28 used to obtain 5,216 high-quality SKS splitting intensity measurements, which are then inverted in  
29 conjunction with 3D sensitivity kernels to obtain the anisotropic model for the region with a multi-  
30 scale resolution. Resolution tests show that our dataset recovers anisotropy anomalies reasonably well  
31 on the scale of  $1^\circ \times 1^\circ$  horizontally and  $\sim 100$  km vertically. Our result suggests that in the southeastern  
32 margin of the Tibetan Plateau the deformations in the lithosphere and asthenosphere are decoupled. The  
33 anisotropy in the lithosphere varies both laterally and vertically as a result of the dynamic interactions  
34 of neighboring blocks as well as lithospheric reactivation. The anisotropy in the asthenosphere largely  
35 follows the direction of regional absolute plate motion, i.e. southeastward under the Songpan-Ganzi  
36 Terrane and the Yangtze Craton and nearly east-west south of  $26^\circ\text{N}$  latitude. The SKS splitting  
37 observed at the surface can be interpreted as the vertical integration of the contributions from  
38 lithosphere and asthenosphere.

39 **Keywords:** seismic anisotropy; splitting intensity; finite-frequency; fullwave tomography;  
40 southeastern Tibetan Plateau

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42 **Plain Language Summary**

43 The southeastern margin of the Tibetan Plateau has experienced significant deformation since the

44 Cenozoic due to the collision with the Indian Plate in the south and interactions with the Yangtze  
45 Craton in the east. Knowledge about the upper mantle seismic anisotropy helps us understand the  
46 regional deformation and dynamic evolution. In this study, we conduct a fullwave multi-scale  
47 anisotropy tomography for the southeastern margin of the Tibetan Plateau using 5,216 high-quality  
48 SKS splitting intensity measurements obtained from the broadband records of 470 teleseismic events  
49 at 111 stations. Our result shows a decoupling between the lithosphere and asthenosphere deformations  
50 in the southeastern margin of the Tibetan Plateau. The anisotropy in the lithosphere varies both laterally  
51 and vertically as a result of the dynamic interactions of neighboring blocks as well as lithospheric  
52 reactivation. The anisotropy in the asthenosphere is largely parallel to the regional absolute plate motion,  
53 and the SKS splitting observed at the surface is the result of vertical integration of the contributions  
54 from lithosphere and asthenosphere.

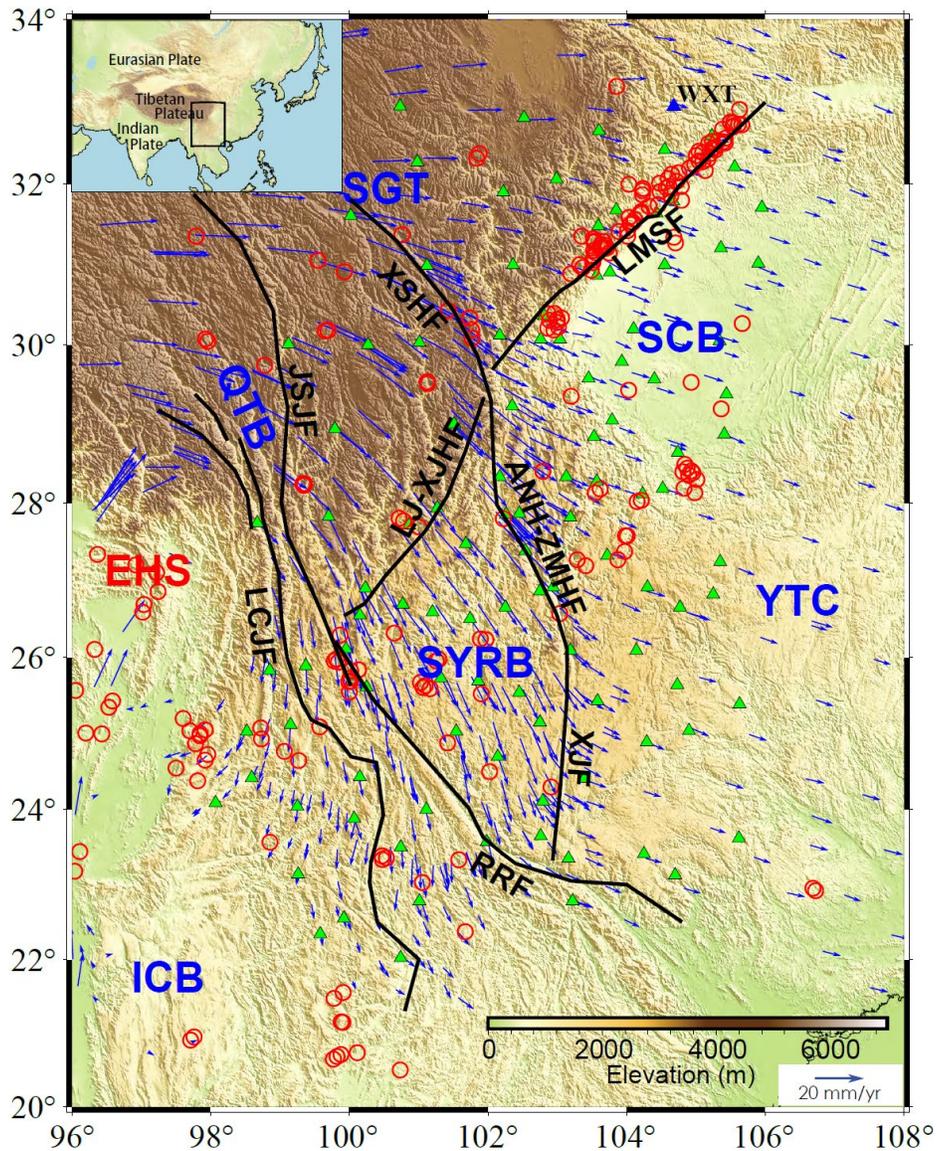
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## 56 **1 Introduction**

57 The ongoing Indian-Eurasian continental collision since 50 Ma has resulted in the greatest plateau  
58 on Earth and deformed large parts of central and east Asia (Yin & Harrison, 2000; Kind et al.,  
59 2002). Despite decades of study, questions remain over the dynamics of the lithospheric  
60 deformation and asthenosphere flow beneath the Tibetan Plateau and the surrounding regions  
61 (Royden et al., 2008).

62 The region in the southeastern margin of the Tibetan Plateau involves many active tectonic  
63 blocks (Figure 1), including the Songpan-Ganzi Terrane (SGT), the Sichuan Basin (SCB), the  
64 Sichuan-Yunnan Rhombic Block (SYRB), the Indo-China Block (ICB), the Qiangtang Block  
65 (QTB), and the Yangtze Craton (YTC). The SGT is part of central Tibetan Plateau. Its eastern part  
66 is separated from the SCB and SYRB by the Longmenshan Fault (LMSF) and Lijiang-Xiaojinhe Fault  
67 (LJ-XJHF), respectively, and bounded in the south by the Jinshajiang Fault (JSJF) from the QTB. The  
68 convergence between the Indian and Eurasian plates caused the SGT to expand eastward against  
69 the SCB during the Cenozoic (Yin & Harrison, 2000). GPS observations show eastward crustal  
70 motion of the eastern SGT with the crustal strain rate decreasing abruptly from  $\sim 20$  mm/year  
71 (relative to the YTC reference frame) in the interior SGT to  $\sim 3\text{--}4$  mm/year or less in the vicinity of  
72 central and southern segments of the LMSF, indicating that the eastward expansion of the SGT is  
73 apparently resisted by the SCB (Shen et al., 2005; Zhang, 2013). Low-velocity zones and high-  
74 conductivity bodies in the mid-lower crust under the SGT revealed by geophysical studies (Zhao  
75 et al., 2012; Bao et al., 2020) suggest the existence of mid-lower crustal flow. However, these  
76 geophysical anomalies exhibit strong lateral heterogeneity in eastern Tibet, implying a complex  
77 internal deformation process. The SCB and SYRB are both parts of the YTC (Zhang et al., 2013;  
78 Li et al., 2021). The former forms the rigid and stable northwestern margin of the YTC, while the

79 crust of the latter is extruding southeastward along the Anninghe-Zemuhe Fault (ANH-ZMHF) and  
 80 Xiaojiang Fault (XJF) in the east and the Red River Fault (RRF) in the southwest (Zhang et al., 2003).  
 81 The Lancangjiang Fault (LCJF) separates the narrow QTBS in the east and the ICB in the west.  
 82 Crustal movements are predominantly characterized by a clockwise rotation around the Eastern  
 83 Himalayan Syntaxis (EHS), transforming the movement of the plateau material from eastward  
 84 north of the syntaxis to southeastward and southward further south (Wang & Shen, 2020).

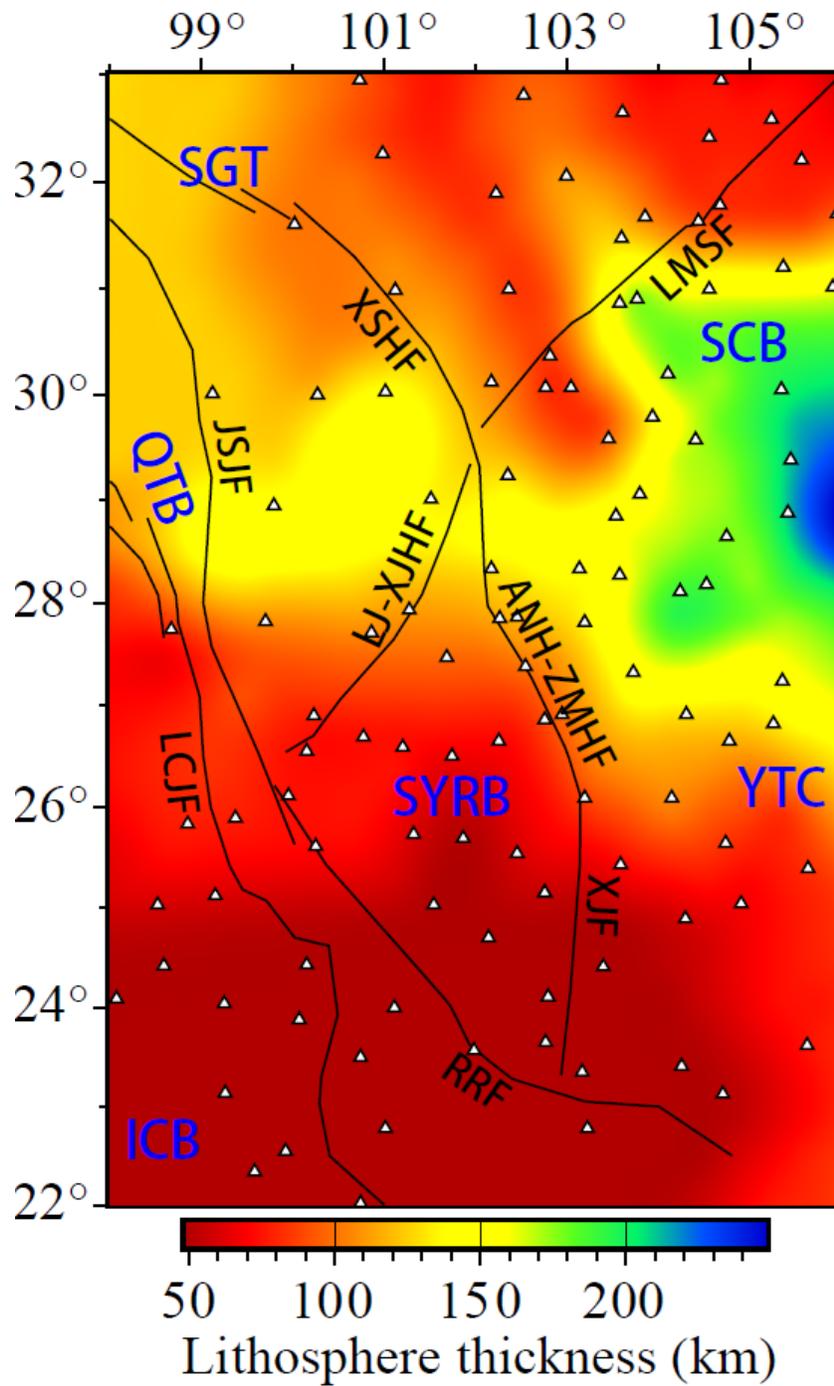


85  
 86 **Figure 1.** Map of the tectonic environment of southeastern margin of the Tibetan Plateau with  
 87 seismic stations (green-filled triangles) and epicenters (red open circles) of earthquakes of

