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## **Active and fossil mantle flows in the western Alpine region unravelled by seismic anisotropy analysis and high-resolution P wave tomography**

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9 Active and fossil mantle flows in the western Alpine region  
10 unravelled by seismic anisotropy analysis and high-resolution *P*  
11 wave tomography

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24 **Abstract.**

25 The anisotropy of seismic velocities in the mantle, when integrated with high-resolution  
26 tomographic models and geologic information, can be used to detect active mantle flows in  
27 complex plate boundary areas, providing new insights on the impact of mantle processes on  
28 the topography of mountain belts. Here we use a densely spaced array of temporary  
29 broadband seismic stations to analyze the seismic anisotropy pattern of the western Alpine  
30 region, at the boundary between the Alpine and Apenninic slabs. Our results are supportive of  
31 a polyphase development of anisotropic mantle fabrics, possibly starting from the Jurassic to  
32 present. Geophysical data presented in this work, and geologic evidence taken from the  
33 literature, indicate that: (i) fossil fabrics formed during Tethyan rifting may be still preserved  
34 within the Alpine and Apenninic slabs; (ii) mantle deformation during Apenninic slab  
35 rollback is not compensated by a complete toroidal flow around the northern tip of the  
36 retreating slab; (iii) the previously observed continuous trend of anisotropy fast axes near-  
37 parallel to the western Alpine arc is confirmed. We observe that this arc-parallel trend of fast  
38 axes is located in correspondence to a low velocity anomaly in the European upper mantle,  
39 beneath regions of the Western and Ligurian Alps showing the highest uplift rates. We  
40 propose that the progressive rollback of the Apenninic slab, in the absence of a  
41 counterclockwise toroidal flow at its northern tip, induced a suction effect at the scale of the  
42 supraslab mantle. The resulting mantle flow pattern was characterized by an asthenospheric  
43 counterflow at the rear of the unbroken Western Alps slab and around its southern tip, and by

44 an asthenospheric upwelling, mirrored by low  $P$  wave velocities, that would have favored the  
45 topographic uplift of the Alpine belt from the Mont Blanc to the Mediterranean sea.

46 **Keywords:** Alpine subduction; Apenninic subduction; seismic anisotropy; fossil mantle flow; asthenospheric  
47 counterflow; topographic uplift

## 48 **1. Introduction**

49 The anisotropy of seismic velocities in the mantle, mainly controlled by the lattice-  
50 preferred-orientation of olivine crystals (Savage, 1999; Mainprice et al., 2000), is widely used  
51 to constrain the asthenospheric flow pattern around lithospheric slabs (e.g., Long and Becker,  
52 2010). However, seismic fast-axis directions may mark either active or fossil mantle flows  
53 (e.g., Savage and Sheehan, 2000; Piromallo et al. 2006; Audet, 2013; Eakin et al., 2016).  
54 Active mantle flows have an impact on present-day topography of continents and mountain  
55 belts (Cloetingh and Willett, 2013; Faccenna et al., 2014), and can be further investigated by  
56 numerical models of mantle dynamics (e.g., Becker et al., 2006; Faccenda and Capitanio, 2012).

57 In the Central Mediterranean, the slab structure is particularly complex, and a number of  
58 studies have already analyzed the seismic anisotropy pattern around the Alpine and Apenninic  
59 slabs separately (e.g., Barruol et al., 2004, 2011; Lucente et al., 2006; Salimbeni et al., 2008,  
60 2013; Qorbani et al., 2015). A major counterclockwise asthenospheric flow has been  
61 proposed to the west of the Alpine slab from the Western Alps to the Tyrrhenian sea (Barruol  
62 et al., 2004, 2011), whereas another counterclockwise toroidal flow has been proposed by  
63 several authors around the northern tip of the Apennines (Vignaroli et al., 2008; Faccenna and  
64 Becker, 2010; Salimbeni et al., 2013). However, the scarcity of seismic anisotropy data at the  
65 boundary between the Alpine and Apenninic slabs, and the uncertainties in the determination  
66 of the slab structure (e.g. Lippitsch et al., 2003; Piromallo and Morelli, 2003; Kissling et al.,  
67 2006; Giacomuzzi et al., 2011; Zhao et al., 2016), have so far precluded a full understanding  
68 of the asthenospheric flow pattern and the potential dynamic topography implications in this  
69 complex plate-boundary area.

70 In order to fill this gap, we present here new seismic anisotropy data from the western  
71 Alpine region, based on the recordings of a densely spaced array of temporary broadband  
72 seismic stations deployed from the European foreland to the Po Plain (CIFALPS experiment;  
73 Zhao et al., 2016b). The new observations of birefringence of core-refracted shear waves  
74 (SKS phase) are integrated with data from previous work (Barruol et al., 2004, 2011;  
75 Salimbeni et al., 2008, 2013) and interpreted in the light of the upper mantle structure  
76 provided by the recent high-resolution  $P$  wave tomography model by Zhao et al. (2016a).

77 Results are discussed within the framework of available geologic constraints and recent  
78 geodynamic reconstructions of the Cenozoic Adria-Europe plate boundary area (e.g.,  
79 Vignaroli et al., 2008; Malusà et al., 2015), providing new insights on the potential impact of  
80 mantle processes on the topographic growth of orogenic belts.

## 81 **2. Tectonic and geodynamic setting**

82 The Central Mediterranean area includes several slabs interacting with the  
83 asthenospheric mantle at the boundary between the European and African plates (Jolivet and  
84 Faccenna, 2000; Handy et al., 2010). The upper mantle structure beneath the Alpine region is  
85 particularly complex (Fig. 1a) due to the presence of a S- to E-dipping European slab beneath  
86 the Central and Western Alps, and of two slabs dipping in opposite directions (SW and NE)  
87 that belong to the Adriatic microplate beneath the Apennines and the Dinarides (Lucente et  
88 al., 1999; Piromallo and Morelli, 2003; Giacomuzzi et al., 2011; Zhao et al., 2016a; Hua et  
89 al., 2017). The Alpine, Apenninic and Dinaric subduction zones accommodated the broadly  
90 N-S post-Jurassic convergence between Europe and Adria/Africa, leading to the progressive  
91 closure of the Alpine Tethys in between (Jolivet and Faccenna, 2000; Malusà et al., 2015).  
92 After the final exhumation of the thick subduction complex of the Western Alps in the late  
93 Eocene (Lardeaux et al., 2006; Dumont et al., 2012; Zhao et al., 2015), the Apenninic slab  
94 progressively translated northward beneath the Alpine orogenic wedge, and possibly started  
95 interacting with the Alpine slab by the end of the Oligocene (Malusà et al., 2015, 2016a). The  
96 rollback of the Apenninic slab during the Neogene (green arrow in Fig. 1b) led to the scissor-  
97 type opening of the Ligurian-Provençal basin and associated counterclockwise rotation of  
98 Corsica-Sardinia in the Apenninic backarc, followed by the opening of the Tyrrhenian basin  
99 since the Tortonian (Jolivet and Faccenna, 2000; Faccenna et al., 2001). The resulting crustal  
100 and upper-mantle structures at the boundary between the Alps and the Apennines are thus  
101 particularly complex (Zhao et al., 2015, 2016a; Malusà et al., 2017; Solarino et al., 2018) and  
102 such a complexity is possibly mirrored by the pattern of vertical motions derived from GPS  
103 data (e.g., Serpelloni et al., 2013; Walpersdorf et al., 2015). Topographic uplift in the Western  
104 Alps is greatest in the westernmost part of the Alpine metamorphic wedge (Briançonnais  
105 units) and in the External Massifs farther west (e.g., Mont Blanc and Pelvoux, Fig. 1b), with  
106 rates generally >1mm/yr (Walpersdorf et al., 2015; Nocquet et al., 2016). Ongoing  
107 topographic uplift also characterizes the Ligurian Alps (Serpelloni et al., 2013), as also  
108 attested by the progressive northward tilting of strath terraces and sedimentary strata of the  
109 overlying Tertiary Piedmont Basin (TPB in Fig. 1b). Moreover, the timing of topographic

110 uplift in these areas is apparently unrelated to the timing of subduction (Cretaceous to  
111 Paleogene) and backarc basin opening (latest Oligocene to Miocene): the Western Alps show  
112 a strong increase in exhumation rate over the last 2 Myr (Fox et al., 2015), the Ligurian Alps  
113 were progressively tilted and uplifted since the Messinian, and the Northern Apennines where  
114 rapidly uplifted during the Pliocene (Malusà and Balestrieri, 2012).

115 

Figure 1
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### 116 **3. Methods and dataset**

117 The temporary network of the CIFALPS experiment (China-Italy-France Alps Seismic  
118 survey, Zhao et al. 2016b) includes 46 broadband seismic stations deployed along a linear  
119 WSW-ENE transect from SE France to NW Italy, and 9 additional stations installed to the  
120 north and to the south of the main profile (Fig. 2 and Table S1). Stations utilized for our  
121 analysis operated from July 2012 to September 2013. Spacing between stations along the  
122 main profile ranges from ~5 km in the Western Alps mountain range to ~10 km in the  
123 European foreland and in the western Po Plain. The seismic anisotropy properties of the  
124 upper mantle beneath each single station were analyzed using the azimuth of the fast axis ( $\phi$ )  
125 and the delay time (dt) as a proxy for the preferred orientation of olivine *a* axes and for the  
126 thickness of the anisotropic layer (Silver et al., 1999). Starting from the whole recordings of  
127 the CIFALPS experiment, we extracted the waveforms of 40 teleseismic events with  $M > 5.8$   
128 (Table S2), selected within an epicentral window between  $80^\circ$  and  $120^\circ$  to enhance the SKS  
129 pulse, and rejecting those pulses affected by preceding S phases.

