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1 Widespread seismic anisotropy in Earth's lowermost
2 mantle beneath the Atlantic and Siberia

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6
7 **ABSTRACT**

8 Deep inside the Earth, just above the core-mantle boundary at around 2,700 km
9 depth, large-scale mantle structures are assumed to play a key role for global geodynamic
10 processes. While unusual hot regions are attributed to feed rising mantle plumes and
11 volcanic hotspots, the accumulation of subducted lithospheric plates is associated with
12 colder than average features. In both environments the appearance of dynamic-driven
13 processes such as deformation and mantle flow can directly be inferred by the presence of
14 seismic anisotropy. However, the geometries as well as the interactions of these massive
15 anomalous structures with the surrounding mantle material are still under debate. Based
16 on new seismic data from a dense and large-aperture recording network in Scandinavia
17 we characterize the anisotropic signatures of two so far unexplored regions in the
18 lowermost mantle by using observations of clearly discrepant SKS-SKKS shear wave
19 splitting measurements. Thereby we can demonstrate that anisotropy is located along the

20 northern edges of the Large Low Shear Velocity Province beneath Africa. Furthermore,
21 we recover an anisotropic structure in a region of fast seismic velocity underneath Siberia
22 which provides additional evidence for widespread deformation caused by a deeply
23 subducted slab.

24 **INTRODUCTION**

25 Teleseismic core-refracted shear waves such as SKS and SKKS sample nearly the
26 same volumes in the upper 500 km of the Earth's mantle for the same source-receiver
27 pair. In contrast, their raypaths differ significantly in the lower mantle (Fig. 1). With the
28 exception of the 200–300 km-thick D'' layer just atop the core-mantle boundary (CMB)
29 the lower mantle is generally assumed to be nearly isotropic (e.g., Meade et al., 1995).
30 Therefore, distinct discrepancies in SKS-SKKS shear wave splitting are a powerful tool
31 to map depth-dependent anisotropic anomalies in D'' (e.g., Lynner and Long, 2014).
32 Recently the observations of discrepant SKS-SKKS splitting pairs increased, especially
33 for areas along the edges of the Large Low Shear Velocity Provinces (LLSVPs) beneath
34 Africa and the Pacific (e.g., Niu and Perez, 2004; Lynner and Long, 2014; Deng et al.,
35 2017) or for more meso-scale structures like the Perm Anomaly beneath Russia (Long
36 and Lynner, 2015). It was inferred that variations of complex and strong anisotropy are
37 located near the boundaries of LLSVPs which are potentially associated with deformation
38 due to mantle flow (e.g., Cottaar and Romanowicz, 2013). Furthermore, there is evidence
39 from SKS-SKKS splitting for anisotropy in D'' caused by remnants of paleo-subducted
40 slab material that induces high shear deformation atop the CMB (e.g., Long, 2009).

41 Here we present striking new observations of discrepant SKS-SKKS splitting
42 pairs that were recorded across a large-aperture seismic network in Scandinavia and

43 surrounding countries. With our findings we can shed light on two widespread and so far
44 poorly sampled or fully unexplored anomalous regions in D'' that are located along the
45 northern edges of the African LLSVP and beneath northwestern Siberia in an area of
46 consistent fast seismic shear wave velocity (v_S). The knowledge on such anomalies
47 provides rare constraints for improved modeling and understanding of mantle dynamics.

48 **DATA AND METHODS**

49 We analyzed seismic data of more than 250 temporary and permanent stations
50 (Fig. 1) that are mainly part of the ScanArray network (Thybo et al., 2012; Grund et al.,
51 2017). Earthquakes with $M_W > 5.8$ at distances of 80° - 140° were selected for the routine
52 shear wave splitting analysis. Here we only focus on a subset of the whole analyzed data
53 set, namely events for which it was possible to identify both clear SKS and SKKS
54 arrivals on the same seismogram (Table DR1 in the GSA Data Repository¹). Shear wave
55 splitting (fast axis ϕ and delay time δt) was measured with the SplitLab package
56 (Wüstefeld et al., 2008), using simultaneously the rotation correlation method (RC,
57 Bowman and Ando, 1987) and the energy minimization method (SC, Silver and Chan,
58 1991). Prior to the measurements we checked the sensor orientations (see Data
59 Repository for details) and processed the waveforms using a zero-phase bandpass filter
60 (5–15 s). For some recordings the corner periods were slightly adjusted to improve the
61 signal-to-noise ratio (SNR) as done in previous studies (e.g., Long, 2009; Grund, 2017).
62 We only consider measurements that agreed for both methods (RC and SC) within their
63 error bounds (95% confidence region) and which have an $\text{SNR} \geq 5$. All splitting
64 measurements (Table DR1) have typical errors of less than $\pm 25^\circ$ for ϕ (average: $\pm 15.5^\circ$)
65 and ± 0.5 s for δt (± 0.32 s). For error estimation we applied the corrected equations by