88 magnitude 5 and above from 2000 to 2022. The blue triangle marks the station WXT for which  
89 SKS waveforms, splitting intensities and sensitivity kernels are shown in Figures 4, 5 and 7,  
90 respectively. Major active faults are shown by thick black lines with abbreviated names in black,  
91 including LMSF: Longmenshan Fault; XSHF: Xianshuihe Fault; JSJF: Jinshajiang Fault; LCJF:  
92 Lancangjiang Fault; LJ-XJHF: Lijiang-Xiaojinhe Fault; ANH-ZMHF: Anninghe-Zemuhe Fault;  
93 XJF: Xiaojiang Fault; and RRF: Red River Fault. Major active tectonic blocks are indicated by  
94 abbreviated texts in blue, including SGT: Songpan-Ganzi Terrane; SCB: Sichuan Basin; QTB:  
95 Qiangtang Block; SYRB: Sichuan-Yunnan Rhombic Block; YTC: Yangtze Craton; and ICB:  
96 Indo-China Block. EHS stands for the Eastern Himalaya Syntax. Blue arrows show the GPS  
97 velocities with respect to the Eurasian Plate (Wang & Shen, 2020). Background color shows the  
98 topography. The black box in the inset map indicates the location of the main figure.

99 Over the past two decades, and in particular after the 12 May 2008 Wenchuan Mw7.9  
100 earthquake on the LMSF, a large number of seismic stations have been deployed in the  
101 southeastern margin of the Tibetan Plateau. Waveforms recorded by the growing number of  
102 broadband stations have provided crucial data for studying the structure and dynamics of the crust  
103 and upper mantle beneath the region, such as the variation in crustal thickness (Wang et al., 2017;  
104 Xu et al., 2020), the widespread low-velocity anomalies in mid-lower crust revealed by receiver  
105 function analysis (Hu et al., 2005; Xu et al., 2007; Zhang et al., 2009; Wang et al., 2010), Lg-wave  
106 high-attenuation zones (Zhao et al., 2013; Wei & Zhao, 2019), joint inversion of receiver function  
107 and surface wave dispersion (Liu et al., 2014), and body- and surface-wave tomographies (Huang et  
108 al., 2002; Wang et al., 2003; Huang et al., 2009; Li et al., 2009; Wei & Zhao, 2022; Yang et al., 2019).

109 Across the LMSF, the drastic change in elevation from ~5–6 km in the west to a few hundred  
110 meters in the east suggests large variation in the lithospheric thickness. Figure 2 shows the  
111 LITHO1.0 model (Pasyanos et al., 2014) in the study region, where the lithosphere has a thickness  
112 of less than 100 km in the northern and southern parts but ~150 km in mid latitudes. The thickest  
113 lithosphere in the study region is more than 200 km beneath the SCB.



114

115 **Figure 2.** Lithosphere thickness in model LITHO1.0 (Pasyanos et al., 2014). Names of major faults  
 116 and tectonic blocks are the same as in Figure 1.

117

Distribution of azimuthal anisotropy is an important proxy for deformation. There have been  
 118 numerous studies devoted to the crustal anisotropy beneath the southeastern Tibetan Plateau

119 utilizing different methods, such as the Pms splitting (Sun et al., 2012; Cai et al., 2016; Han et al.,  
120 2020), anisotropic tomography of P and Pn waves (Lei et al., 2014; Huang et al., 2018), surface  
121 wave anisotropic tomography (Yang et al., 2010; Yao et al., 2010; Legendre et al., 2015; Zhang et  
122 al., 2023), and the splitting of shear waves (Shi et al., 2012). In the upper crust, the fast axis directions  
123 are mainly parallel to the strike of active faults (e.g., Yao et al., 2010; Shi et al., 2012; Huang et al.,  
124 2018), whereas the anisotropic pattern in the lower crust is different. Huang et al. (2018) showed  
125 that the fast velocity direction deviates from the strikes of active faults significantly using P-wave  
126 anisotropic tomography. Han et al. (2020) used the Markov-chain Monte Carlo inversion of receiver  
127 functions to isolate the effect of potential dipping interfaces. Their results showed that the fast axis  
128 directions in the lower crust are in good agreement with the topography contours, implying that the  
129 gravitational potential may be the driving force for the crustal deformation in southeastern Tibet.

130 The XKS-wave splitting is routinely used to probe the anisotropic structure in the upper mantle  
131 (Long & Becker, 2010). Flesch et al. (2005) conducted joint analysis of GPS, surface geology and  
132 shear-wave splitting measurements to argue for a vertically coherent deformation in the crust and  
133 upper mantle in the Tibetan Plateau but a decoupling beneath Yunnan Province in southwestern  
134 China. Lev et al. (2006) also supported the decoupling beneath Yunnan using shear-wave splitting  
135 observations, but they were not able to constrain the level of coupling beneath the Tibetan Plateau.  
136 Based on a joint analysis using more shear-wave splitting measurements and GPS observations,  
137 Wang et al. (2008) argued for the crust-mantle coupling in the Tibetan Plateau and the surrounding  
138 regions.

139 Substantial efforts have been made to develop a theoretical framework as well as practical  
140 strategies for the inversion of 3D distribution of anisotropy. A fullwave approach has been developed  
141 for the measurement of shear-wave splitting intensities and interpretation in terms of shear-wave

142 azimuthal anisotropy parameters (Chevrot, 2000; Favier & Chevrot, 2003; Chevrot, 2006; Sieminski  
143 et al., 2008; Monteiller & Chevrot, 2011; Lin et al., 2014a), which has been applied to anisotropy  
144 tomographies for southern California (Monteiller & Chevrot, 2011; Lin et al., 2014b), the High  
145 Lava Plain (Mondal & Long, 2020), and the southeastern Tibetan Plateau (Huang & Chevrot,  
146 2021). The depth variations of anisotropy obtained by these studies have shed new lights in  
147 understanding the sources of anisotropy and the associated mantle dynamics.

148 In this study, we conduct a fullwave multiscale anisotropy tomography for the southeastern  
149 margin of the Tibet Plateau. We collect seismic records at regional permanent broadband  
150 stations from globally distributed earthquakes and obtain high-quality measurements of SKS  
151 splitting intensities. We then invert the splitting intensities using a wavelet-based parameterization  
152 of the 3D model to achieve a multi-scale resolution to the anisotropic structure. We also provide  
153 an interpretation of our anisotropic model for the southeastern margin of the Tibet Plateau in  
154 terms of regional geodynamics.

## 155 **2 Data and Methods**

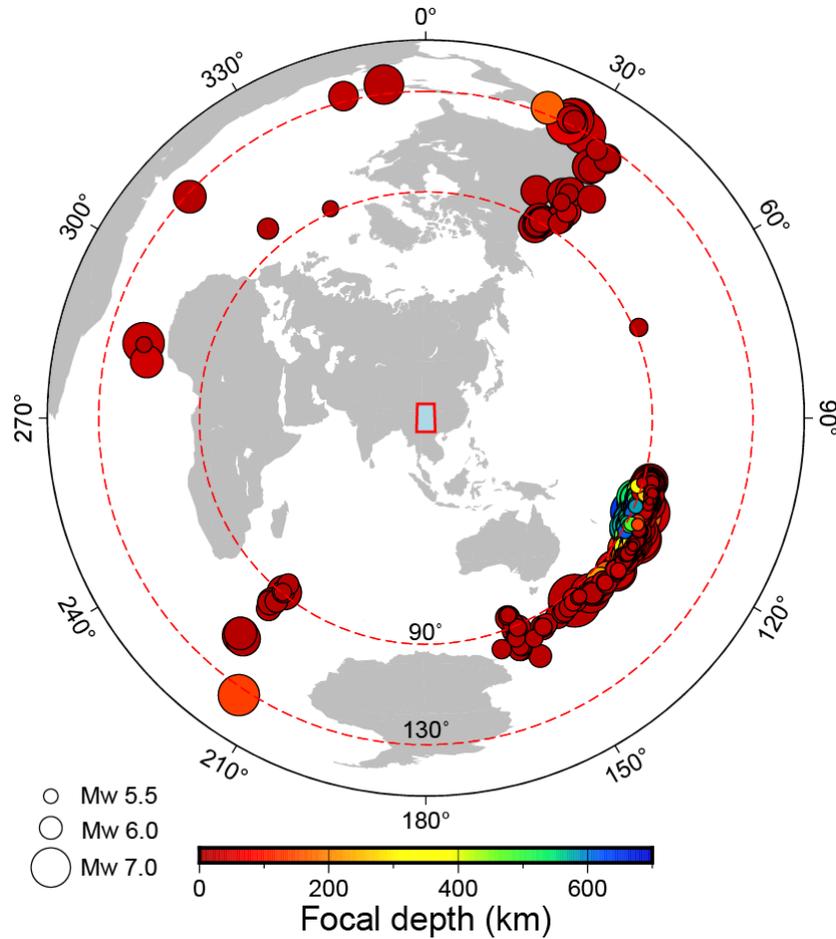
### 156 **2.1 Waveform records**

157 We collect waveforms recorded by 111 permanent broadband stations (green triangles in Figure 1)  
158 deployed in the study region. To guarantee a wide range of azimuthal distribution, we select events  
159 of magnitude  $M_w \geq 5.5$  from 2009 to 2020, located in the epicentral distance range of  $90^\circ$ – $130^\circ$ .  
160 After quality control of the waveforms and removal of outliers of the data (see Section 2.2), a total  
161 of 470 events are used in the subsequent inversions. Figure 3 displays the event distribution.

### 162 **2.2 Splitting intensity measurements**

163 Shear wave splitting measurement is nowadays a routine procedure in the study of seismic  
164 anisotropy. Several previous studies have documented the measured SKS splitting parameters (fast

165 directions and delay times) at stations in our study region (e.g., Chang et al., 2015; Yang et al.,  
 166 2018; Liu et al., 2020; Huang & Chevrot, 2021; Li et al., 2021). In this study, we invert for the  
 167 3D anisotropy structure using the splitting intensity (SI) measurements obtained by computing the  
 168 zero-lag cross-correlation between the transverse-component record and the time derivative of the  
 169 radial-component record (Chevrot, 2000).