130 The analysis of the SKS pulse was performed in two steps. As a first step, an automated  
131 SKS-splitting method based on energy minimization on the transverse waveform component  
132 (Silver and Chan, 1991) was applied on the entire array to the 9 earthquakes with the highest  
133 Signal-to-Noise ratio (SNR). We used the same time window and bandpass filter (5-50 sec)  
134 for each stations-event pair, obtaining 90 new SKS splitting measurements (marked by a “A”  
135 in Table S3), mostly for stations in the western part of the profile, and 15 for stations in the  
136 eastern part of the profile or off-profile. Then, we manually analyzed 31 additional events  
137 using the SplitLab software (Wüstefeld et al., 2008) to fill the gap in back-azimuthal  
138 coverage and homogenize the dataset for all of the stations. The SplitLab software allows  
139 estimating the splitting parameters by using two different techniques, the cross-correlation  
140 and the minimization of the energy on the transverse component (see Wüstefeld et al., 2008  
141 for details), under the assumption that SKS rays cross through a horizontal anisotropy (Silver  
142 and Chan, 1991). We considered only measurements showing consistent results using both

143 techniques, according to the indications of Wüstefeld and Bokelmann (2007). In particular,  
144 we selected those measurements with SNR  $>3$  and delay time  $<3$  s, and sufficiently high  
145 quality to satisfy the visual inspection performed by operators during manual revision. Null  
146 measurements were only considered in case of no energy on the transverse component or  
147 when splitting was precluded (e.g., in the case of fast axes oriented perpendicular or parallel  
148 to the back-azimuth of analyzed earthquakes). Differently from the automatic method, the  
149 manual analysis was performed considering, for each station-event pair, the proper time  
150 window (seconds before and after the SKS arrivals) and filter (bandpass with corner  
151 frequency between 1 and 100 sec) performing the highest SNR of the measurement. The  
152 complete set of utilized filters is summarized in Tables S3 and S4.

153 Manual analysis was further extended to 13 permanent stations, belonging to the Italian  
154 National Seismic Network and to the Regional Seismic Network of northwestern Italy, that  
155 are located near the eastern termination of the CIFALPS array leading to a total of 2380  
156 results. After the application of the selection criteria described above, we obtained a final  
157 dataset of 506 new SKS splitting measurements (Table S3) and 169 new null measurements  
158 (Table S4) that will be considered for interpretation.

159 We analyzed the vertical and lateral variations in anisotropy properties beneath selected  
160 stations based on the analysis of the Fresnel zone, taking into account the seismic ray paths at  
161 various depths (50, 100, 150 and 200 km) for a SKS phase with dominant period of 10 s  
162 (Alsina and Snieder, 1995; Margheriti et al., 2003). We used the formulation of Pearce and  
163 Mittlemann (2002) and a shear wave velocity for S-phase as defined in the IASP91 model  
164 (4.48 km/s at 50 km depth, 4.49 km/s at 100 km depth, 4.45 km/s at 150 km depth and 4.51  
165 km/s at 200 km of depth). By retrieving the ray paths of two teleseismic events arriving at the  
166 same station from opposite back-azimuths and sampling different fast-axis directions, we thus  
167 determined the minimum depth of lateral anisotropic variations.

168 

Figure 2
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#### 169 **4. Results**

170 Results of our single SKS splitting measurements along the CIFALPS profile, and in  
171 the Po Plain farther east, are shown in Figure 2. Measurements are projected at the 150 km  
172 piercing point depth, and are plotted as shades-of-blue segments parallel to the fast axis and  
173 scaled with the delay time, according to a color scale indicating the back-azimuth of the  
174 event, i.e. the incoming direction of the seismic ray at the station. Shear wave splitting data  
175 from previous works are plotted in yellow for comparison (Barruol et al., 2004, 2011;

176 Salimbeni et al., 2008, 2013). Measurements lying within a 60-km-wide swath parallel to the  
177 CIFALPS profile (indicated in green in Figure 2) are additionally plotted along the cross  
178 section of Figure 3a.

179 Along the western part of the CIFALPS transect, teleseismic events yielded good  
180 quality results from all available back-azimuths. Fast-axes show NW-SE to WNW-ESE  
181 directions, and are part of a continuous trend of fast axes that follows the shape of the Alpine  
182 arc in the northern and western parts of the map of Figure 2, from NE-SW in the Central  
183 Alps, to N-S in the northern Western Alps, and NW-SE in the southern Western Alps. This  
184 trend was first described by Barruol et al. (2004, 2011), and finds its prolongation along the  
185 French Mediterranean coast and the Ligurian Alps, where fast-axes have WNW-ESE to E-W  
186 trends. Our new measurements in the Ligurian Alps, north of Genoa, show NE-SW and NW-  
187 SE fast-axis directions in agreement with previous data.

188 Along the eastern part of the CIFALPS transect, and more generally in the whole  
189 central part of the map of Figure 2, measurements show variable fast-axis directions, and NE-  
190 SW, E-W and NW-SE directions are all equally frequently sampled (see rose diagrams in Fig.  
191 3c). The percentage of good quality results is lower than in the western part of the map, due  
192 to the impact of the thick sedimentary cover of the Po Plain on the quality of the waveforms  
193 (see Fig. S2). In the southeastern part of the map, corresponding to the Northern Apennines  
194 (Fig. 2), the fast-axis directions define a broadly N-S trend north of Florence, and a NW-SE  
195 trend between Florence and Genoa, where our new data are consistent with those published  
196 by Salimbeni et al. (2008, 2013).

197 Variations in shear wave splitting parameters are clearer when data are projected onto a  
198 cross section parallel to the CIFALPS profile (Fig. 3). This allows to distinguish three  
199 different parts of the profile, labelled as western, central and eastern segments in Figure 3a.  
200 The western segment of the profile (stations 1-17) shows quite homogeneous fast-axis  
201 directions in the range of  $-80^{\circ} \pm 20^{\circ}$  (pale to dark blue marks in Fig. 3a), with minor  
202 differences depending on the back-azimuth of analyzed events (see Fig. 3c). The distribution  
203 of single fast-axis directions is also confirmed by the distribution of average fast-axis  
204 directions calculated for stations having at least 6 splitting measurements (red stars in Fig.  
205 3a). Ray paths coming from the west (dark blue marks in Fig. 3a) show a trend of delay time  
206 that increases from 1-1.5 s in the westernmost 100 km to 2.4 s at ~140 km, and linearly  
207 decreases farther east.

208 In the central segment of the profile (stations 18-31), ray paths coming from the west  
209 sample a dominant NW-SE direction, whereas those coming from the east sample fast-axis



210 directions with more dispersed trends, not only E-W to NW-SE, but also NNE-SSW (see Fig.  
211 3c). Ray paths coming from the west (dark blue marks in Fig. 3a) define a trend of linearly  
212 decreasing delay times, from 2.4 s at 140 km, to 1.0 s at 220 km. This trend is not observed  
213 farther east.

214 In the eastern segment of the profile (stations 32-46), the fast-axis directions are even  
215 more dispersed (see also the average values marked by red stars in Fig. 3a), and show  
216 dominant N-S and NE-SW directions depending on the back-azimuth (Fig. 3c). Delay time is  
217 strongly scattered in the range from <1 s to 2.8 s. Teleseismic events coming from the west  
218 mainly capture a N-S trend, whereas those coming from the east yield a maximum frequency  
219 of NNE-SSW fast-axis directions (see Fig. 3c). Null measurements (empty dots in Fig. 3a)  
220 are quite common in the central and eastern segments of the CIFALPS profile, as well as  
221 farther east in the Po Plain (see Table S4). A few null measurements are also found along the  
222 western segment of the CIFALPS profile, between abscissae 50 and 100 km (Fig. 3a).

223 The results of Fresnel zone analysis for stations CT30 and CT33 are shown in Figure 4.  
224 In both stations, rays coming from NE have a  $30^\circ$  fast-axis direction, whereas rays coming  
225 from SW have a  $-50^\circ$  fast-axis direction. At station CT30, the Fresnel zones around the ray  
226 piercing points partly overlap at 50 km depth (orange circles in Fig. 4b), whereas they are  
227 fully separated at greater depths, pointing to an anisotropy source located at depth  $>50$  km. At  
228 station CT33, the Fresnel zones partly overlap at 50 and 100 km depth (orange and green  
229 circles in Fig. 4c), pointing to a source of anisotropy at depth  $> 100$  km. The same  
230 considerations can be made for stations CT29, CT31, CT32 and CT35 (see Supplementary  
231 Fig. S1b) where we have enough information to calculate the Fresnel Zone, and where we  
232 obtained similar results. These results are in agreement with the Fresnel zone analysis  
233 performed by Barruol et al. (2011) from two stations (see their Fig. 6), and confirm that the  
234 change in seismic anisotropy pattern observed between the central and eastern segments of  
235 the CIFALPS profile is due to the sampling of different mantle regions and does not reflect a  
236 crustal contribution, as also suggested by the high values of delay time. Farther east in the Po  
237 Plain, Fresnel zone analysis from two stations (CT41 and CT43) is supportive of an  
238 additional lithospheric contribution to the observed anisotropy pattern, from depths shallower  
239 than 50 km (see Supplementary Figure S1a). However, SKS measurements, for their  
240 characteristics and the strong heterogeneity of the measured anisotropy directions in the Po  
241 Plain, do not allow to locate this shallower contribution more precisely.