66 Walsh et al. (2013) as implemented in the StackSplit plugin (Grund, 2017). Phase arrivals
67 with a clear signal on the radial component, $\text{SNR} \geq 5$ and (nearly) linear particle motion
68 before the correction for splitting were classified as so-called nulls (no splitting). In our
69 data set we classified a pair of SKS-SKKS as discrepant if one phase was null and the
70 other phase was clearly split. If both phases were split (similar ϕ and δt) or both were
71 null, the pair was considered as non-discrepant (e.g., Long and Lynner, 2015). In order to
72 characterize contributions from lowermost mantle (LMM) anisotropy at stations with
73 complex splitting characteristics (Fig. DR2), we followed the approach of Deng et al.
74 (2017) by measuring the splitting intensity (SI) as described by Chevrot (2000). Based on
75 this approach null arrivals in our data set have to fulfill the condition of an absolute SI
76 value that is < 0.2 and for a discrepant SKS-SKKS pair the absolute SI-difference (ΔSI)
77 including the errors has to be ≥ 0.2 . For a potential contribution from LMM-anisotropy,
78 ΔSI between SKS and SKKS is expected to be at least ≥ 0.4 (Deng et al., 2017).

79 **RESULTS AND DISCUSSION**

80 **Observation of Clearly Discrepant SKS-SKKS Waveforms**

81 Using shear wave splitting analysis, in total we received 332 pronounced SKS-
82 SKKS pairs. (Table DR1). Out of these, 49 pairs show clear discrepancies and 283 pairs
83 offer no anomalous pattern. Figure 2 presents a waveform example of a discrepant SKS-
84 SKKS pair. Further recordings are shown in Figure DR3. If possible we cross-checked
85 the SKS results by measuring splitting also for sSKS. Both phases sample nearly the
86 same volumes along their raypaths and, as expected, the splitting parameters reveal
87 consistency within the limits of uncertainty (Fig. DR4).

88 Taking into account finite frequency effects (e.g., Favier and Chevrot, 2003), it is
89 quite unlikely that such waveform discrepancies originate only from shallow anisotropy
90 directly beneath the station. With dominant periods of 6–10 s, the Fresnel zones for SKS
91 and SKKS overlap significantly in the mantle transition zone and uppermost lower
92 mantle (Fig. DR5). For this reason both phases of a pair are sensitive to the same volume
93 and we would expect the same ϕ - δt characteristics. Furthermore, we rule out major
94 influences due to waveform interference between phases arriving at the stations within
95 short time periods (Lin et al., 2014). The observed discrepancies occur for distances of
96 100° - 130° and event depths > 20 km (Fig. DR6). This was assumed to be sufficient to
97 avoid dominant interference effects (Deng et al., 2017) (Figs. DR7, DR8). Hence, our
98 observed SKS-SKKS discrepancies are first-order indicators that a component of LMM-
99 anisotropy plays a key role in this context. However, for observations of non-discrepant
100 pairs (Fig. DR4) a contribution of LMM-anisotropy cannot necessarily be ruled out (e.g.,
101 Long and Lynner, 2015). Depending on the raypaths and the dimension of an anomaly
102 with consistent anisotropic properties (ϕ , δt), both phases could be equally split or not
103 split (Fig. DR9).

104 In order to detect any geographical correlation between the splitting discrepancies
105 and large-scale LMM features, we summarize our results in Figure 3 along with the
106 GyPSuM global vs tomography model (Simmons et al., 2010) and the pierce points of the
107 SKS-SKKS raypaths in 2,700 km depth. Due to contributions from shallower anisotropy
108 in the upper mantle, at most stations in our network the splitting pattern is not well-
109 constrained or it indicates a non-simple nature of anisotropy (Fig. DR2). Thus, we
110 explicitly cannot correct for likely upper mantle contributions here as done in previous

111 studies with more simple splitting characteristics (e.g., Lynner and Long, 2014).
112 Nevertheless, the evaluation of measured ΔSI allows to explore potential contributions of
113 LMM-anisotropy to the overall splitting signals (Deng et al., 2017).