170  
 171 **Figure 3.** Distribution of 470 teleseismic events used for SKS splitting intensity inversion in this  
 172 study. Events of magnitudes Mw5.5 and greater in the epicentral distance range of 90°–130° during  
 173 2009–2020 are selected. The red box in the center indicates the study area.

174 For a given station, the SI of the SKS wave from the  $i$ -th event is defined as

175

$$S_i = -2 \frac{\int_{t_{i1}}^{t_{i2}} \dot{u}_i^R(t) u_i^T(t) dt}{\int_{t_{i1}}^{t_{i2}} [\dot{u}_i^R(t)]^2 dt}, \quad (1)$$

176 where  $[t_{i1}, t_{i2}]$  is the time window for the SKS wave, and  $u_i^R(t)$  and  $u_i^T(t)$  are the radial and  
 177 transverse-component records, respectively, from the  $i$ -th event. A dot above a variable indicates  
 178 derivative with respect to time. The conventional SKS splitting parameters at the given station,  
 179 namely the fast-direction azimuth  $\theta$  and delay time  $\Delta t$ , are related to the SIs measured at the station  
 180 from all events through a sinusoidal curve fitting (Chevrot, 2000; Lin et al., 2014a):

$$181 \quad S_i = \Delta t \sin 2(\theta - \theta_i^b), \quad (2)$$

182 where  $\theta_i^b$  is the back azimuth of the  $i$ -th event.

183 In this study, we obtain the SI measurements of SKS waves with the help of SplitRacer (Link  
 184 et al., 2022), an efficient and automatic toolbox developed for the measurement and quality control  
 185 of XKS splittings. An example of the SplitRacer processing is shown in Figure 4. We use SplitRacer  
 186 to determine the SKS time window automatically, followed by a manual check on the quality of the  
 187 SKS signals. Then, we calculate the SIs using Eq. (1). The period band we use in this study is 8–  
 188 50 s considering the dominant periods of the SKS signals as well as minimizing the interference  
 189 with neighboring phases. As shown in Figure 4, the spectral powers of the radial- and transverse-  
 190 component records are calculated by the short-time Fourier transform (Quatieri, 2006) and summed.  
 191 Then, the dominant frequency band of the SKS waveform can be identified (between the red dashed  
 192 horizontal lines in Figure 4c). At each time, the powers within the dominant frequency band are  
 193 summed (Figure 4d), which defines the SKS window by the two crossing points at 50% of the peak  
 194 level (vertical green lines in Figure 4d). The final SKS window is given by either expanding or  
 195 shrinking the 50% energy window to a fixed 30-s window (red vertical lines). After completing  
 196 the quality check using SplitRacer, we obtain a total of 12,457 SKS wave SI measurements.

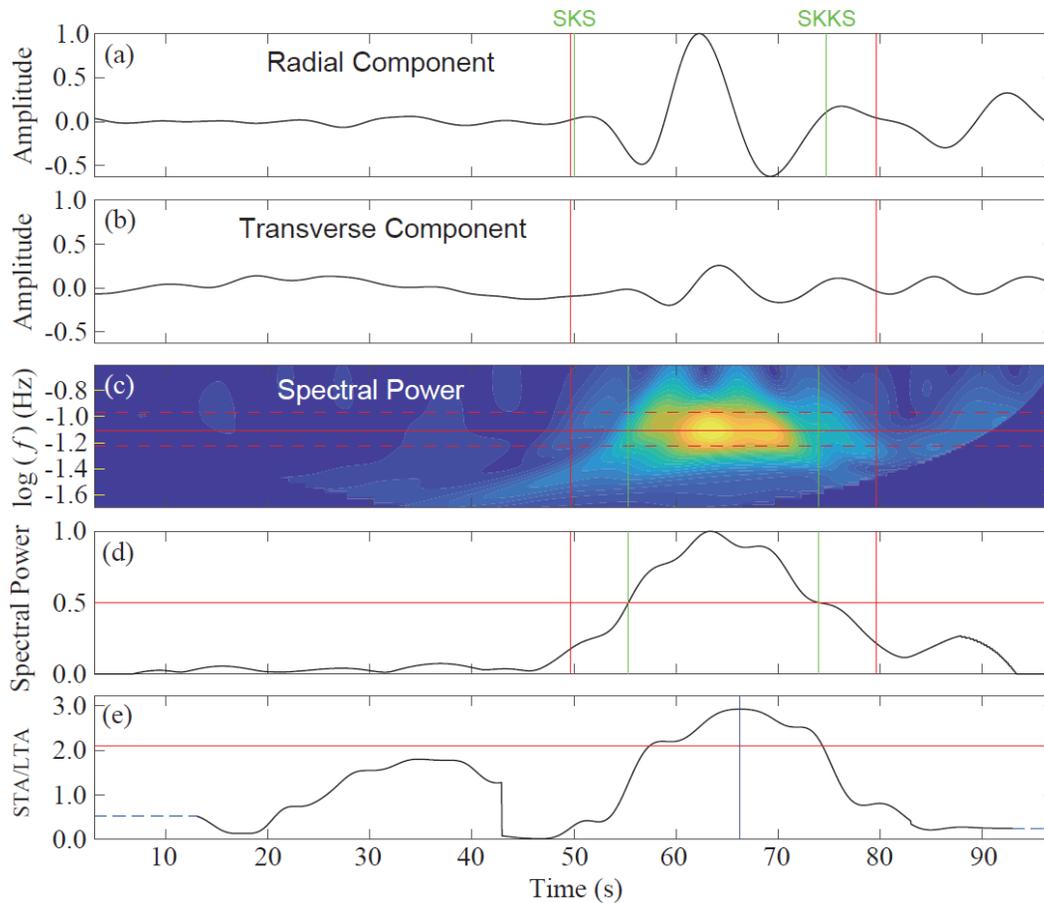
197 Following Chevrot (2000), we estimate the uncertainty of each SI measurement using the  
 198 following equation

199

$$\sigma_i = \sqrt{\frac{1}{N_i} \left\{ \sum_{j=1}^{N_i} [u_i^T(t_j)]^2 - \frac{S_i^2}{4} \sum_{j=1}^{N_i} [\dot{u}_i^R(t_j)]^2 \right\}}, \quad (3)$$

200 where  $S_i$  is the  $i$ -th SI measurement, and  $N_i$  is the number of time samples used for the window to

201 obtain the measurement.



202

203 **Figure 4.** Example of SKS window selection using SplitRacer. (a) and (b) show normalized radial

204 and transverse records, respectively, around the SKS arrival at station WXT (blue triangle in

205 Figure 1) from the 24 June 2019 earthquake in New Zealand with a back azimuth of  $122^\circ$ . The

206 green lines mark the theoretical SKS and SKKS arrival times of seismic phases corresponding to

207 the event of interest. Red vertical lines mark the start and end time of the final window containing

208 the SKS waveform. (c) Summed spectral power of the spectrogram of the radial and transverse

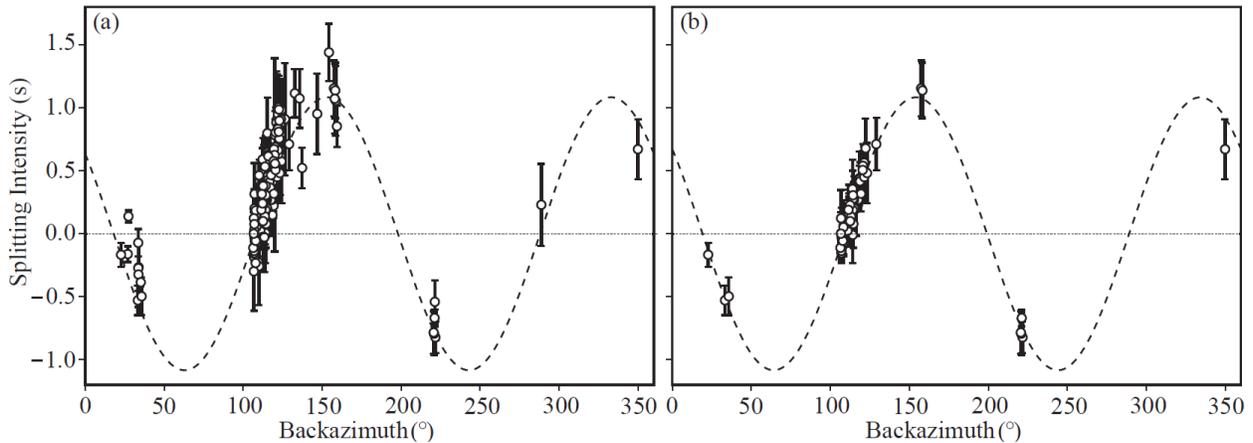
209 records in (a) and (b). The red horizontal line marks the frequency of maximum spectral power,

210 and the red dashed lines show the frequency bounds of more than 80% of the maximum. The green

211 vertical lines mark the time window in which the summed spectral power is more than 50% of the

212 maximum. (d) Summed spectral power over all frequencies. The green vertical lines mark the time  
 213 window in which the summed spectral energy is more than 50% of the maximum. (e) STA/LTA  
 214 ratio of the radial-component record used as quality check. The blue vertical line denotes the time  
 215 when the STA/LTA ratio reaches its peak within the window determined in (d). The red horizontal  
 216 line is the acceptance threshold of 2.1 (Link et al., 2022).

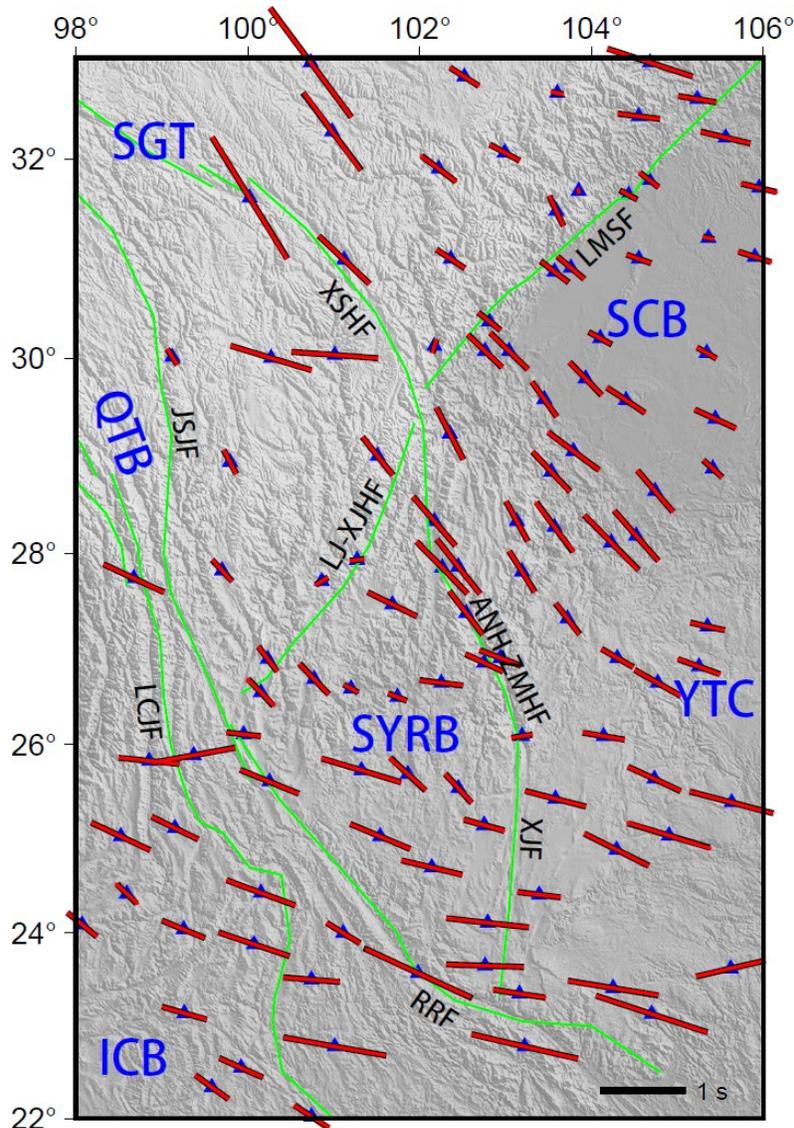
217 We further clean our dataset of outliers based on two criteria: (1) At a given station, SI  
 218 measurements with uncertainties  $\sigma_i$  larger than 1.5 times the average uncertainty  $\bar{\sigma}$  for that station,  
 219 i.e.  $\sigma_i > 1.5\bar{\sigma}$ , are removed; (2) all SI measurements at a given station are fit by a sinusoidal curve,  
 220 and measurements that deviate from the sinusoidal curves by more than  $2\sigma_i$  are also removed.  
 221 After removing the outliers, we retain a total of 5,216 high-quality SI measurements as our final  
 222 dataset for subsequent anisotropy inversion. The standard deviation of the final dataset (the  
 223 average of uncertainties of all retained data) is 0.074 s. Figure 5 shows the effect on the distribution  
 224 of SI measurements before and after applying the above two criteria for station WXT, which  
 225 reduces the number of SI data from 184 to 61.