242

Figures 3, 4

## 243 **5. Comparison with *P* wave tomography data**

244 Seismic anisotropy data are plotted in Figure 5a onto the high-resolution *P* wave  
245 tomography model of Zhao et al. (2016a). Colours in the 150 km depth slice of the  
246 tomography model indicate low-velocity (red to yellow) and high-velocity (light to dark blue)  
247 anomalies, the latter corresponding to the traces of the Central and Western Alps slabs (CS  
248 and WS) and Apenninic (Adriatic) slab (AS) at 150 km depth. The location of the high-  
249 velocity anomalies in the tomography model of Zhao et al. (2016a) shows no major variation  
250 in the whole depth range relevant for our seismic anisotropy study. In fact, both the Alpine  
251 and the Adriatic slabs dip almost vertically in the upper mantle of the study region. Any depth  
252 slice would thus show the same relationships between velocity anomalies and anisotropy as  
253 those shown in Figure 5a.

254 Two main low-velocity anomalies are imaged in the map of Figure 5a, the first one  
255 located to the west of the Alpine slab, running from western Switzerland to SE France and the  
256 Ligurian coast, and the second one located in the eastern part of the map, to the north of the  
257 Apenninic slab. The low-velocity anomaly located to the west of the Alpine slab is  
258 particularly evident at 100–250 km depth (see cross section in Figure 3b) and can be  
259 recognized, with lower amplitudes, down to the mantle transition zone (Zhao et al. 2016a). A  
260 comparison between *P* wave tomography and anisotropy data was already performed by  
261 Barruol et al. (2011) using the tomography model of Piromallo and Morelli (2003) and a  
262 dataset of 644 anisotropy measurements for the European mantle. When compared to the  
263 tomography model of Zhao et al. (2016a), the tomography model of Piromallo and Morelli  
264 (2003) shows major differences that may influence the interpretation of the anisotropy pattern  
265 of the study area. In the Piromallo and Morelli (2003)'s model: (i) the low-velocity anomaly  
266 imaged to the west of the Alpine slab is discontinuous, unlike shown in our Figure 5; (ii) the  
267 high-velocity anomaly corresponding to the Alpine slab would have a southwestern tip along  
268 the French Mediterranean coast, which implies that the slab would be crosscut by the  
269 continuous trend of fast axes running to the west of the Alpine arc (cf. Barruol et al. (2011),  
270 their Fig. 4b); (iii) the Alpine and Apenninic slabs would be separated by a major low-  
271 velocity gap, which is not observed in Zhao et al. 2016a (see Fig. 5a). All of these features, as  
272 well as other features such as the broken Alpine slab proposed by Lippitsch et al. (2003),  
273 were dismissed by the higher-resolution tomography model used in this work, and the  
274 interpretation of the mantle flow pattern was consequently improved.

275 When our seismic anisotropy dataset is compared with the tomography model of Zhao et  
276 al. (2016a), the majority of null measurements observed in the Po Plain are clustered within

277 the high-velocity anomalies corresponding to the Alpine and Apenninic slabs (blue areas in  
278 Fig. 5a). These regions of high-velocity anomaly also show slab-parallel and oblique fast-axis  
279 directions, the former mainly in correspondence to the Western Alps and Apenninic slabs, and  
280 the latter mainly in correspondence to the Central Alps slab. The complexity of the anisotropy  
281 pattern in these blue regions may result from the complexity of the medium traversed by the  
282 SKS waves: for example, waves recorded in the Po Plain stations may have crossed the  
283 Alpine slab as well as the overlying and underlying mantle (Figs. 3 and 4). A large number of  
284 nulls may thus result from such a complex path. Moreover, seismic anisotropy in the blue  
285 regions of Figure 5a may also reflect fossil fabrics in the lithospheric mantle of the Alpine  
286 and Apenninic slabs, possibly acquired during mantle exhumation prior to the opening of the  
287 Tethyan ocean in the Jurassic (Lemoine et al., 1986; Vissers et al., 1995; Piccardo and  
288 Vissers, 2007). This hypothesis is discussed in detail in Section 6.1.

289 The fast-axis directions observed north of Florence mainly range from NNW-SSE to NE-  
290 SW (see rose diagram Fig. 5b). According to the tomography model of Zhao et al. (2016a),  
291 they lay within the low-velocity anomaly located north of the Apenninic slab. Figure 5a also  
292 shows that the continuous trend of fast axes following the Alpine arc from the Central Alps to  
293 the Ligurian coast (large red arrow in the map) lays in correspondence with a continuous low-  
294 velocity anomaly unravelled by *P* wave tomography to the west of the Alpine slab. This trend  
295 of fast-axis directions does not cut the Alpine slab.

296 Finally, the abrupt change in seismic anisotropy pattern observed between the central and  
297 eastern segments of the CIFALPS profile occurs in close correspondence with the transition  
298 between the Alpine slab and the western low velocity anomaly. Null measurements are  
299 common in both segments of the profile, but may have different origin as they reflect  
300 different situations at depth. The lateral changes in anisotropy parameters, unravelled by  
301 Fresnel zone analysis beneath stations CT30 and CT33 at depth >50-100 km (as well as  
302 beneath stations CT29, CT31, CT32 and CT35, see Supplementary Fig. S1b), are consistent  
303 with the presence of a steeply dipping slab beneath the eastern part of the CIFALPS profile  
304 (Fig. 4a). In the western and central segments of the CIFALPS profile, delay time variations  
305 for ray paths coming from the west (Fig. 3a) fit the pattern of *P* wave velocity perturbations  
306 (Fig. 3b). Lower delay times are found at abscissae 0-100 km and 150-200 km where the low-  
307 velocity anomaly in the mantle is stronger, whereas delay times are stronger at ~140 km  
308 where the low-velocity anomaly in the mantle is weaker (Fig. 3).

309

Figure 5

## 310 **6. Discussion**

### 311 *6.1. Potential preservation of fossil fabrics within the Alpine and Apenninic slabs*

312 Common patterns of trench-parallel fast directions along active margins, evidenced by  
313 shear-wave splitting measurements, are generally interpreted as the evidence of alignment of  
314 olivine crystals induced by mantle flow around downgoing slabs, whereas fossil fabrics  
315 within the slab are generally considered as a negligible source of anisotropy (Long and Silver,  
316 2008, 2009; Audet, 2013). However, a fossil fabric defined by olivine crystallographic  
317 preferred orientation (CPO) can be preserved in the oceanic lithosphere since the time of  
318 plate formation (Mercier et al., 2008). This fossil fabric is generally aligned with the direction  
319 of plate spreading (Shinohara et al., 2008), and may either survive subduction-induced  
320 deformation (Audet et al., 2013), or be overprinted if the slab is sufficiently weak to undergo  
321 internal deformation. Along-strike extension during flattening of the slab may lead to trench-  
322 parallel olivine CPO (Eakin et al., 2016), whereas the bending of the slab entering the trench  
323 may form vertically-aligned serpentized faults in the uppermost slab portion (Faccenda et  
324 al., 2008). This would lead to trench-parallel fast directions resulting from both serpentine  
325 strong CPO (Bezacier et al. 2010) and larger-scale shape preferred orientation (SPO)  
326 determined by the alternation of dry and hydrated sections of mantle rocks (Faccenda et al.  
327 2008).

328 When seismic anisotropy data of the western Alpine region are plotted onto the high-  
329 resolution *P* wave tomography model of Zhao et al. (2016a) (Fig. 5a), the regions of high-  
330 velocity anomaly that are interpreted as slabs include a number of slab-parallel and oblique  
331 fast-axis directions. Here, we use available geologic and geodynamic constraints to explore  
332 the possibility that these fast-axis directions may reflect fossil fabrics in the lithospheric  
333 mantle of the Alpine and Apenninic slabs.

334 Fossil fabrics acquired during Tethyan rifting have long been recognized in mantle  
335 slivers accreted in orogenic belts of the Cenozoic Adria-Europe plate boundary (e.g., Nicolas  
336 et al., 1972; Vissers et al., 1995) (Fig. 6a). These mantle slivers mainly consist of coarse-  
337 grained spinel lherzolite tectonites displaying well-developed olivine CPO, consistent with  
338 deformation by dislocation creep (Tommasi et al., 1999; Vauchez et al., 2012). This tectonite  
339 fabric, developed at 900°-1000°C and ~1.4 GPa (corresponding to depths of 40–45 km), is  
340 the result of low-angle simple shearing during Jurassic asymmetric rifting (Hoogerduijn  
341 Strating et al., 1993), and is expected to characterize a thick section of the slab. The tectonite  
342 fabric of exhumed spinel lherzolites is generally overprinted by spinel-, plagioclase-,

343 hornblende- and chlorite-bearing mylonites, developed as a result of strain localization during  
344 progressive mantle exhumation towards the Tethys seafloor (Piccardo and Vissers, 2007).  
345 Serpentine gently dipping mylonites overprint these rocks during the latest stages of mantle  
346 exhumation, at temperature  $< 500^{\circ}\text{C}$ , and are only expected in the uppermost portions of the  
347 slab (e.g. Guillot et al., 2015 for a review). Pervasive serpentized faults, crosscutting  
348 perpendicularly these tectonite and mylonitic fabrics, and pre-dating subduction as postulated  
349 by Faccenda et al. (2008), are not documented in the geologic record of the Alps and the  
350 Apennines.