114 **Geographic Clusters in the Lowermost Mantle**

115 From the locations of the D'' pierce points, the anomalous pairs can be divided
116 into a western and eastern region relative to our station network (Fig. 3). As observed in
117 previous SKS-SKKS studies, the pierce points of discrepant pairs are interleaved by non-
118 discrepant ones that are mostly null/null observations (especially for phase arrivals from
119 west). A possible explanation is that small-scale heterogeneity of anisotropic structure is
120 located along the slightly varying raypaths in the LMM (e.g., Long and Lynner, 2015).

121 For the eastern region we observe two types of discrepant splitting pairs. First, a
122 set of 22 pairs with split SKKS phases and clear nulls for SKS. The split SKKS phases
123 sample the LMM roughly along an east-west transect (65°N, 60°-92°E) near the edges of
124 a major fast- v_S anomaly in D'' beneath northwestern Siberia (Fig. 3). Besides nearly
125 consistent orientations for ϕ (average 5.3°), ΔSI is > 0.4 for the majority of pairs (Fig.
126 DR10). Moreover, these pairs were recorded at stations that are located on different
127 geological units from southwest Sweden up to northern Finland (Figs. DR7-DR8, DR11).
128 Therefore, such a consistent splitting pattern indicates a large-scale feature of uniform
129 LMM-anisotropy beneath northwestern Siberia that is observed independently from
130 structures directly underneath the network. In contrast, the second group in the east
131 consists of six pairs with split SKS and nulls for SKKS. Beyond that, the orientations for
132 ϕ with nearly east-west alignments differ significantly compared to the first group. The
133 SKS pierce points in D'' are located within a narrow north-south swath (60°-72°N, 45°E)

134 that encompasses areas with strong variations in v_s . The two split SKS phases in the
135 south fall into a region of anomalously low v_s that is known as Perm Anomaly (Fig. 3).

136 Within the western cluster most pierce points of the split SKKS phases cover a
137 nearly north-south oriented area in the LMM beneath the Atlantic west of UK and
138 northwest of France. For the orientations of ϕ (only split SKKS) we also determined
139 consistent directions (average of 39°) whereas δt varies with values ranging from 0.7 s up
140 to 2.1 s. As for the eastern cluster, there is evidence for a contribution from LMM-
141 anisotropy by taking ΔSI into account, with values mostly > 0.4 (Fig. DR10). Most non-
142 discrepant pairs show clear nulls for both phases. A considerable amount of the
143 corresponding pierce points is located close to or within the slow- v_s anomaly beneath
144 Iceland.

145 **Nature of Anisotropy Below Siberia**

146 Below Siberia several global tomography models (including GyPSuM) agree in
147 terms of relatively fast v_s (Shephard et al., 2017, Fig. DR12). This anomaly was
148 interpreted as a remnant of paleosubducted slab material that is reaching down to the
149 CMB (Van der Voo et al., 1999). This hypothesis is supported by previous (source- and
150 receiver-side corrected) S-ScS splitting that revealed a dipping symmetry axis for the
151 anisotropic fabric in a neighboring area (Wookey and Kendall, 2008). Furthermore, in a
152 common geographical reference frame, the estimated orientation for ϕ is similar to ours
153 for a nearly east-west raypath (Fig. DR10). From geodynamic modeling it has been
154 shown that sinking slab material can imprint strong strain-induced anisotropy at the base
155 of the lower mantle (e.g., McNamara et al., 2002). Such a scenario is mainly controlled
156 by the lattice-preferred orientation (LPO) of lower-mantle minerals like post-perovskite

157 (e.g., Merkel et al., 2007). Therefore, we infer that our discrepant SKS-SKKS
158 observations indicate a widespread, so far unsampled region of coherent LPO-induced
159 anisotropy in D'' , caused by downwelling slab material that impinges on the CMB
160 beneath Siberia (Fig. 4).

161 However, so far we cannot fully constrain the geometry of the anisotropic region due to
162 limited ray coverage (except for events from the South Pacific area) and the observed ϕ -
163 δt variations at most of our stations (Fig. DR2). Moreover, it remains unclear whether a
164 change in the geometry or the mechanism of anisotropy is responsible for the significant
165 difference in ϕ between the split SKS and SKKS phases. Nevertheless, based on
166 significant ΔSI (Fig. DR10), we can demonstrate that a component of LMM-anisotropy
167 contributes to the overall splitting signal.