226 **Figure 5.** Variations of measured SI with event back azimuth for station WXT (blue triangle in  
 227 Figure 1) before (a) and after (b) removal of SI outliers. The vertical error bars show two standard  
 228 deviations ( $2\sigma_i$ ) of individual measurements. The dashed lines represent the sinusoidal curves that  
 229 best fit the measurements. According to Eq. (2), the conventional SKS splitting parameters for this  
 230 station are:  $\Delta t = 1.08$  s and  $\theta = 109.14^\circ$ .  
 231

232 Based on Eq. (2), we can obtain the conventional fast-direction azimuth  $\theta$  and delay time  $\Delta t$   
 233 at each station using all the SI measurements, and they are displayed in Figure 6. The spatial

234 distribution of  $\theta$  has a similar pattern as seen in previous studies, i.e. a generally NW-SE oriented  
 235 fast axis and a nearly uniform EW alignment of the fast-axis directions south of  $\sim 26^\circ\text{N}$  latitude.



236  
 237 **Figure 6.** Black line segments show the conventional SKS fast-direction azimuths and delay times  
 238 at all station obtained from the SI measurements according to Eq. (2). Red line segments are fast-  
 239 direction azimuths and delay times derived from Eq. (2) based on the model-predicted SIs obtained  
 240 by integrating the sensitivity kernels (see Figure 7) with the anisotropy model in Figure 12  
 241 according to Eq. (4). Names of major faults and tectonic blocks are the same as in Figure 1.

### 242 2.3 Multiscale inversion for 3D anisotropic structure

243 We implement the full-wave multiscale anisotropy tomography framework developed by Lin et al.

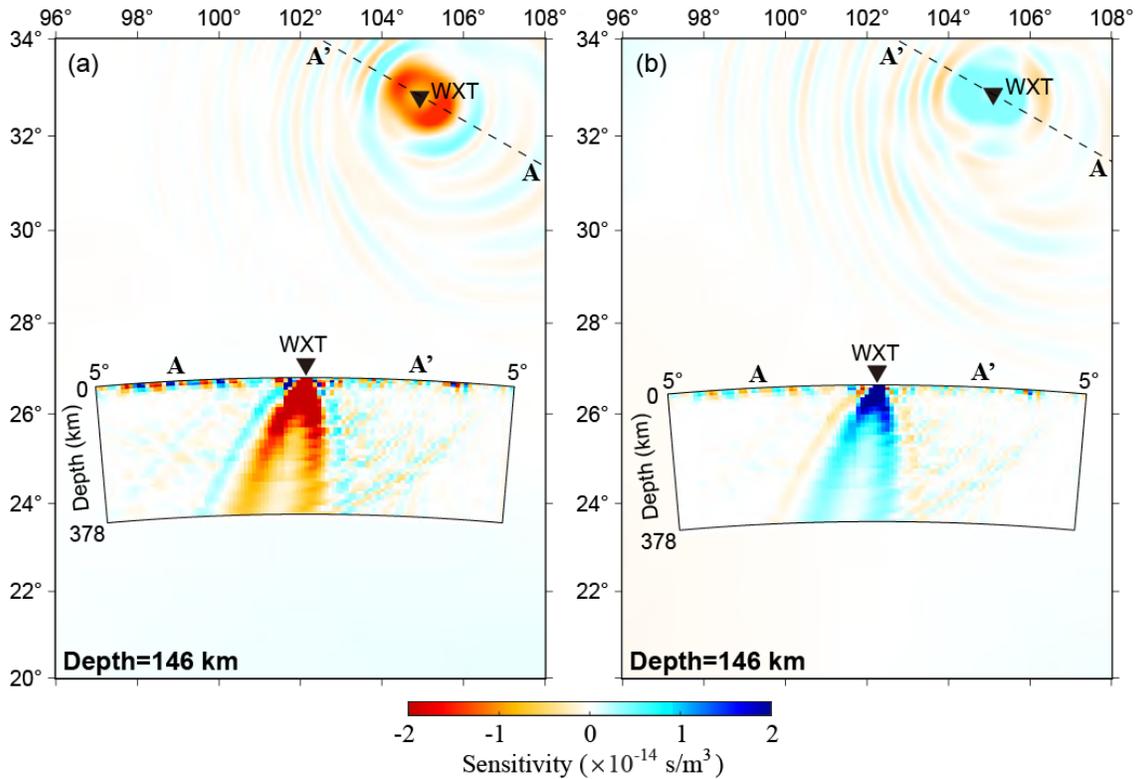
244 (2014b). Here we briefly describe our methodology. Interested readers may consult Lin et al.  
 245 (2014b) for a full description of the method.

246 Becker et al. (2006) point out that upper-mantle anisotropy is to first-order hexagonal and the  
 247 hexagonal parameters  $\varepsilon$  (describing P-wave anisotropy),  $\gamma$  (describing S-wave anisotropy) and  $\delta$   
 248 (an extra parameter describing the shape of P- and S-wave slowness surfaces) are strongly  
 249 correlated. Furthermore, Zhao & Chevrot (2011) demonstrated that the sensitivity of the SI of  
 250 an SKS wave is mostly sensitive to  $\gamma$ , and is about 10 times larger than that to the isotropic  
 251 heterogeneity. This allows us to considerably simplify the modeling of upper mantle anisotropy in  
 252 two aspects: (1) it is sufficient to use 1D reference model; and (2) the anisotropy can be described by  
 253 only two parameters: the strength of anisotropy  $\gamma$  and the azimuth  $\phi_f$  of the symmetry axis of  
 254 anisotropy. We assume that the symmetry axis is horizontal since the sub-vertically propagating  
 255 SKS waves are insensitive to the dip angle of the symmetry axis of anisotropy (Mondal & Long,  
 256 2019). Note that the anisotropy strength  $\gamma$  and azimuth  $\phi_f$  are spatially varying, and the  
 257 dependence of the SI on  $\phi_f$  is nonlinear. As documented in Favier & Chevrot (2003), we can  
 258 introduce two independent parameters,  $\gamma_c = \gamma \cos(2\phi_f)$  and  $\gamma_s = \gamma \sin(2\phi_f)$  to enable a linear  
 259 relationship with the SI measurement

$$260 \quad S = \iiint [K_{\gamma_c}^S(\mathbf{r})\gamma_c(\mathbf{r}) + K_{\gamma_s}^S(\mathbf{r})\gamma_s(\mathbf{r})]d\mathbf{r}, \quad (4)$$

261 where  $K_{\gamma_c}^S$  and  $K_{\gamma_s}^S$  are the Fréchet sensitivity kernels of the splitting intensity  $S$  to  $\gamma_c$  and  $\gamma_s$ ,  
 262 respectively. After obtaining  $\gamma_c$  and  $\gamma_s$  from a linear inversion, we can obtain the more familiar  
 263 anisotropy parameters by utilizing the relations:  $\phi_f(\mathbf{r}) = 0.5 \tan^{-1}[\gamma_s(\mathbf{r})/\gamma_c(\mathbf{r})]$  and  $\gamma(\mathbf{r}) =$   
 264  $\sqrt{[\gamma_c(\mathbf{r})]^2 + [\gamma_s(\mathbf{r})]^2}$ . In this study, we use PREM (Dziewonski & Anderson, 1981) as the  
 265 reference model and compute the sensitivity kernels using the normal mode summation algorithm  
 266 developed by Zhao & Chevrot (2011). Examples of the Fréchet kernels for  $\gamma_c$  and  $\gamma_s$  are shown in

267 Figure 7. Chevrot (2006) first noted the similarity between the definition of the SI in Eq. (1) and  
 268 that of the traveltime delay (e.g. Dahlen et al., 2000; Zhao et al., 2000), which implies that the sensitivity  
 269 kernels of the SI to anisotropy parameters exhibit the distinct banana-doughnut shapes typically seen in  
 270 the sensitivities of the finite-frequency traveltimes to isotropic velocities, as shown in Figure 7.



271  
 272 **Figure 7.** Examples of the sensitivity kernels of the SI to shear wave anisotropy parameters  $\gamma_c$  (a)  
 273 and  $\gamma_s$  (b) shown in mapviews for the 146-km depth and in profiles (insets) along source-receiver  
 274 path AA' for station WXT (blue triangle in Figure 1). The SKS wave is from the 24 June 2019  
 275 event in New Zealand with a back azimuth of 122°, and the waveforms are shown in Figure 4.