351 Because fabrics developed during Tethyan rifting are still preserved in rock slivers that  
352 underwent major deformation at eclogitic depths within the Alpine subduction channel (e.g.,  
353 the Erro-Tobbio unit; Scambelluri et al., 1995; Hermann et al., 2000), we can infer that these  
354 fabrics are likely preserved within low-strain domains of the Alpine and Apenninic slabs, too.  
355 The attitude of these fabrics within the slab is of primary importance for the interpretation of  
356 shear-wave splitting measurements in the western Alpine region, and depends on: (i) the  
357 direction of plate spreading in the Jurassic, (ii) the trench orientation relative to the  
358 paleomargin, and (iii) the present-day slab dip.

359 The direction of plate spreading in the Jurassic was likely perpendicular to the trend of  
360 the European and Adriatic paleomargins of the Tethys, which are independently constrained  
361 by a wealth of tectonic, stratigraphic and thermochronologic data (e.g., Winterer and  
362 Bosellini, 1981; Lemoine et al., 1986; Guillot et al., 2009; Fantoni and Franciosi, 2010;  
363 Malusà et al., 2016b). Available data consistently point to a NNW-SSE plate-spreading trend,  
364 with a progressive counterclockwise rotation from NNW-SSE to NW-SE in the Adriatic  
365 microplate accomplished during post-Jurassic Adria-Europe convergence (Fig. 6b). The  
366 orientations of the Alpine and Apenninic trenches are well constrained by *P* wave  
367 tomography models (Piromallo and Morelli, 2003; Zhao et al., 2016a) and paleotectonic  
368 reconstructions. In the Western Alps segment of the Alpine trench, subduction was strongly  
369 oblique relative to the European paleomargin (Malusà et al., 2015), and the direction of plate  
370 spreading is consequently at low-angle to the trend of the trench (Fig. 6c). In the Central Alps  
371 segment of the Alpine trench, subduction was near-parallel to the trend of the European  
372 paleomargin, and the direction of plate spreading is consequently near-perpendicular to the  
373 trench (Fig. 6c). Subduction in the Apennines was initially near-parallel to the Adriatic  
374 paleomargin (see Fig. 1b). However, during Neogene rollback of the Apenninic slab, the  
375 Apenninic trench progressively rotated towards its present-day NW-SE trend (Jolivet and  
376 Faccenna, 2000), which is parallel to the direction of plate spreading inferred for the Adriatic

377 microplate (Fig. 6c). According to *P* wave tomography models (Zhao et al., 2016a), both the  
378 Alpine and Apenninic slabs are now plunging near-vertically in the upper mantle.

379 Figure 6c illustrates the expected attitude, within the steeply-dipping Alpine and  
380 Apenninic slabs, for the olivine CPOs of spinel lherzolite tectonites and for the larger-scale  
381 SPOs determined by the alternation between dry mantle rocks and serpentine mylonites  
382 formed during Tethyan rifting. Both in the Western Alps and Apenninic slabs, the fast *a* axes  
383 of A-type olivine should be near-parallel to the trench (Fig. 6c), in agreement with the trench-  
384 parallel fast directions derived from shear-wave splitting measurements (Fig. 5a). In the  
385 uppermost part of the slab, a similar polarization of seismic waves would be favored by the  
386 near-vertical attitude of tilted serpentine mylonites initially formed during Tethyan extension.  
387 Within the Central Alps slab, serpentine mylonites are still inferred to be near-vertical, but the  
388 different attitude of the olivine *a* axes may explain the more oblique fast-axis directions,  
389 relative to the slab, derived from shear-wave splitting measurements in the Central Alps area.  
390 Notably, part of the measurements reported in Figure 5a may reflect not only the complex  
391 fossil fabric of the slab, but also the mantle structure below and above the slab (Fig. 3, 4).  
392 The resulting complex anisotropy signature may thus explain part of the null measurements  
393 of Fig. 5a.

394 In summary, based on available geologic and geodynamic constraints, preserved fossil  
395 fabrics within the Alpine and Apenninic slabs may satisfactorily explain the seismic  
396 anisotropy patterns documented within the areas of high-velocity anomaly in Figure 5a. At  
397 the eastern termination of the CIFALPS transect, in the light of the relationships among fossil  
398 fabrics summarized in Figure 6c, the transition from dominant NE-SW fast axes (to the west)  
399 to dominant NW-SE axis (to the east) may mark the boundary between the Alpine and  
400 Apenninic slabs (Fig. 5a).

## 401 ***6.2 No toroidal mantle flow north of the Apenninic slab***

402 Several previous papers dealing with the geodynamics of the Central Mediterranean have  
403 postulated a counterclockwise toroidal mantle flow around the northern tip of Apenninic slab  
404 (e.g., Vignaroli et al., 2008; Faccenna and Becker, 2010). Such a toroidal flow would  
405 compensate the effects of Apenninic slab retreat on the adjoining asthenospheric mantle, by  
406 transferring mantle material from the rear of the retreating Apenninic slab towards a  
407 supraslab position in front of the SE-dipping Alpine slab (Vignaroli et al., 2008; Salimbeni et  
408 al., 2013). However, the seismic anisotropy data provided in this work are not supportive of  
409 an efficient toroidal flow in the study region. This is particularly clear when considering the

410 area of low-velocity anomaly located north of the Apenninic slab (Fig. 5a). This area, under  
411 the hypothesis of a toroidal flow, should be characterized by dominant slab-parallel NW-SE  
412 fast-axis directions, progressively rotating around the northern tip of the Apenninic slab to  
413 yield dominant E-W to ENE-WSW fast-axis directions. As shown in the rose diagram of  
414 Figure 5b, these directions are instead the least represented in the area to the north of the  
415 Apenninic slab, ruling out the hypothesis of a counterclockwise toroidal mantle flow around  
416 its northern tip. The only few measurements with a direction perpendicular to the Apenninic  
417 slab are located north of Genoa, exactly at the boundary between the two slabs, where the  
418 high-velocity anomaly in the tomography model of Zhao et al. (2016a) is slightly weaker  
419 (Fig. 5a).

420 The typical distribution of seismic anisotropy directions in the case of toroidal flow in  
421 the asthenospheric mantle has been successfully described in various segments of the  
422 Apenninic slab that show evidence of a major slab window or a slab tear (Civello and  
423 Margheriti, 2004; Baccheschi et al., 2011). The tomography model of Figure 5a, unlike  
424 previous models (e.g., Piromallo and Morelli, 2003), shows no evidence of a major gap in the  
425 slab structure between the Alps and the Apennines at upper mantle depths, in line with  
426 independent geologic evidence (Malusà et al., 2016a). The absence of space between the two  
427 slabs, as a result of Africa-Eurasia collision that put the system under compression and the  
428 two slabs in contact, may have precluded any flows around the northern tip of the Apenninic  
429 slab, with major implications, discussed in detail in Section 6.3, also for the asthenospheric  
430 flow pattern imaged to the west of the Alpine slab (Barruol et al., 2004, 2011).

431 Notably, the dominant NNW-SSE to NE-SW fast-axis directions in the region of low-  
432 velocity anomaly to the north of the Apenninic slab (Fig. 5a) are largely consistent with the  
433 direction of relative Adria-Europe plate motion inferred from magnetic anomalies since the  
434 Late Cretaceous (Fig. 5b) (Dewey et al., 1989; Jolivet and Faccenna, 2000). This suggests  
435 that the anisotropic fabric unravelled by shear-wave splitting measurements may have formed  
436 during post-Jurassic Adria-Europe convergence, and possibly before the onset of Apenninic  
437 slab rollback. The observation that WNW-ESE fast axes are poorly represented beneath the  
438 Adriatic microplate is in agreement with the asymmetric configuration of the Tethyan rifting  
439 long-recognized from geologic evidence (Lemoine et al., 1986; Manatschal, 2004;  
440 Manatschal and Muntener, 2009; Malusà et al., 2015). Asymmetric rifting implies that  
441 tectonite fabrics, during lithospheric extension, are best developed within the Tethyan oceanic  
442 lithosphere and within the European subcontinental mantle, but are not expected to be

443 widespread within the Adriatic subcontinental mantle, in line with the results of our SKS  
444 splitting measurements.