168 **Anisotropic Source Beneath the Atlantic**

169 Different global tomography models (including GyPSuM) consistently have
170 anomalously low v_S and strong lateral velocity gradients from fast to slow seismic
171 velocities along the northern edges of the African LLSVP beneath the Atlantic (Lekic et
172 al., 2012, Fig. DR13). Beyond that, for some models also a potential connection between
173 the African LLSVP and a 250-650 km-wide region of heavily reduced v_S ($\sim -6\%$ to -10% ,
174 Fig. DR10) in D'' below Iceland is detectable (e.g., He et al., 2015) which is located in
175 the so far poorly sampled area of our 19 split SKKS observations up to $\sim 50^\circ N$ (Fig. 3).
176 These splitting observations are in good agreement with previous studies, suggesting
177 strong and complex anisotropy along the edges of LLSVPs and meso-scale structures of
178 similar character (e.g., Long and Lynner, 2015; Deng et al., 2017). In general, this
179 anisotropy is assumed to be induced by complex mantle flow toward the boundaries of

180 the low- v_s zones (e.g., Cottaar and Romanowicz, 2013). The absence of splitting within
181 this zones, however, may indicate vertical mantle flow that feeds the upwelling hot
182 mantle plume beneath Iceland (Fig. 4, He et al., 2015). Taking into account the overall
183 splitting pattern at our long-running permanent stations (Fig. DR2), for most SKS phases
184 from South American earthquakes we received clear nulls indicating no contributions
185 from upper mantle anisotropy for these raypaths. In contrast, the SKKS phases of the
186 same events exhibit consistent splitting with nearly the same orientation for ϕ . Such a
187 scenario allows us to suppose that the orientation of ϕ (measured at the stations), mirrors
188 the true direction of the anisotropy fast axis in the LMM without further influence from
189 the upper mantle. Therefore our striking observations of mainly $\Delta SI > 0.4$ in this area
190 (Fig. DR10) support the idea that anisotropy is also located along the edges of the
191 northern extensions of the African LLSVP towards the low- v_s anomaly beneath Iceland.

192 CONCLUSIONS

193 Benefiting from a dense and large-aperture recording network in Scandinavia, we
194 are able to explore two widespread areas on the fragmentary global map of LMM-
195 anisotropy beneath the Atlantic and northwestern Siberia. While previous studies
196 sampled several smaller partly overlapping patches of the LMM, with our observations of
197 clearly discrepant SKS-SKKS splitting pairs we can draw a more complete picture of the
198 whole area (Fig. DR14) although the geometry and mechanism of the anisotropic D''
199 fabrics cannot be fully derived from our results alone. Nevertheless, this demonstrates
200 that the ongoing deployment of dense and large-aperture seismic networks not only helps
201 to understand the anisotropic structure directly beneath a station itself but can also reveal

202 valuable and poorly needed information about extensive and dynamically active regions
203 in D'' relatively far away from the receiver.