276 As in Lin et al. (2014b), we adopt a wavelet-based model parameterization (Chiao & Kuo,  
 277 2001) to obtain multi-scale resolutions in both sparsely- and densely-sampled regions of data  
 278 coverage. The inverse problem can be expressed as:

279 
$$(\mathbf{GW}^{-1})(\mathbf{Wm}) = \mathbf{d}, \quad (5)$$

280 where  $\mathbf{G}$  is Gram matrix containing the Fréchet kernels,  $\mathbf{W}$  is the 3D wavelet transformation matrix,

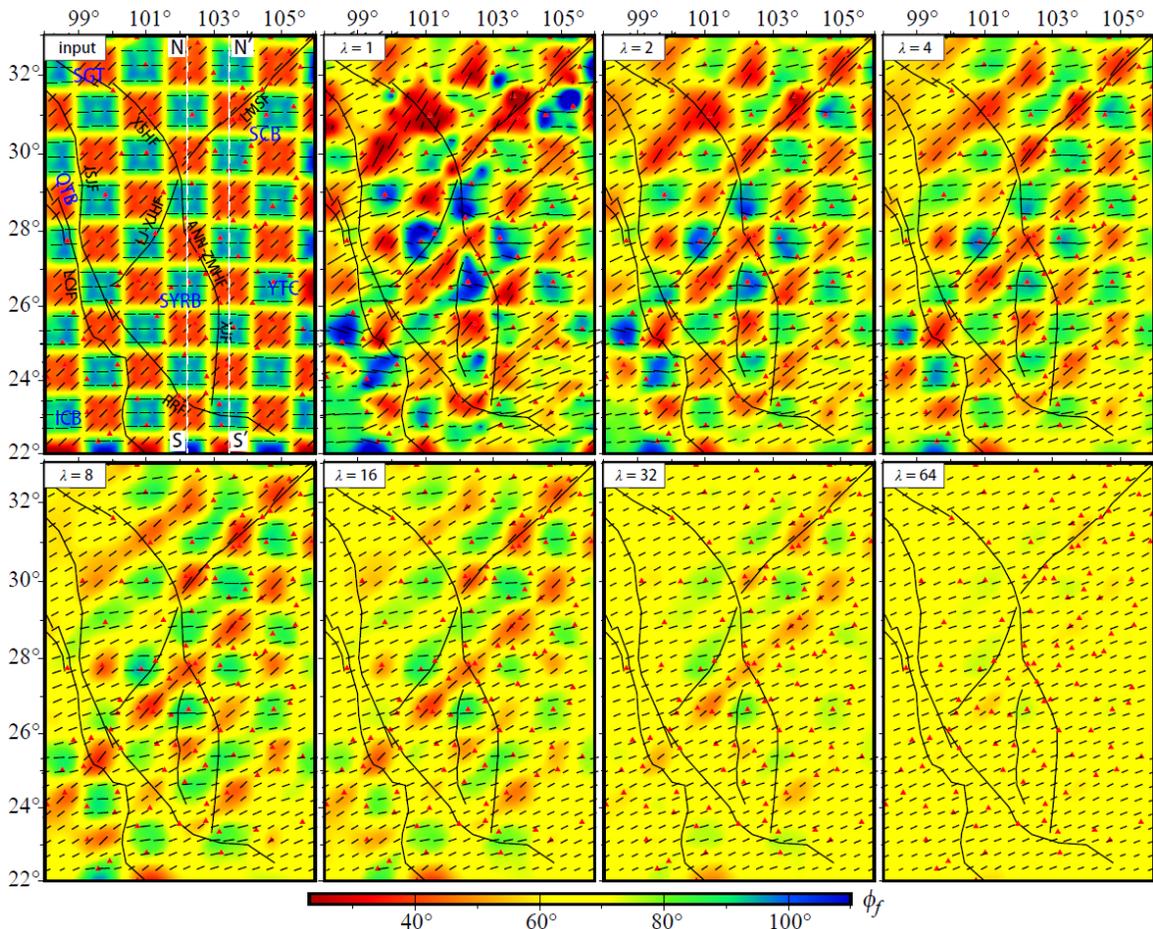
281 **m** is the vector comprising the model parameters at spatial nodes, and **d** is the data vector of the  
 282 SI measurements. In this study, we first parameterize the model by a 3D mesh with  $33 \times 33$  nodes  
 283 horizontally and 17 nodes vertically, and apply the operator  $(\mathbf{W}^{-1})^T$  on each row of **G**. A damped  
 284 least-squares solution to the inverse problem in Eq. (5) is solved by the LSQR algorithm (Paige &  
 285 Saunders, 1982), with the damping factor  $\lambda$  selected empirically by a series of inversion  
 286 experiments (see Section 2.4), and the final model can be obtained by an inverse wavelet transform.  
 287 Readers may refer to Hung et al. (2011) for implementation details of the multi-scale  
 288 parameterization. The wavelet approach achieves a finer spatial resolution in regions of better data  
 289 coverage and coarser resolution in less well-sampled regions, thus resolving the structure with an  
 290 objective and data-driven multi-scale resolution.

#### 291 **2.4 Resolution tests**

292 Careful selection of the damping factor  $\lambda$  and objectively evaluating the resolution for a given  
 293 dataset in an inversion problem is paramount to interpreting the inversion results. Thus, it is important  
 294 to characterize how reliable our anisotropic models are, and to restrict our interpretations to robust  
 295 features that are well-resolved and required by the observations.

296 We present three sets of resolution tests to illustrate the selection of the optimal damping  
 297 factor and the resulting resolution of our SI dataset. Given the input model in a resolution test, the  
 298 SI is predicted for each SKS path in our final dataset by integrating the products of 3D sensitivity  
 299 kernels with the distributions of  $\gamma_c$  and  $\gamma_s$  in the input model according to Eq. (4). A Gaussian  
 300 noise with the same standard deviation as our final inversion dataset (0.074 s) is added to the SI  
 301 predictions. We first perform a series of tests using checkerboards of two different sizes ( $1^\circ \times 1^\circ$   
 302 and  $1.5^\circ \times 1.5^\circ$ ) with horizontally alternating azimuthal angles of fast axes  $\phi_f = 90^\circ$  and  $\phi_f = 45^\circ$   
 303 but a fixed anisotropy strength  $\gamma = 4\%$ . Figure 8 shows the input and recovered models for

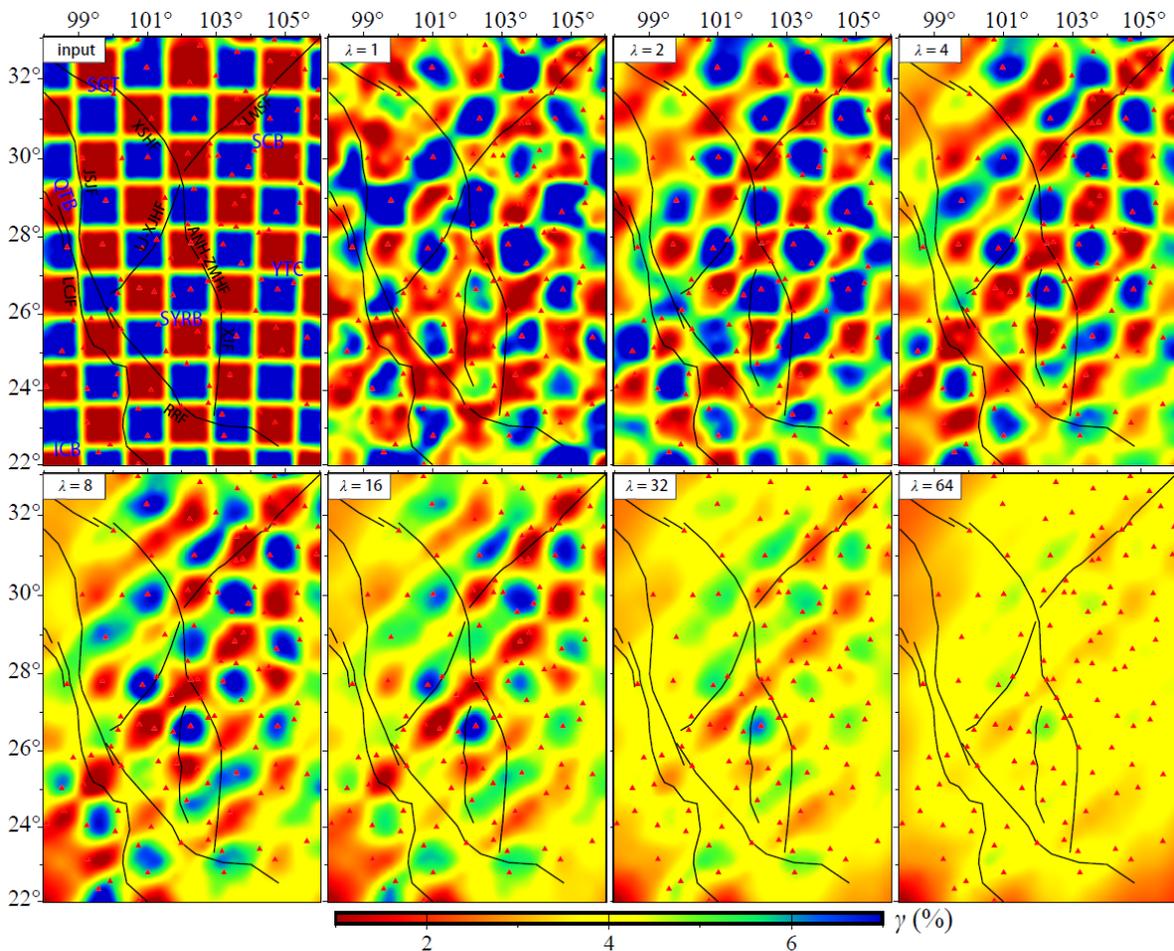
304 different values of the damping factor  $\lambda$  at a depth of 55 km for the  $1^\circ \times 1^\circ$  checkerboard test. The  
 305 effect of damping factor on the anisotropy pattern in the inversion result is obvious. The recovery  
 306 results suggest an optimal damping factor of  $\lambda = 4$ , and the checkerboard pattern is well-resolved  
 307 in most parts of the study area except in the northwest and southeast corners where stations are  
 308 more sparse. Results for recovered models at different depths as well as for  $1.5^\circ \times 1.5^\circ$   
 309 checkerboards are presented in Figures S1 and S3 in Supporting Information.



310  
 311 **Figure 8.** Resolution tests for the azimuth of symmetry axis using  $1^\circ \times 1^\circ$  checkerboard. (Top-left)  
 312 The input model has horizontally alternating azimuthal angles of fast axes  $\phi_f = 90^\circ$  and  $\phi_f = 45^\circ$   
 313 shown by both the color and the directions of the line segments, and a fixed anisotropy strength  
 314  $\gamma = 4\%$  represented by the lengths of the line segments. The two white dashed lines show the  
 315 locations of profiles NS and N'S' in Figure 11. The other panels show the recovered models at a  
 316 depth of 55 km for different damping factors  $\lambda$ . We choose  $\lambda = 4$  as the optimal value for the

317 damping factor (top-right panel). Red triangles show locations of stations used.