### 445 **6.3 Insights on the asthenospheric flow around the Western Alps slab**

446 Our seismic anisotropy analysis confirms the occurrence of a continuous trend of fast  
447 axes that follows, to the west of the Alpine slab, the whole arc of the Western Alps down to  
448 the Ligurian coast, where this trend merges with a WNW-ESE trend in part already described  
449 by Barruol et al. (2004) along the Mediterranean coast of SE France. Such seismic anisotropy  
450 pattern shows different directions compared to the azimuthal anisotropy from noise and  
451 surface waves in the same region, which sample a maximum depth of 120-125 km (Fry et al.,  
452 2010; Zhu and Tromp, 2013), and from the  $P_n$  anisotropy that samples the shallow  
453 lithospheric mantle (Diaz et al., 2013). Along the CIFALPS profile, the azimuthal anisotropy  
454 from surface waves invariably shows an E-W trend (see Zhu and Tromp, 2013, their Fig. 2),  
455 whereas the fast polarization directions of  $P_n$  anisotropy show a N-S trend along the western  
456 and central segments of the profile, and an E-W trend along the eastern segment of the profile  
457 (see Diaz et al., 2013, their Fig. 9). Therefore, the seismic anisotropy pattern that we obtain to  
458 the west of the Alpine slab can be safely ascribed to a re-orientation of the olivine fast axis  
459 within the European asthenospheric mantle.

460 Since its first detection, the seismic anisotropy pattern described along the Mediterranean  
461 coast of SE France was readily interpreted as an effect of asthenospheric flow due to the  
462 eastward retreat of the Apenninic slab (Barruol et al., 2004; Lucente et al., 2006; Jolivet et al.,  
463 2009), whereas the belt-parallel trend of fast axes around the Alpine arc was tentatively  
464 ascribed, in the absence of high-resolution tomographic images of the Alpine area, to a range  
465 of different geodynamic processes (Barruol et al., 2011), i.e.: (i) a possible toroidal flow  
466 induced by the keel effect of the Alpine slab during the motion of the European plate; (ii) a  
467 mantle flow around the sinking Alpine slab after slab detachment; or (iii) an effect of Alpine  
468 and Apenninic slab rollback. The hypothesis of a mantle flow around the detached Alpine  
469 slab is ruled out by the slab continuity attested by  $P$  wave tomography (Zhao et al., 2016a),  
470 whereas the hypothesis of Alpine slab rollback is ruled out by independent geologic and  
471 paleomagnetic evidences (Handy et al., 2010; Malusà et al., 2015).

472 The observed correspondence between the continuous trend of fast axes parallel to the  
473 trend of the Alpine arc (large red arrow in Fig. 5a) and the low velocity anomaly in the  
474 European upper mantle (yellow to red background colors in Fig. 5a) allows a refined  
475 interpretation of the mantle flow pattern to the west and beneath the Western Alps. The



476 westward-plunging low-velocity anomaly may be generated by the presence of fluids, or may  
477 have a thermal origin. The former hypothesis can be excluded in the light of the location and  
478 the depth of the anomaly with respect to the nearby slabs. A potential thermal origin may be  
479 due to asthenospheric upwelling, possibly related to a counterflow induced by the retreat of  
480 the Apenninic slab in the absence of an adequate mass compensation by a toroidal mantle  
481 flow (Fig. 7). The mantle upwelling hypothesis is consistent with the delay-time pattern  
482 observed in the western and central segments of the CIFALPS profile. In fact, the shorter  
483 time delays are found where the low-velocity anomaly is stronger (Fig. 3), which may  
484 indicate that the anisotropy is not fully confined within the horizontal plane (e.g., Savage and  
485 Sheenan, 2000). The same relationships between delay times and velocity structure based on  
486 finite-frequency *P* wave tomography is also observed in map view in Figure 5a. Moving from  
487 the western to the central segment of the CIFALPS profile, the number of null measurements  
488 increases drastically, and the fast-axis directions start to become more scattered, all clues  
489 pointing to the presence of a possible vertical component of the mantle flow in that area  
490 (Long and Becker, 2010; Diaz et al., 2013). A better characterization of the inferred vertical  
491 component of the mantle flow around the Western Alps slab would require a combined  
492 analysis of Love and Rayleigh waves that is beyond the aims of this work. Its magnitude is  
493 probably much smaller than the magnitude of the long-recognized horizontal component, but  
494 anyway of great consequence. We speculate that such vertical mantle-flow component,  
495 progressively propagating towards the east during the Neogene rollback of the Apenninic slab  
496 (Fig. 1b), determined a temperature increase in the vicinity of the retreating slab that may be  
497 responsible for the low-velocity anomaly imaged by *P* wave tomography (Zhao et al., 2016a).

#### 498 ***6.4. Hypothesis of a linkage between asthenospheric counterflow and topographic uplift***

499 The Western Alps include the highest summits in Europe, but factors controlling their  
500 topographic uplift still remain poorly understood. Convergence rates in the western Alpine  
501 area are below the detection limit (Calais et al., 2002), ruling out a primary control of  
502 horizontal plate motion on topography development. GPS and levelling measurements (e.g.  
503 Walpersdorf et al., 2015) unravel a pattern of rock uplift with rates locally >2 mm/yr that are  
504 only partly explained by the isostatic response to erosion and glaciation (Chéry et al., 2016;  
505 Nocquet et al., 2016; Nguyen et al., 2016). Thermochronologic data (e.g. Fox et al., 2015)  
506 show that the areas with highest uplift rates have also experienced the highest long-term  
507 erosion rates during the Neogene, ruling out the hypothesis of a crustal-scale collapse of the  
508 mountain range previously suggested on the basis of structural analysis and earthquake focal

509 mechanisms (Champagnac et al., 2004; Selverstone, 2005). In the absence of active  
510 convergence, recent works suggested that the highest rates of rock uplift and erosion in the  
511 Western Alps might be a surficial response to European slab breakoff (Sue et al., 1999; Fox et  
512 al., 2015; Nocquet et al., 2016). However, this latter hypothesis is ruled out by the down-dip  
513 continuity of the European slab documented by recent high-resolution tomographic images of  
514 the upper mantle beneath the Alpine region (Zhao et al., 2016a). Toroidal flow has been also  
515 suggested as a potential player controlling topography development and mantle upwelling  
516 next to retreating slab edges (e.g., Piromallo et al., 2006; Zandt and Humphreys, 2008;  
517 Schellart, 2004; 2010; Faccenna and Becker, 2010; Long et al., 2012). Data presented in this  
518 work are not supportive of a complete toroidal mantle flow around the northern edge of the  
519 retreating Apenninic slab. However, our data may suggest an alternative mantle driver for  
520 Alpine topography. The map of Figure 5a shows a good correspondence not only between the  
521 asthenospheric counterflow inferred from seismic anisotropy analysis and the low velocity  
522 anomaly imaged by *P* wave tomography, but also with the area of faster topographic uplift in  
523 the core of the Western Alps (green contour lines in Fig. 5a) and with the area of anomalous  
524 uplift in the Ligurian Alps, which are flanked to the south by a Neogene backarc basin. The  
525 observed uplift rates beneath the External Massifs and the Briançonnais units cannot be  
526 simply explained by tectonic shortening or by an isostatic response to erosion and  
527 deglaciation (Calais et al., 2002; Chéry et al., 2016; Nocquet et al., 2016). Moreover, the  
528 Ligurian Alps were neither affected by glaciations, nor by major tectonic shortening (Malusà  
529 et al., 2015). Our results suggest that Apenninic slab rollback, in the absence of a toroidal  
530 flow around the northern tip of the Apenninic slab, may have induced not only a suction  
531 effect and an asthenospheric counterflow at the rear of the unbroken Western Alps slab and  
532 around its southern tip, but also an asthenospheric upwelling in the same region, leading to a  
533 temperature increase in the upper mantle. As already discussed by Nocquet et al. (2016), the  
534 replacement of a dense and cold mantle material by hot and buoyant asthenospheric mantle at  
535 the base of the European lithosphere (estimated at 100 km depth, Lyu et al., 2017) would  
536 induce uplift. Furthermore, the weakening of the lithosphere and the lower crust by  
537 asthenospheric heat advection, as documented in the cross-section of Fig. 3b, can also foster  
538 Alpine uplift (Chéry et al., 2016). The occurrence of hot springs in the core of the Western  
539 and Ligurian Alps (Marty et al., 1992), right above the low-velocity anomaly, are also  
540 supportive of a focused thermal anomaly.

541 A deep control of Alpine topography, in the light of the inferred thermal origin for the  
542 low-velocity anomaly detected by *P* wave tomography, may explain the higher average

543 elevation of the Western Alps compared to other segments of the Alpine belt located farther  
544 east (i.e., the central and eastern Alps). However, it is unlikely that the elevated topography of  
545 the External Massifs and the Briançonnais is exclusively due to a mantle driver. A first-order  
546 estimate of the relative impact of mantle vs surface processes in determining topographic  
547 uplift can be attempted by comparing the present-day uplift rates in the glaciated and rapidly  
548 eroded Western Alps areas with those of the Ligurian Alps, where tilting of the overlying  
549 Tertiary Piedmont strata is associated to minor erosion, and the impact of glaciations is minor.  
550 In the Ligurian Alps, cosmogenic data (Wittmann et al., 2016) point to uplift rates not greater  
551 than  $\sim 0.4$  mm/yr that are likely ascribed to a mantle driver. A full understanding of the impact  
552 of mantle processes in shaping the Alpine topography, compared to surface processes and  
553 crustal-scale tectonic processes, would now require a numerical modelling of dynamic  
554 topography based on the recent high-resolution *P* wave tomography of the Alpine region and  
555 the pattern of active mantle flow highlighted in this work.