204 **ACKNOWLEDGMENTS**

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208 Swedish National Seismic Network (SNSN). Devices for the German contribution to
209 ScanArray were provided by the GFZ GIPP instrument pool. Maps were prepared using
210 GMT (Wessel et al., 2013). Abundant helpful comments on the manuscript by T.
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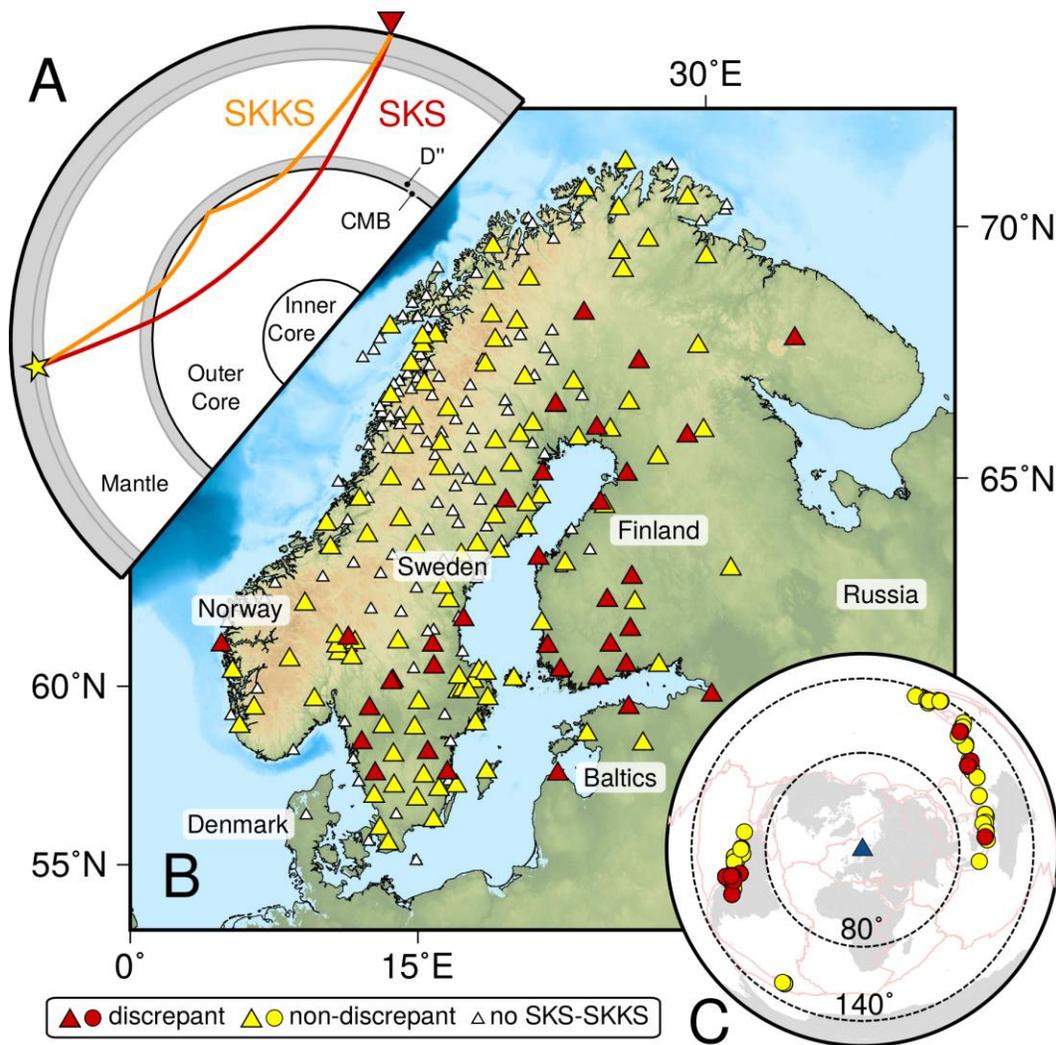
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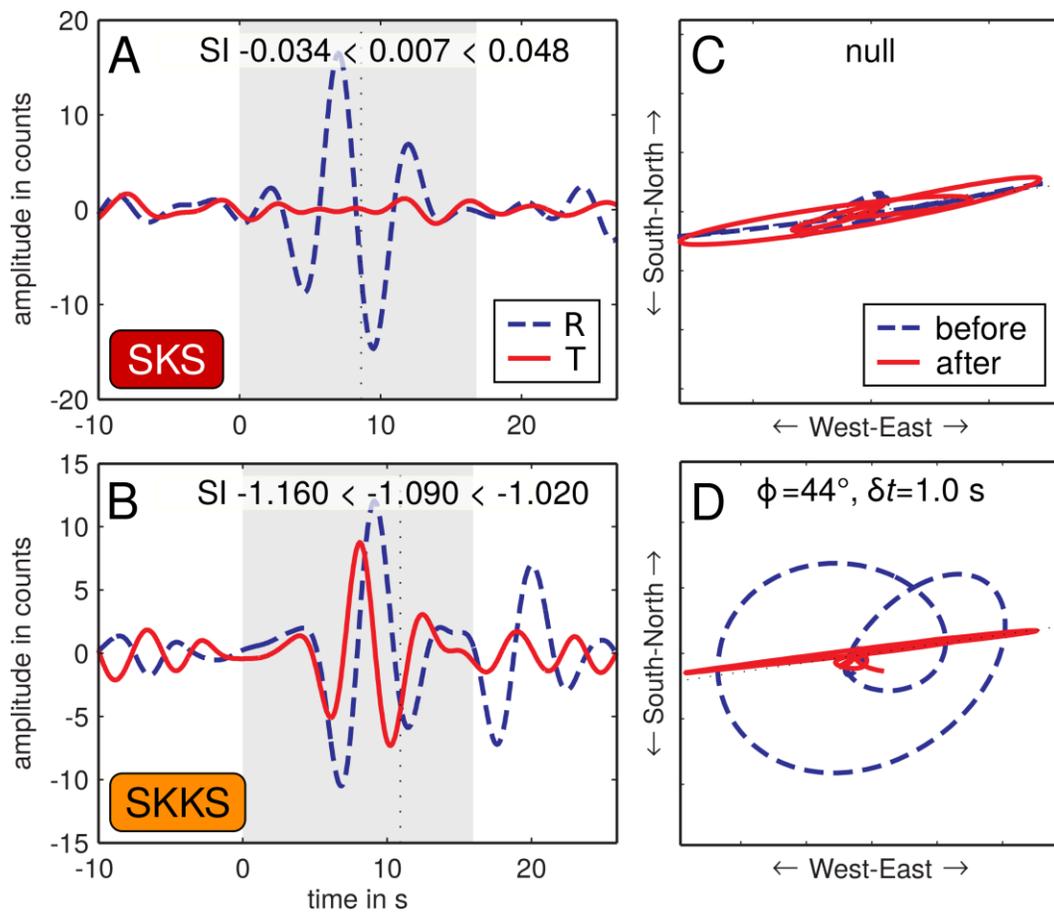
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296 **FIGURES AND CAPTIONS**