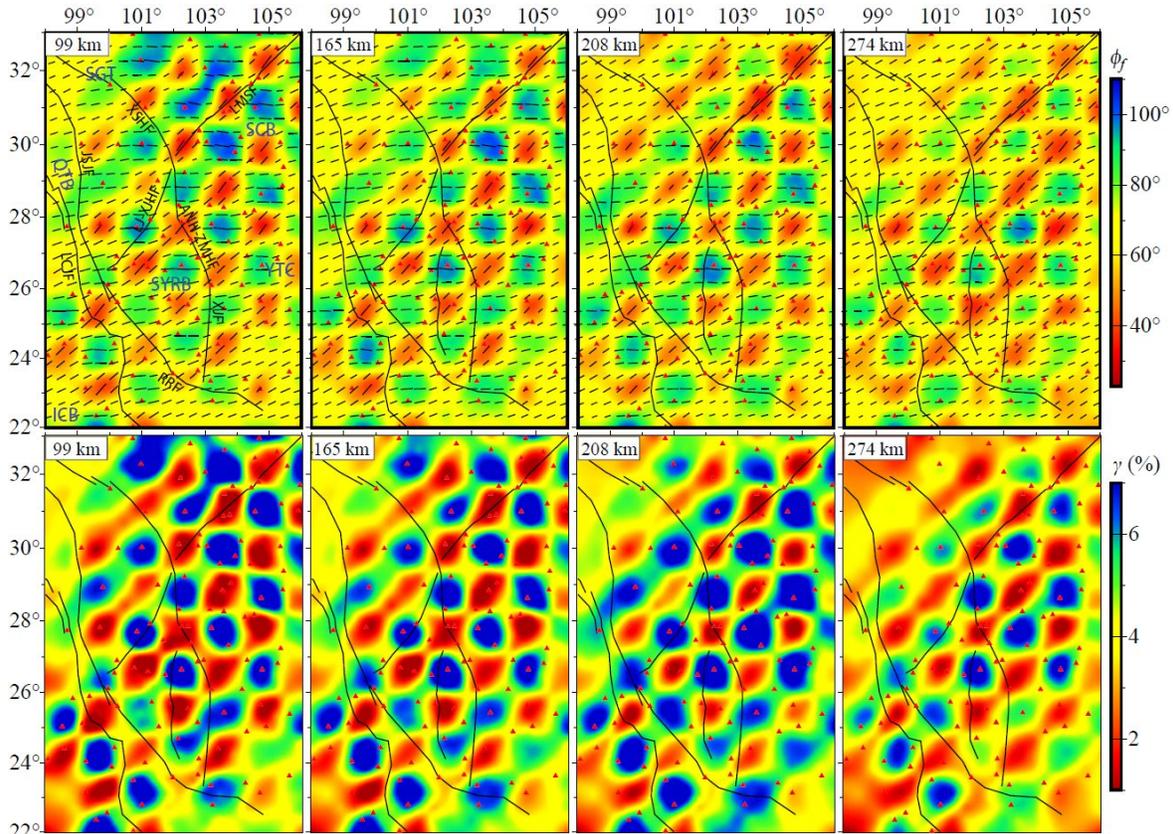
318 In the second set of tests, we use input checkerboard models with a fixed azimuthal angle of  
 319 symmetry axis  $\phi_f = 22.5^\circ$  but alternating perturbations of anisotropy strength of  $\delta\gamma = \pm 3\%$   
 320 relative to a background anisotropy strength of  $\gamma = 4\%$ . Figure 9 shows the recovery results at the  
 321 depth of 55 km using different damping factors for the  $1^\circ \times 1^\circ$  input checkerboard model. Results  
 322 for recovered models at different depths as well as for  $1.5^\circ \times 1.5^\circ$  checkerboards are presented in  
 323 Figures S2 and S4 in Supporting Information.



324  
 325 **Figure 9.** Resolution test using  $1^\circ \times 1^\circ$  checkerboard. (Top-left) The input model has horizontally  
 326 alternating anisotropy strengths shown by the colors representing perturbations of  $\delta\gamma = \pm 3\%$   
 327 relative to a background anisotropy strength of  $\gamma = 4\%$  and a fixed azimuthal angle of symmetry  
 328 axis  $\phi_f = 22.5^\circ$ . The other panels show the recovered models at a depth of 55 km for different

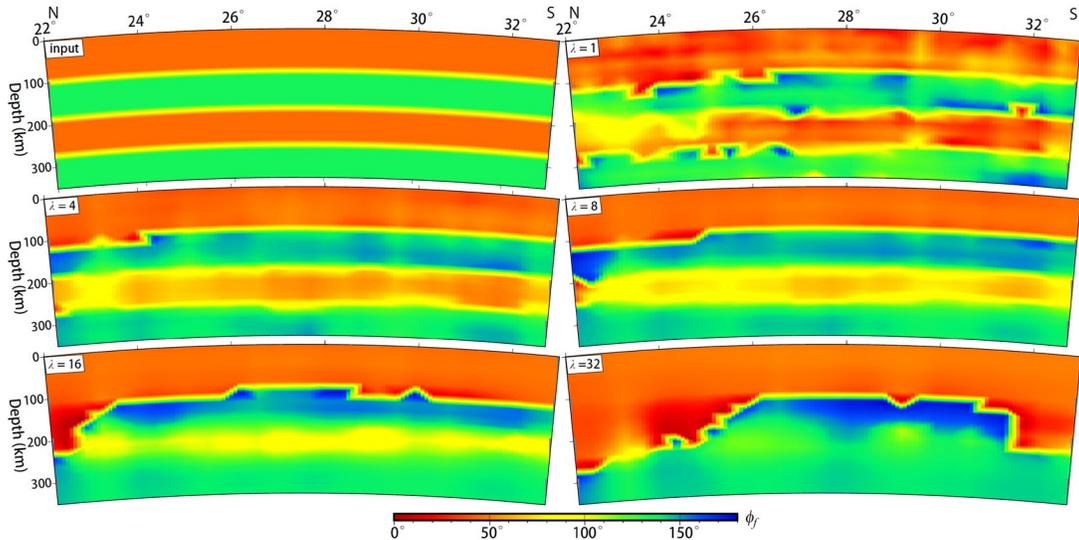
329 damping factors  $\lambda$ . We choose  $\lambda = 4$  as the optimal value for the damping factor (top-right panel).  
 330 Red triangles show locations of stations used.

331 The tests in Figures 8 and 9 both show that the damping factor of  $\lambda = 4$  yields the best  
 332 resolved checkerboard pattern. For convenience, resolution test results at different depths for  
 333 damping factor  $\lambda = 4$  are collected and displayed in Figure 10.



334  
 335 **Figure 10.** Resolution test using  $1^\circ \times 1^\circ$  checkerboard with damping factor  $\lambda = 4$ . (Upper panels)  
 336 Recovered model at the depths of 99 km, 165 km, 208 km and 274 km for an input model having  
 337 horizontally alternating azimuthal angles of fast axes  $\phi_f = 90^\circ$  and  $\phi_f = 45^\circ$  with a fixed  
 338 anisotropy strength  $\gamma = 4\%$ . The input model and the recovered model at 55-km depth are shown  
 339 in Figure 8. (Lower panels) Recovered model at the depths of 99 km, 165 km, 208 km and 274 km  
 340 for an input model with horizontally alternating anisotropy strengths of  $\gamma = 1\%$  and  $\gamma = 7\%$  with  
 341 a fixed azimuthal angle of symmetry axis  $\phi_f = 22.5^\circ$ . The input model and the recovered model  
 342 at 55-km depth are shown in Figure 9. Red triangles show locations of stations used.

343 The third set of tests is intended to probe the depth resolution of our SI dataset with full-  
 344 waveform anisotropy tomography. We use input models with a fixed anisotropy strength of  $\gamma =$   
 345 4% but several layers of alternating azimuthal angles of symmetry axes. Figure 11 shows the  
 346 recovery results for a 4-layer input model along a north-south vertical cross-section (cross-section  
 347 NS in the top-left panel of Figure 8) for different damping factors.



348 **Figure 11.** Resolution tests for an input model with 4 layers of alternating azimuthal angles of  
 349 symmetry axes  $\phi_f = 45^\circ$  and  $\phi_f = 135^\circ$  but a fixed anisotropy strength of  $\gamma = 4\%$ . Shown here  
 350 are the input model (top-left panel) and recovered models for different damping factors  $\lambda$  along  
 351 the north-south cross-section NS through the middle of the study region (see top-left panel in  
 352 Figure 8). The optimal damping is  $\lambda = 4$  (middle-left panel).  
 353

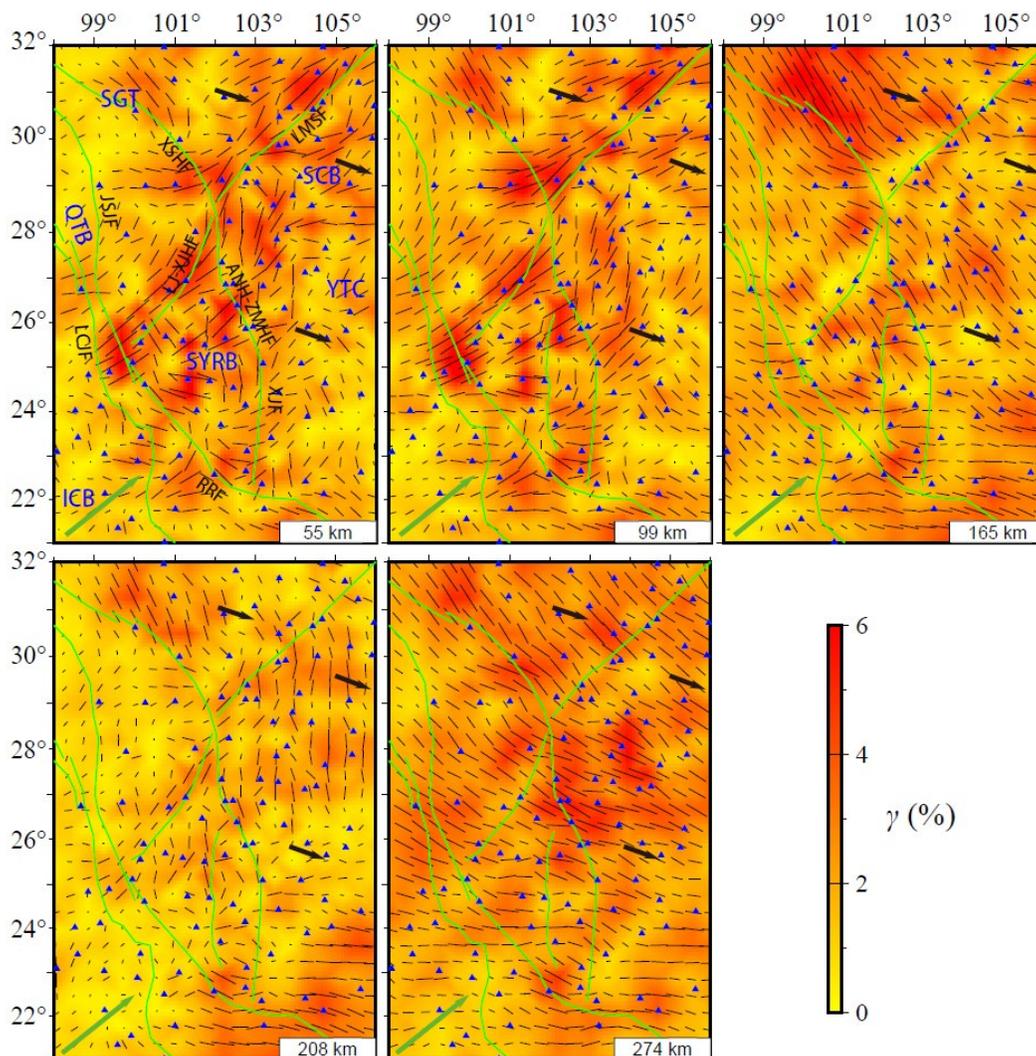
354 Recovered models along another profile as well as for a 2-layer input model are presented in  
 355 Supporting Information (Figures S5-S8). These results also suggest an optimal damping factor of  
 356  $\lambda = 4$  in most parts of the study area. Based on all the resolution test results, we determine  $\lambda = 4$   
 357 to be the optimal damping factor for the SI data inversions in this study.

358 The above resolution tests demonstrate that with the available distributions of seismic stations  
 359 and teleseismic earthquakes, our SKS wave SI dataset can resolve reasonably well the shear-wave  
 360 azimuthal anisotropy with a horizontal dimension of  $1^\circ \times 1^\circ$  and a vertical thickness of  $\sim 100$  km in

361 the main part of the study region. Near the western border and in the SE corner, the resolution is  
 362 poor due to larger station spacing and fewer crossing SKS ray paths.