556

Figures 6, 7

## 557 **7. Conclusion**

558 The seismic anisotropy pattern in the western Alpine region, when interpreted within the  
559 framework of the upper mantle structure unravelled by high-resolution *P* wave tomography  
560 complemented with available geologic and geodynamic constraints, unravels a polyphase  
561 development of anisotropic fabrics in the mantle of the western Alpine area. Fossil fabrics  
562 formed during Tethyan rifting are possibly preserved within the Alpine and Apenninic slabs,  
563 which would suggest that these slabs are sufficiently stiff and did not undergo major internal  
564 deformation during the Cenozoic. The Neogene rollback of the Apenninic slab was not  
565 compensated by a complete toroidal flow in the upper mantle around the northern tip of the  
566 retreating slab. This finding has major implications for the asthenospheric flow pattern  
567 imaged to the west of the Alpine slab. The continuous trend of seismic anisotropy fast axes,  
568 which follows the whole arc of the Western Alps down to the Ligurian coast, marks the  
569 horizontal component of an asthenospheric flow developed as a response to Apenninic slab  
570 rollback, and recognized from the fore-arc side of the Alpine slab to the backarc of the  
571 Apenninic slab. The low-velocity anomaly detected by *P* wave tomography in the upper  
572 mantle beneath the Western Alps can be ascribed to a temperature increase due to the vertical  
573 component of such asthenospheric flow, which may have favored the topographic uplift of  
574 the overlying lithosphere thus explaining the higher average elevation of the Western Alps  
575 compared to the central and eastern segments of the Alpine belt. Our results suggest that the

576 impact of mantle flow in response to active subduction may foster the topographic uplift of  
577 distant orogenic belts, where subduction processes have been inactive for several millions of  
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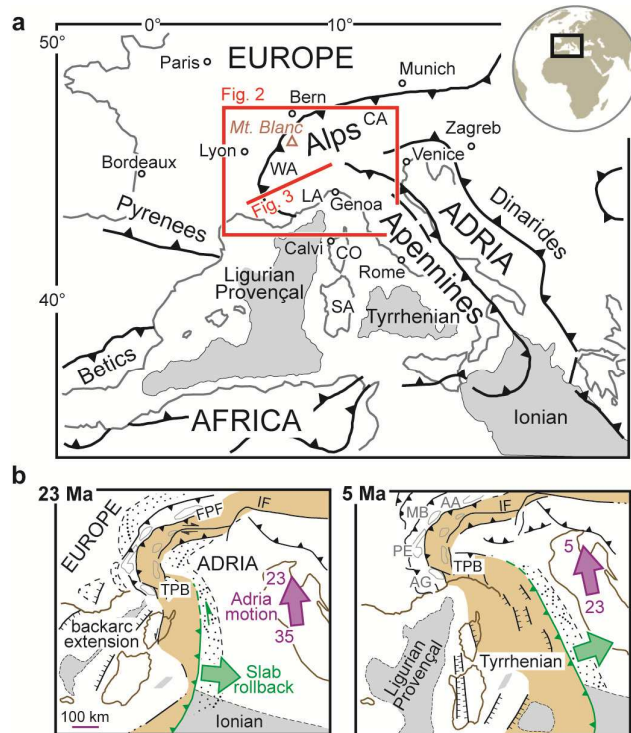
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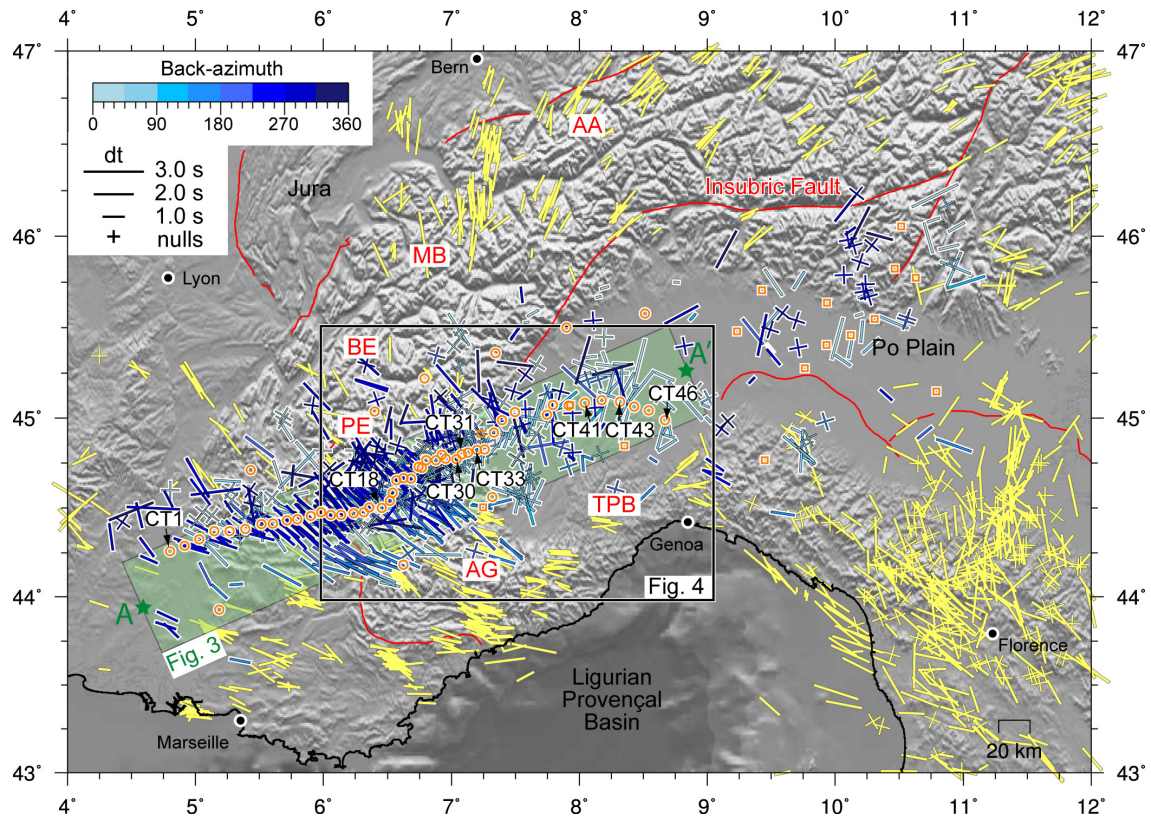
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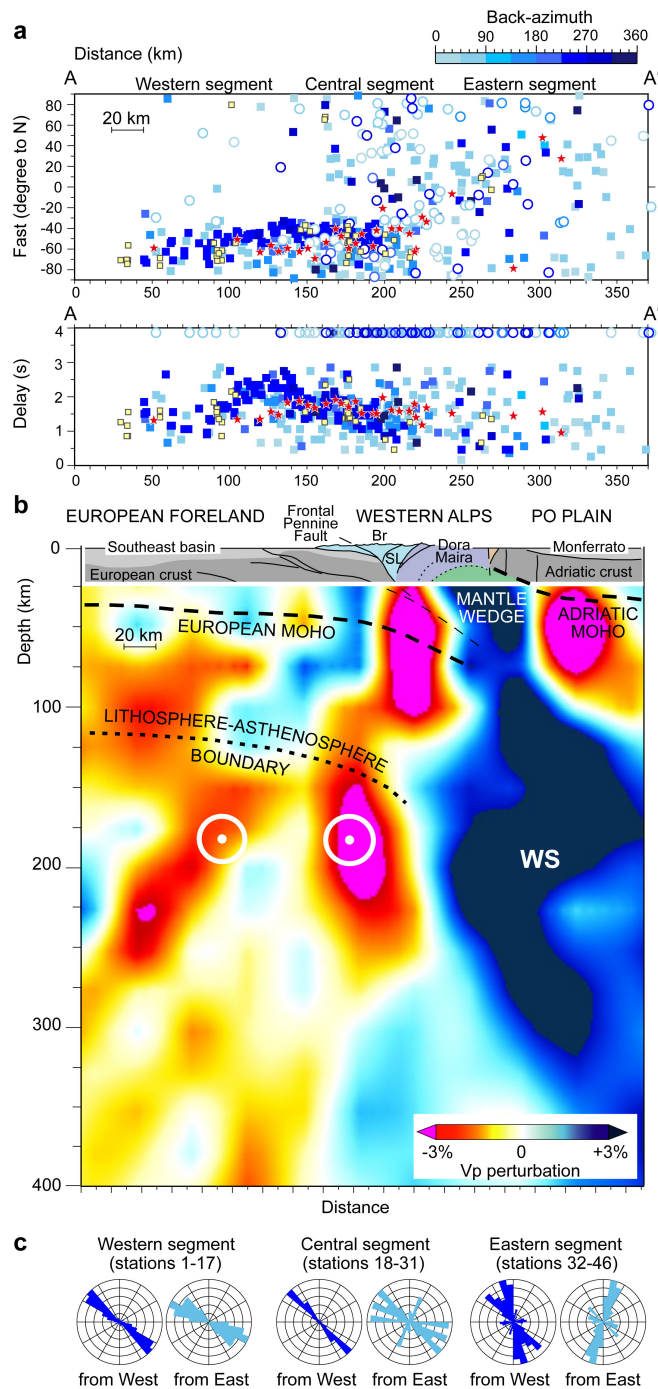
830 **Fig. 1. a)** Tectonic sketch map of the western Mediterranean, and location of the study area  
 831 (in red; acronyms: CA, Central Alps; CO, Corsica; LA, Ligurian Alps; SA, Sardinia; WA,  
 832 Western Alps). **b)** Neogene evolution of Alpine and Apenninic subductions (simplified after  
 833 Malusà et al., 2015). Brown areas mark the metamorphic Alpine wedge and the Apenninic  
 834 accretionary wedge; purple arrows indicate Adria trajectories relative to Europe (numbers =  
 835 age in Ma); acronyms indicate the External Massifs (AA, Aar; AG, Argentera; MB, Mont  
 836 Blanc; PE, Pelvoux), major faults (IF, Insubric Fault; FPF, Frontal Pennine Fault) and the  
 837 Tertiary Piedmont Basin (TPB).