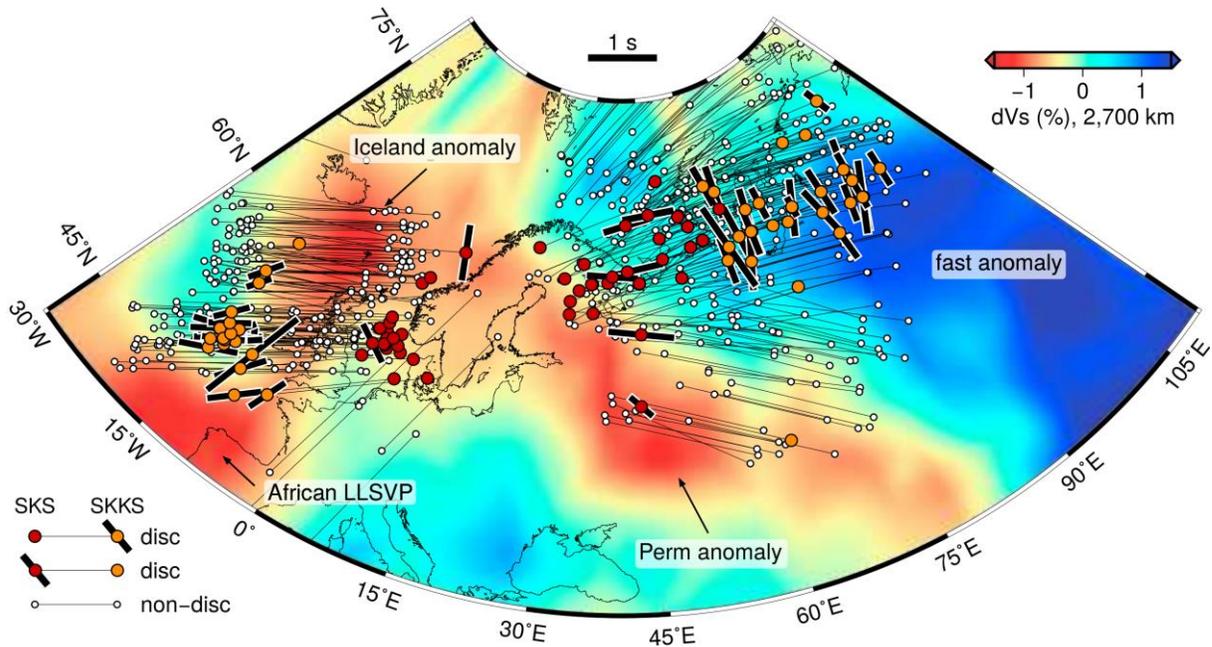
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298 Figure 1. A: SKS-SKKS raypaths from hypocenter (star) to receiver (500 km depth, Δ
299 $\sim 100^\circ$). B: Seismic stations used in this study (triangles). Color fill represents the
300 observation of SKS-SKKS waveforms, with red for at least one discrepant pair and
301 yellow for only non-discrepant recordings. White triangles display sites at which no SKS-
302 SKKS pairs were observed. C: Distribution of earthquakes that yielded at least one
303 discrepant (red) or non-discrepant (yellow) SKS-SKKS pair.
304