### 363 **3 Result**

364 As stated in Section 2.2, our final dataset contains 5,216 SI measurements at 111 permanent seismic  
 365 stations from 470 events, which are used to invert for the 3D azimuthal anisotropy structure of the  
 366 study region. Figure 12 displays our inverted model at five representative depths.



367  
 368 **Figure 12.** Three-dimensional anisotropic model for southeast margin of the Tibetan Plateau at 55  
 369 km, 99 km, 165 km, 208 km and 274 km depths. The anisotropy strength and the azimuth of the  
 370 fast axes are shown by the background color and the black line segments, respectively. The lengths  
 371 of the line segments are proportional to the anisotropy strength. The black and green arrows denote

372 the absolute plate motion (APM) of the Eurasian and Indian plates, respectively, according to the  
373 model NNR-MORVEL56 (Argus et al., 2011). Names of major faults and tectonic blocks are the  
374 same as in Figure 1. Blue triangles show locations of stations used.

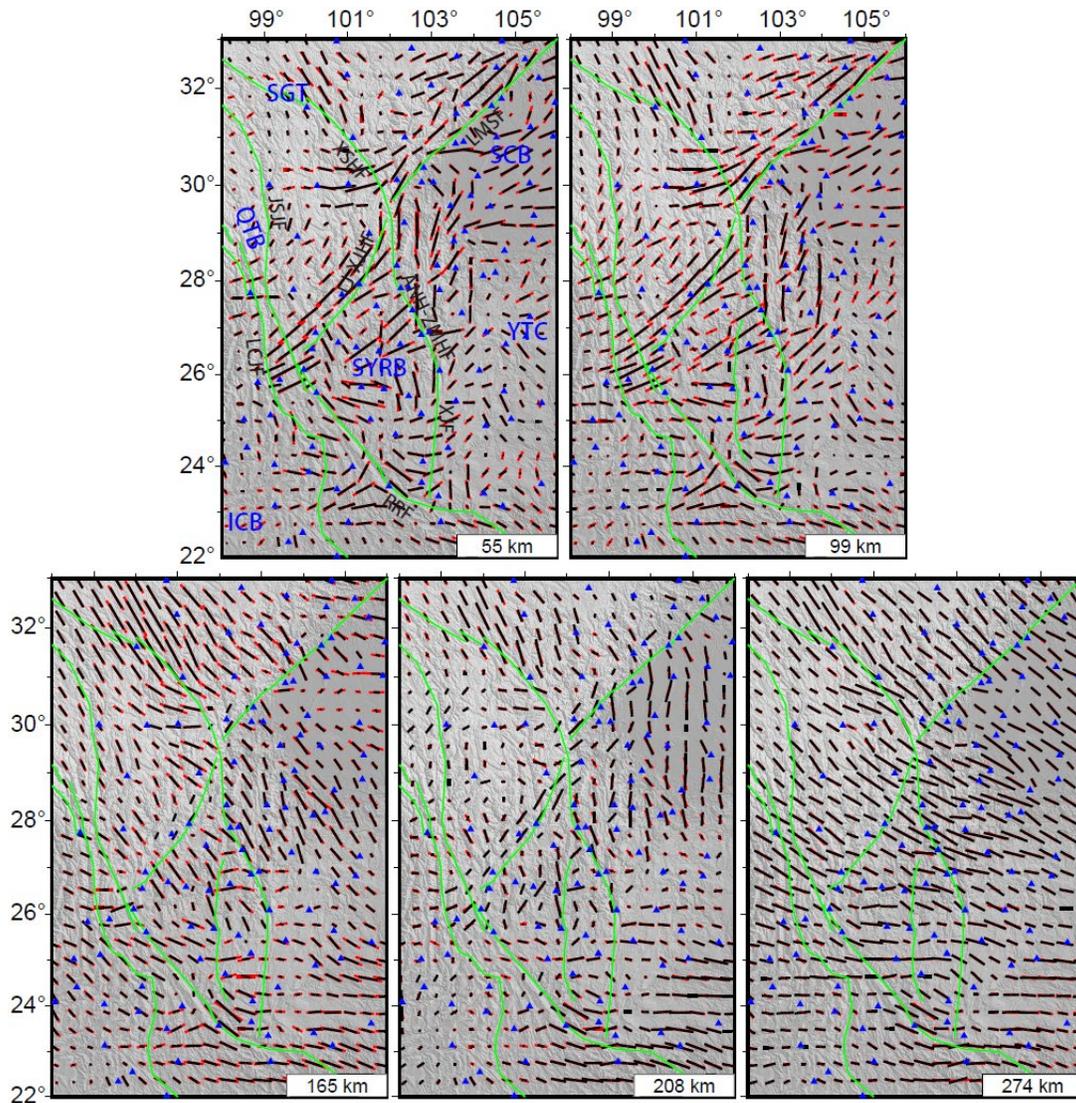
375 As a first check of the inversion result, we calculate the model-predicted conventional SKS  
376 splitting time  $\Delta t$  and fast-direction azimuth  $\theta$  by integrating the anisotropy model (Figure 12) with  
377 sensitivity kernels (Figure 7) according to Eq. (4) and compare with observations. The comparison  
378 in Figure 6 shows excellent agreement between the model-predicted splitting parameters with  
379 observations at all stations.

380 We also carry out a recovery test for our inversion result, in which we use the model in Figure  
381 12 as the input model and calculate the synthetic SI data, then invert them using the same model  
382 discretization and damping factor as in the inversion of the real data. The comparison in Figure 13  
383 shows that the output model strongly resembles the input model at all depths. The synthetic inversion  
384 successfully reproduces all the major features of the input model.

## 385 **4 Discussion**

### 386 **4.1 Comparison with previous results**

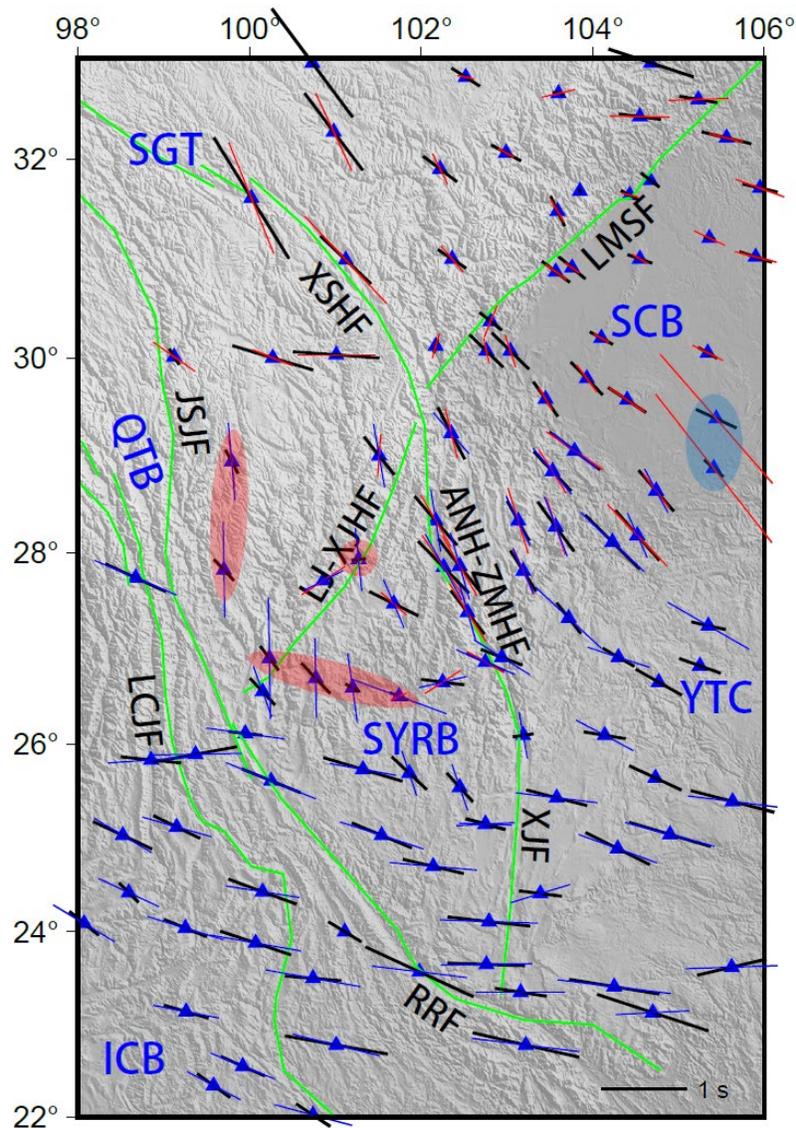
387 SKS splitting observation has been widely used to investigate the upper mantle anisotropy in the  
388 southeastern margin of the Tibetan Plateau (e.g., Lev et al., 2006; Flesch et al., 2005; Wang et al., 2008;  
389 Shi et al., 2012; Chang et al., 2015; Yang et al., 2018; Liu et al., 2020; Huang & Chevrot, 2021; Li et  
390 al., 2021), with many overlapping seismic stations and teleseismic events. Here, we compare our  
391 tomography result at common stations with those of Chang et al. (2015) and Liu et al. (2020) whose  
392 SKS splitting measurements are available at the Shear Wave Splitting Product Query website  
393 (<http://ds.iris.edu/spud/swsmeasurement>). In Figure 14, the SKS splitting parameters (splitting times  
394 and fast-direction azimuths) predicted by our model in Figure 12 are compared with those from the  
395 above two studies.



396  
 397 **Figure 13.** Result of the recovery test. The recovered and input anisotropic models are compared  
 398 at five depths marked at the bottom-right corner in each panel. Black and red line segments denote  
 399 the directions of fast axes in the input and recovery models, respectively, and their lengths indicates  
 400 the anisotropy strength. Names of major faults and tectonic blocks are the same as in Figure 1.  
 401 Blue triangles show locations of stations used.

402 Figure 14 shows that the fast axes determined from our tomographic results are in good agreement  
 403 with previous studies at most stations. Major differences occur at two stations in the southern tip of the  
 404 SCB (highlighted by the blue ellipse in Figure 14), where anomalously large splitting times can be seen  
 405 in the results of Liu et al. (2020), shown by the red line segments. There are also discrepancies in both

406 delay time and fast-axis azimuth at a few stations (highlighted by the red ellipses in Figure 14) in the  
 407 SYRB where Chang et al. (2015) reported large splitting times and nearly NS fast axes, whereas our  
 408 model predicts moderate-to-small splitting times and more EW orientation of fast axes. Note that a  
 409 strictly quantitative comparison of different studies is difficult due to differences in earthquake and  
 410 window selections, data processing and frequency bands used in the measurement of SKS splitting  
 411 parameters.



412  
 413 **Figure 14.** Comparison of SKS splitting times and fast axis directions predicted by our anisotropy  
 414 model (Figure 12) with previous studies. Black line segments are results from the present study, whereas

415 blue and red line segments show results from Chang et al. (2015) and Liu et al. (2020), respectively.  
416 Blue and red ellipses highlight stations where there are large discrepancies in splitting parameters  
417 between this study and Liu et al. (2020) and Chang et al. (2015), respectively. Names of major faults  
418 and tectonic blocks are the same as in Figure 1.