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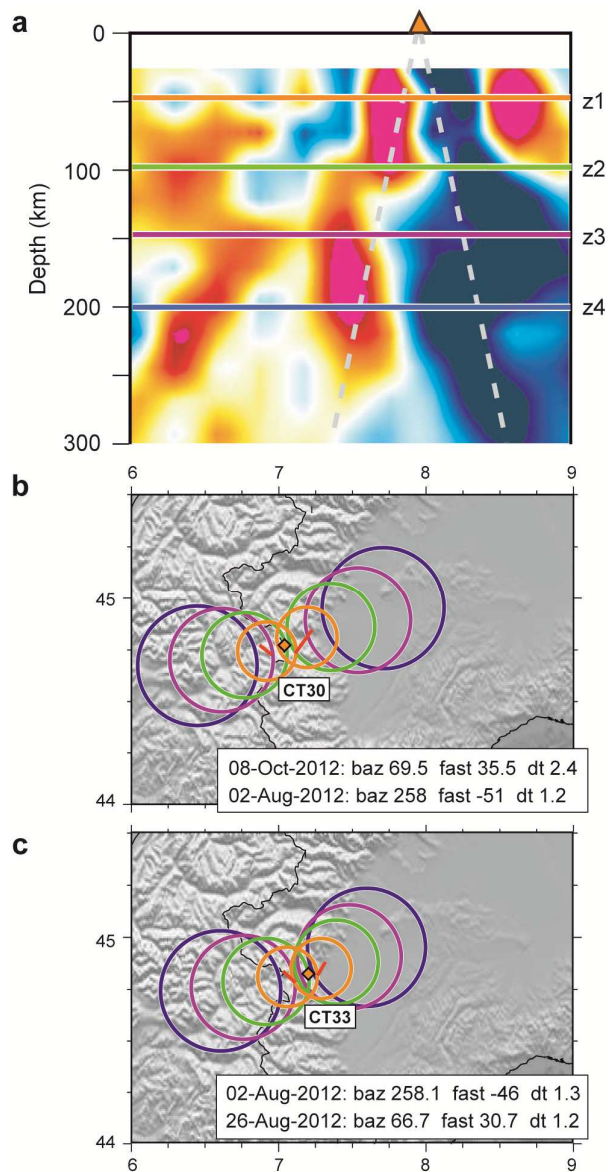
840 **Fig. 2.** Map of single SKS splitting measurements (blue = this work; yellow = previous  
 841 works). Each measurement is plotted at 150 km depth as a segment parallel to the fast axis  
 842 and scaled with delay time; null measurements are plotted as a cross with segments oriented  
 843 parallel and perpendicular to the back-azimuth (see colour scale for the back-azimuth of  
 844 analysed events). Seismic stations from the CIFALPS experiment (orange circles) and  
 845 additional stations from permanent networks utilized in this work (orange squares) are also  
 846 shown. Literature data are from Barruol et al. (2004, 2011) and Salimbeni et al. (2008, 2013)  
 847 (datasets from Barruol et al., 2004, 2011 do not include null measurements). Acronyms: AA,  
 848 Aar; AG, Argentera; BE, Belledonne; MB, Mont Blanc; PE, Pelvoux; TPB, Tertiary Piedmont  
 849 Basin.  
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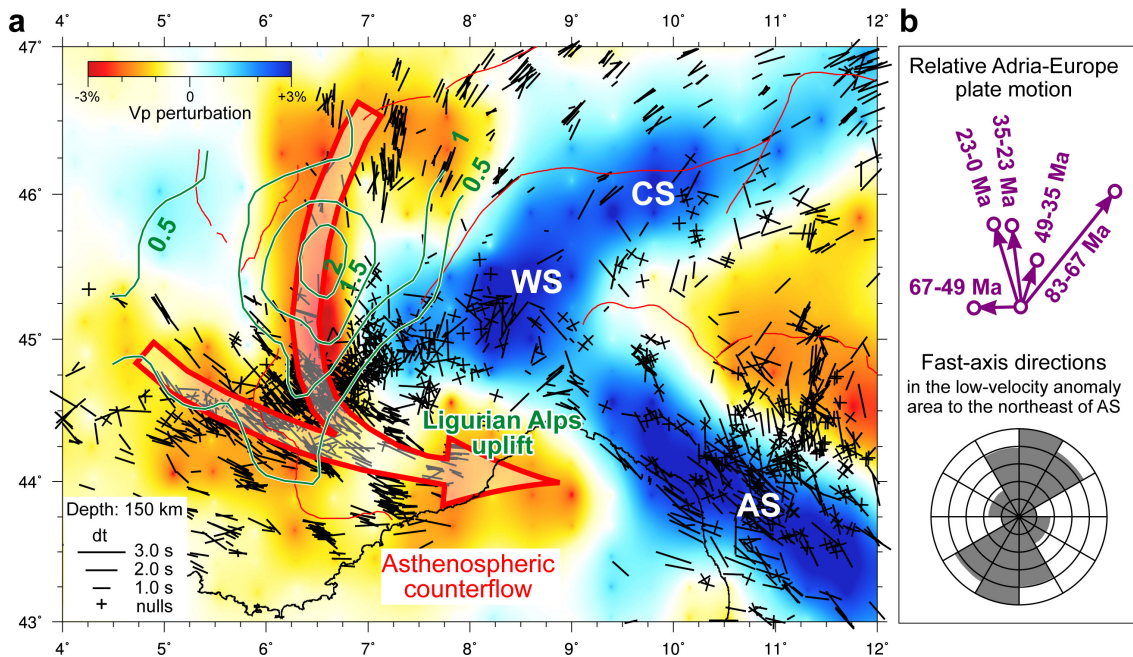
852 **Fig. 3. a)** Distribution of fast axes and delay times along a 60-km-wide swath following the  
 853 CIFALPS transect (see location in Fig. 2). Full squares are splitting measurements from this  
 854 work (in blue) and previous works (in yellow; from Barruol et al. 2004, 2011, Salimbeni et  
 855 al., 2008, 2013); empty circles are null measurements, plotted as fast axes parallel to the  
 856 back-azimuth and dt equal to 4s. The colour of markers depends on the event back-azimuth.  
 857 Red stars indicate average fast-axis directions calculated for stations having at least 6

858 splitting measurements. Note the sharp change in fast axis orientation and delay time beneath  
859 the Western Alps, in the central segment of the CIFALPS profile. **b)** From top to bottom: (i)  
860 geologic cross-section along the CIFALPS transect (Br, Briançonnais; SL, Schistes lustrés);  
861 (ii) depth and geometry of the European and Adriatic Mohos based on receiver-function  
862 analysis (from Zhao et al., 2015), depth of the lithosphere-asthenosphere boundary based on  
863 array analysis of surface waves (from Lyu et al., 2017), and exhumed mantle wedge beneath  
864 the Dora-Maira based on local earthquake tomography (from Solarino et al., 2018); (iii)  
865 velocity structure of the underlying upper mantle based on finite-frequency *P* wave  
866 tomography (from Zhao et al., 2016a). Low velocity anomalies (yellow to red) are located to  
867 the west of the Western Alps slab (WS), beneath the core of the Western Alps and the  
868 European foreland. White circles correspond to the asthenospheric counterflow illustrated in  
869 Figure 5. **c)** Rose diagrams of fast-axis directions in the western, central and eastern  
870 segments of the CIFALPS profile (west and east back-azimuths).  
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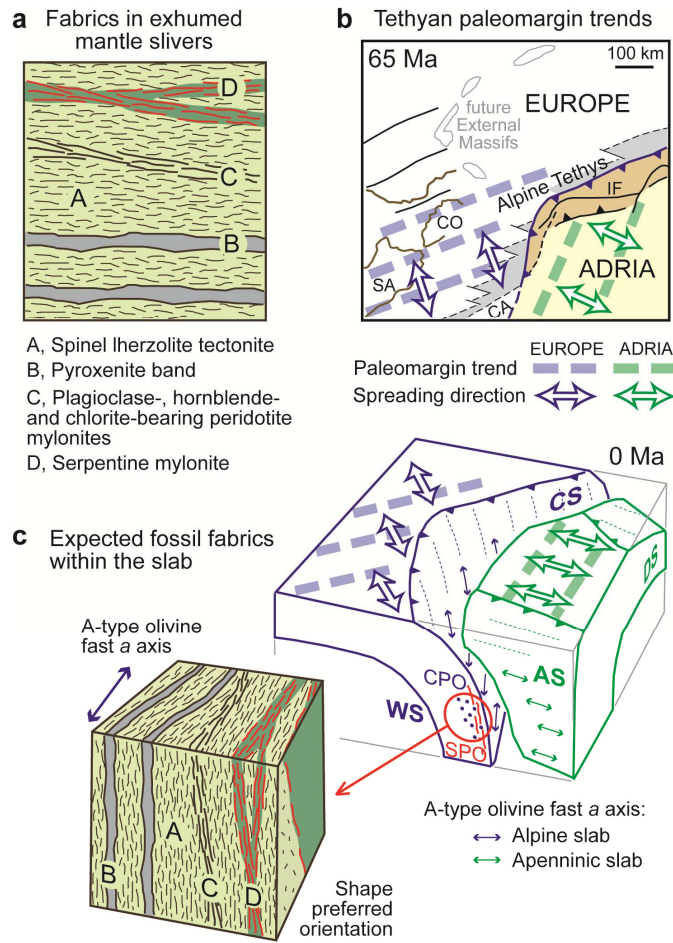
873 **Fig. 4:** Results of Fresnel zone analysis for ray paths emerging at the boundary between the  
 874 Western Alps slab and the European asthenospheric mantle. **a)** Idealized ray paths for stations  
 875 CT30 and CT33 (orange triangle) plotted on the tomographic cross section of Zhao et al.  
 876 (2016a). Lines in color show the depths (z1 to z4) analyzed in map view. **b-c)** Map views  
 877 showing the Fresnel zones of analyzed ray paths at depths of 50 km (orange), 100 km (green),  
 878 150 km (purple) and 200 km (blue). Circles are scaled with the diameter of the Fresnel zone.  
 879 The anisotropic parameters for each station-event pair (in red, details in map inset) are  
 880 projected at 50 km depth.  
 881