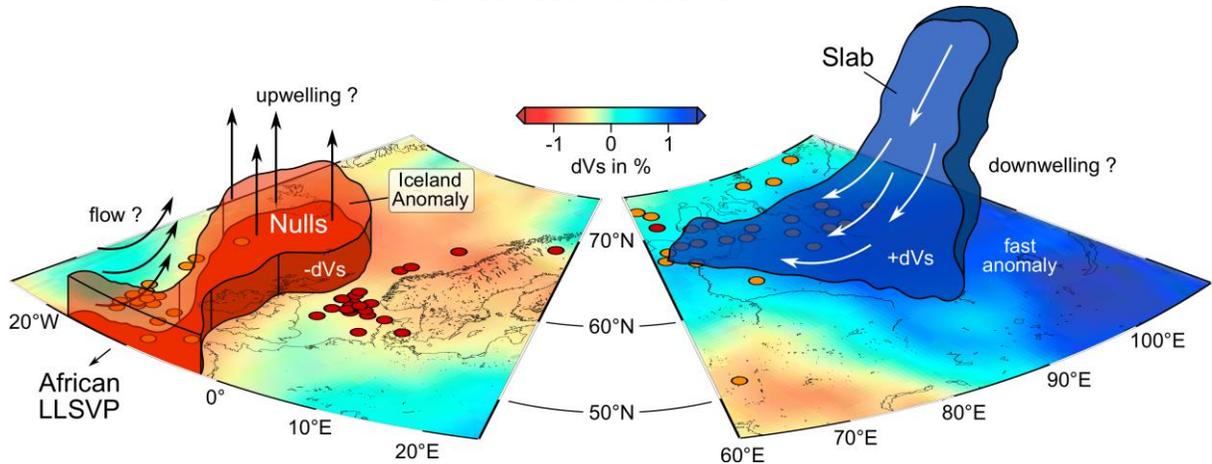
305
306 Figure 2. A and B: Original (uncorrected) radial (R, blue dashed) and transverse (T, solid
307 red) component seismograms at station PVF for SKS (top) and SKKS (bottom) of the
308 same event at 25/07/2016. At the top the splitting intensity (SI) value along with its

309 uncertainty (95% confidence interval) is shown. C and D: Particle motions before (blue
310 dashed) and after (solid red) correcting the splitting using the Silver and Chan (1991)
311 method. Splitting parameters ϕ and δt or null are indicated at the top of each panel.
312



313
314 Figure 3. D'' pierce points of SKS-SKKS pairs calculated with the tauP toolkit based on
315 the iasp91 earth model (Crotwell et al., 1999) atop the GyPSuM global vs tomography
316 model at 2,700 km depth (Simmons et al., 2010). Discrepant pairs are marked with red
317 (SKS) and orange (SKKS) dots, the split phase is indicated with a black bar oriented in
318 the direction of ϕ and scaled by δt (as observed at the station). Related pierce points are
319 connected by thin black lines. White dots indicate non-discrepant pairs.

320
321



322

323 Figure 4. Interpretation of our findings based on two of the most plausible sources of D''
324 anisotropy. Beneath the Atlantic, nearly horizontal mantle flow potentially induces
325 anisotropy along the northern extensions of the African Large Low Shear Velocity
326 Province (LLSVP) toward the Iceland Anomaly. Absence of splitting (null) is observed
327 for the majority of measurements that correspond to pierce points located within the
328 Iceland Anomaly and potentially indicates vertical flow. Beneath Siberia downwelling
329 (colder than average) material of a subducted slab imprints anisotropy in a widespread
330 area atop the core-mantle boundary.

331

332 ¹GSA Data Repository item **2019049**, Table DR1 (individual splitting measurements) and
333 Figures DR2-DR14 (stereoplots, examples of SKS-SKKS and sSKS splitting, Fresnel
334 zone estimates, event statistics, two record sections, map of split-split pairs, map of ΔSI ,
335 geological units, model agreement for fast and slow v_s , overview LMM studies), is
336 available online at <http://www.geosociety.org/datarepository/2019/>, or on request from
337 editing@geosociety.org.