#### 419 **4.2 Overall variation of shear wave anisotropy**

420 In the shear-wave anisotropy model displayed in Figure 12, we can see that the overall  
421 anisotropy strength  $\gamma$  can reach 6% in the lithosphere and asthenosphere under the southeastern  
422 margin of the Tibetan Plateau. Both the strength and fast-axis directions of anisotropy show strong  
423 lateral and vertical variations. Within the lithosphere (depths of 55 km and 99 km), the anisotropy  
424 is stronger in the transition zone between the Tibetan Plateau and YTC (along the LJ-XJHF and  
425 LMSF) than other regions, whereas at greater depths in the asthenosphere (e.g. 274 km), the entire  
426 region exhibits strong anisotropy with a largely NW-SE orientation of fast axis parallel to the  
427 direction of the APM (black arrows in Figure 12), which turns to more E-W direction south of  
428 26°N. At intermediate depths (165 km and 208 km), the anisotropy is highly variable, both in terms  
429 of strength and the direction of symmetry axis. Therefore, in the southeastern margin of the  
430 Tibetan Plateau, our model shows an apparent decoupling in the overall deformations  
431 between the lithosphere and asthenosphere, consistent with previous studies (e.g. Flesch  
432 et al., 2005).

433 Previous studies have reported two major features in the SKS splitting pattern in the southeastern  
434 margin of the Tibetan Plateau: an overall NW-SE direction of the fast axis and an alignment of the fast  
435 axis in nearly EW direction south of ~26°N latitude (e. g., Lev et al., 2006; Wang et al., 2008; Chang  
436 et al., 2015; Huang & Chevrot, 2021), as shown in Figures 6 and 14. Our model suggests that this  
437 relatively simple splitting pattern observed at the surface may be a manifestation of vertically averaged  
438 complex variation of anisotropy over lithospheric and asthenospheric depths. For instance, along the

439 LMSF, the fast axes in the lithospheric depth (e.g. 55 km and 99 km) are mainly oriented NE-SW with  
440 relatively high anisotropy strength, but change to NW-SE in the asthenosphere. As a result, we observe  
441 relatively small SKS splitting times ( $< 0.5$  s) with a fast-axis direction of NW-SE at the surface. On the  
442 other hand, the moderate SKS splitting times (1 s or less) and the alignments of nearly EW orientation  
443 of symmetry axes observed at the surface are resulted from a discordant anisotropy in the lithosphere  
444 and a nearly uniform EW-oriented anisotropy in the asthenosphere.

### 445 **4.3 The Songpan-Ganzi Terrane**

446 The SGT is the central portion of the Tibetan Plateau and has been elevated by the collision  
447 between the Indian and Eurasian plates. In its eastern part the eastward expansion of the terrane  
448 has been blocked by the SCB of the YTC. In our study region, the SGT occupies an area of  
449 inverted-triangle shape in the north bounded by the JSJF in the southwest and LMSF and LJ-XJHF  
450 in the southeast (Li et al., 2021). Our model shows two distinct types of anisotropy. In the area far  
451 away from the LMSF, the anisotropy is moderate to strong (3–6%) with NW-SE oriented fast axes  
452 in both lithosphere and asthenosphere, parallel to the regional APM direction (black arrows in  
453 Figure 12) and asthenospheric flow, suggesting a vertical coupling of deformation there and in  
454 agreement with Flesch et al. (2005). The NW-SE orientation of anisotropy in the SGT is  
455 consistent with previous tomography results from Rayleigh waves (Bao et al., 2020; Legendre et al.,  
456 2015) and Pn waves (Lei et al., 2014). However, in the area near the LMSF, the fast axis of  
457 anisotropy in the lithosphere (e.g. 55 km and 99 km depths) becomes NE-SW, parallel to the  
458 proposed lithospheric material flow as a result of the resistance of the SCB to the eastward  
459 expansion of the Tibetan Plateau at LMSF. Near the LMSF, the lithospheric material of the SGT  
460 appears to come apart at  $\sim 102^\circ$  longitude, going in the opposite NE and SW directions. In the  
461 asthenosphere, the fast axis of anisotropy returns to NW-SE, consistent with the regional APM

462 direction. The relatively sharp turn of the fast axis of the lithospheric anisotropy from SE-NW to  
463 NE-SW in the southern tip of SGT is a clear evidence for the redirection of the lithospheric flow  
464 from eastward to southward in the southeastern margin of the Tibetan Plateau.

#### 465 **4.4 The Yangtze Craton**

466 The YTC is a Precambrian continental block which was accreted to the North China Craton in the  
467 Triassic. Our study region covers the western margin of the YTC, namely the SCB and SYRB, and  
468 the model in Figure 12 shows that the anisotropy in the region varies significantly both horizontally  
469 and vertically, as a result of the complex geodynamic evolution of the YTC involving multiple  
470 rounds of lithospheric reactivation, such as the Permian-Triassic Emeishan flood basalt eruption  
471 (e.g. Xu et al., 2001), as well as interactions with surrounding tectonic blocks. In our anisotropy  
472 model, the SCB exhibits a moderate anisotropy with a NE-SW orientation near the LMSF at shallow  
473 depths (e.g. 55 km and 99 km), presumably the effect of dominant shearing in the vicinity of the  
474 LMSF by the moving SGT lithosphere in NE and SW directions. Further east, EW compression  
475 gradually takes over NE-SW shear at shallow depths, and the fast axis of anisotropy turns to more  
476 EW (e.g. 55 km, 99 km and 165 km). This turn of anisotropy from NE-SW to more EW away from  
477 the LMSF has also been observed in surface-wave studies (e.g. Zhang et al., 2023). At greater  
478 depth in the lithosphere (208 km in Figure 12), the anisotropy under the SCB becomes nearly NS,  
479 which is consistent with a frozen anisotropy in the lithosphere generated by the mantle flow in the  
480 Cenozoic (Li et al., 2021) without being modified by the SGT-SCB block interaction at shallower  
481 depths. At asthenospheric depth (274 km), the anisotropy is largely aligned with the regional APM.

482 The anisotropy under the SYRB appears to be continuous across the ANH-ZMHF and XJF,  
483 suggesting that both fault systems are crustal boundaries where the SYRB is escaping in the  
484 southeast direction. In the lithosphere (55 km and 99 km under SYRB and above 208 km depth

485 east of ANH-ZMHF between the SCB and 26°N), the anisotropy has a complex pattern of  
486 relatively small-scale horizontal variations of fast-axis orientation, perhaps a result of multiple  
487 phases of lithospheric reactivations that have modified the previously frozen anisotropy. In the  
488 asthenosphere (> 100 km depth in SYRB and > 200 km between the SCB and 26°N), the anisotropy  
489 largely follows the direction of the regional APM or mantle flow. In the 208-km depth plot of the  
490 model in Figure 12, the azimuthal anisotropy south of the SCB is very weak, which may indicate  
491 a more complex local mantle flow pattern due to the regionally predominant NW-SE mantle flow  
492 being disturbed by the root of the YTC lithosphere. South of 26°N, the anisotropy under the YTC  
493 is returns to largely parallel to the direction of APM.

#### 494 **4.5 Anisotropy south of 26°N latitude**

495 All SKS splitting studies in the southeastern margin of the Tibetan Plateau have shown the that the  
496 SKS splitting south of 26°N latitude appears to be consistently oriented in the EW direction. Our  
497 model suggests that this apparently simple pattern is resulted predominantly from strong EW  
498 oriented azimuthal anisotropy generated by the EW asthenosphere flow due to the eastward  
499 subduction of the Indian Plate under Myanmar (e.g. Yang et al., 2022), and regional variation of  
500 lithospheric and asthenospheric contributions to anisotropy leads small but discernable differences  
501 in SKS splitting observations. For example, under the SYRB, the anisotropy in the lithosphere  
502 between 24°N and 26°N is relatively strong (55 km and 99 km in Figure 12) with different  
503 orientations of fast axes. The integration of lithospheric and asthenospheric anisotropy results in  
504 horizontally variable SKS splitting delay times and fast-axis directions observed at the surface, as  
505 shown by the stations in SYRB in Figures 6 and 14. In the rest of the study region south of 26°N,  
506 the asthenospheric contribution dominates, and the surface SKS splitting parameters exhibit  
507 relatively uniform EW fast axes.

## 508 **5 Conclusions**

509 In this study, we have carried out a fullwave multiscale tomography to obtain the 3D model for  
510 the shear-wave anisotropy in the southeastern margin of the Tibetan Plateau. A total of 5,216 high-  
511 quality SKS splitting intensities are obtained from the broadband records of 470 teleseismic events  
512 at 111 permanent stations after a series of quality control measures. In conjunction with the 3D  
513 sensitivity kernels and a wavelet-based parameterization, this dataset is inverted to achieve a data-  
514 driven multi-scale resolution to anisotropy structure in the upper mantle.

515 The vertical variation of the anisotropy in our result indicates that the lithospheric and  
516 asthenospheric deformations are decoupled in the southeastern margin of the Tibetan Plateau. On  
517 the other hand, the anisotropy appears to be vertically consistent under the Songpan-Ganzi Terrane,  
518 suggesting a coupling of the deformations in the lithosphere and asthenosphere in the interior of  
519 the Tibetan Plateau.

520 The strength of anisotropy in our model is spatially variable and can reach 6%, with strongest  
521 anisotropy in the asthenosphere due to large-scale and relatively steady mantle flow, and in the  
522 lithosphere along the Longmenshan Fault and Lijiang-Xiaojinhe Fault, presumably due to large  
523 shearing effect generated by the relative movement between the Songpan-Ganzi Terrane and the  
524 Yangtze Craton.

525 The azimuth of the fast axis of anisotropy in the asthenosphere largely follows the direction of  
526 regional absolute plate motion or mantle flow, i.e. mostly SE beneath the Songpan-Ganzi Terrane and  
527 the Yangtze Craton and nearly east-west south of 26°N latitude. In the lithosphere, however, the fast  
528 axis is highly variable. In the Sichuan Basin, the frozen anisotropy dominates in the deep lithosphere;  
529 whereas at shallower depths, the anisotropy is modified by the interaction with the Songpan-Ganzi  
530 Terrane into SW in the vicinity of the Longmenshan Fault and nearly EW further east. In the Sichuan-

531 Yunnan Rhombic Block and east of the Anninghe-Zemuhe Fault, the azimuth of the fast axis of  
532 anisotropy exhibits complex spatial pattern due to multiple phases of lithospheric reactivation. The  
533 vertical integration of the contributions from complex lithospheric anisotropy and relatively uniform  
534 asthenospheric anisotropy gives rise to the seemingly simple pattern of conventional SKS splitting  
535 parameters observed at the surface. Our 3D model of azimuthal anisotropy provides important new  
536 insights into the lithospheric and asthenospheric dynamics in the southeastern margin of the  
537 Tibetan Plateau.

538

539

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544

545

#### 546 **Data Availability Statement**

547 The processed SKS waveforms and their corresponding splitting intensities as well as the final  
548 inverted anisotropic model can be accessed at <https://doi.org/10.5281/zenodo.8232748>. Most of  
549 the figures are generated using the Generic Mapping Tools (Wessel et al., 2019,  
550 <https://www.generic-mapping-tools.org>).

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