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883 **Fig. 5. a)** Single shear wave splitting measurements (in black, projected to 150 km depth),  
 884 and location of topographic uplift in the Western Alps (green contour lines = rates in mm/yr,  
 885 after Nocquet et al., 2016) and in the Ligurian Alps, plotted onto the 150 km depth slice of  
 886 the P-wave tomographic model of Zhao et al. (2016a). Null measurements in the Po Plain are  
 887 clustered within the slabs (blue background colors), which also show dominantly slab-parallel  
 888 fast axes (AS, Apenninic slab; CS, Central Alps slab; WS, Western Alps slab). Major faults  
 889 (red lines) as in Figure 2. Note the correspondence between (i) the low velocity anomaly in  
 890 the European upper mantle (yellow to red background colors in the western region of the  
 891 map), (ii) the asthenospheric counterflow inferred from the orientation of fast axes (large red  
 892 arrow), and (iii) the area of faster topographic uplift in the core of the Alps (green contour  
 893 lines), which merges with the area of anomalous uplift in the Ligurian Alps (see text). **b)**  
 894 Rose diagram of fast-axis directions, based on shear-wave splitting measurements in the area  
 895 corresponding to the low-velocity anomaly north of the Apennines, attesting no toroidal flow  
 896 around the northern tip of the Apenninic slab. Relative Adria-Europe plate motion after  
 897 Dewey et al. (1989) (arrows are scaled with distance, numbers indicate the age in Ma).  
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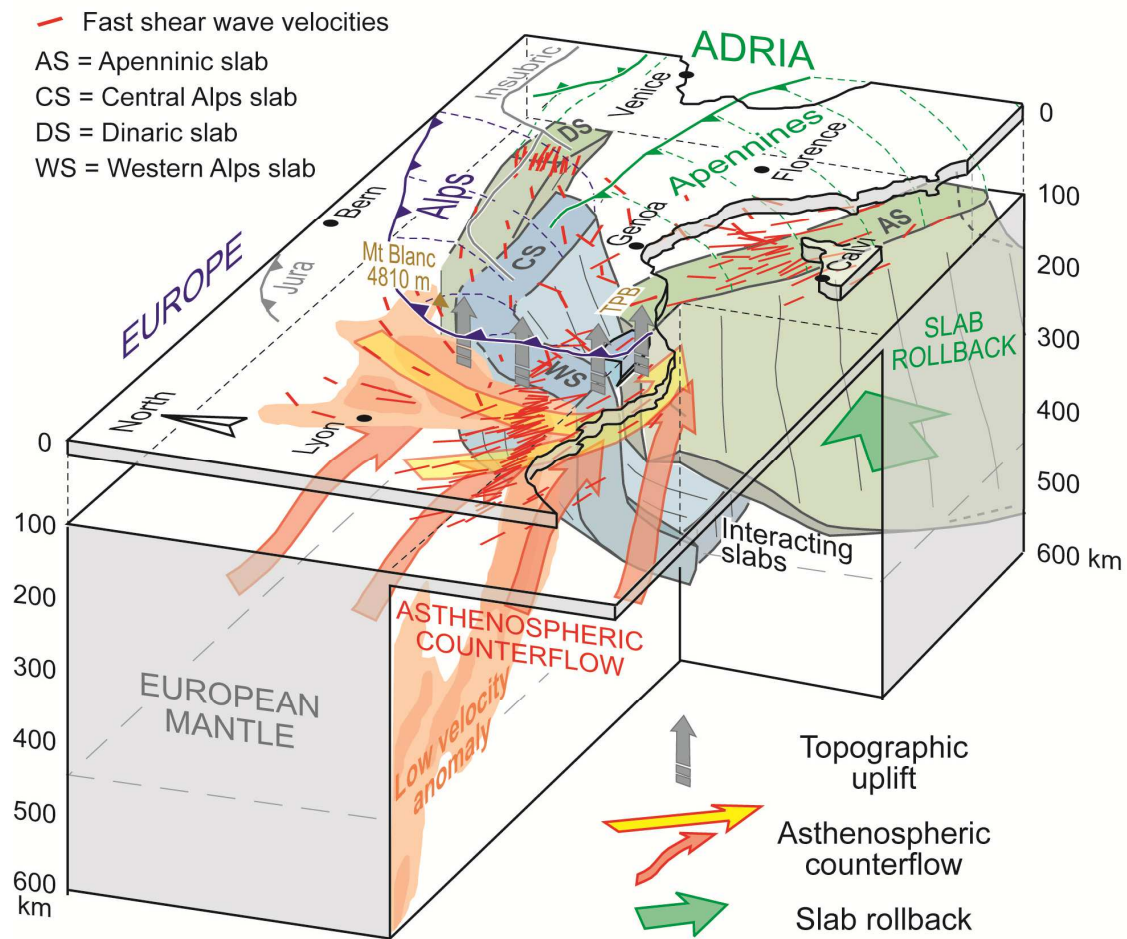




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900 **Fig. 6. a)** Anisotropic fabrics inherited from the Tethyan rifting as observed in outcrops of  
 901 exhumed mantle rocks within the Alpine orogenic wedge (Erro-Tobbio unit, e.g., Piccardo  
 902 and Vissers, 2007 and references therein). **b)** Palinspastic reconstruction of the Cenozoic  
 903 Adria-Europe plate boundary at 65 Ma (based on Malusà et al., 2015, 2016b) showing the  
 904 trends of the European and Adriatic paleomargins and the inferred directions of Tethyan  
 905 spreading (CA, Calabria; CO, Corsica; IF, Insubric Fault; SA, Sardinia). **c)** Expected attitude  
 906 of fossil anisotropic fabrics within the Alpine and Apenninic slabs, based on the direction of  
 907 plate spreading, trench orientation and slab dip (AS, Apenninic slab; CS, Central Alps slab;  
 908 DS, Dinaric slab; WS, Western Alps slab). CPO = crystallographic preferred orientation; SPO  
 909 = shape preferred orientation.

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911

912 **Fig. 7.** Interpretive 3D model showing the relationships between slab structure, active mantle  
 913 flow and topographic uplift in the Western and Ligurian Alps regions. The progressive  
 914 rollback of the Apenninic slab, in the absence of a toroidal flow around its northern tip,  
 915 induces a suction effect and asthenospheric counterflow at the rear of the unbroken Western  
 916 Alps slab and around its southern tip. The temperature increase due to asthenospheric  
 917 upwelling, mirrored by a low velocity anomaly in the European mantle (detected by *P* wave  
 918 tomography), may have favored the topographic uplift from the Mt Blanc to the Ligurian  
 919 coast. Station-averaged shear wave splitting measurements are in red; slab structure and low  
 920 velocity anomalies are after Zhao et al. (2016a); TPB = Tertiary Piedmont basin.

921 **Supplementary material**

- 922 • **Table S1:** List of temporary and permanent stations used for the analysis.
- 923 • **Table S2:** Teleseismic earthquakes analyzed in this work.
- 924 • **Table S3:** Shear wave splitting data obtained at the end of the analysis.
- 925 • **Table S4:** Nulls shear wave splitting data obtained at the end of the analysis.

- 926       • **Figure S1:** Results of Fresnel zone analysis for ray paths emerging in the Po Plain  
927       beneath stations CT41 and CT43 (a), and beneath stations CT29, CT31, CT32 and CT35  
928       at the boundary between the Po Plain and the Alpine mountain range (b). Circles show  
929       the Fresnel zone of analyzed ray paths at depths of 50 km (orange), 100 km (green), 150  
930       km (purple) and 200 km (blue). The anisotropic parameters for each station-event pair (in  
931       red) are projected at 50 km depth.
- 932       • **Figure S2:** Examples of waveform quality in different parts of the transect