



**HAL**  
open science

## Dynamic history of the inner core constrained by seismic anisotropy

Daniel A Frost, Marine Lasbleis, Brian Chandler, Barbara Romanowicz

► **To cite this version:**

Daniel A Frost, Marine Lasbleis, Brian Chandler, Barbara Romanowicz. Dynamic history of the inner core constrained by seismic anisotropy. *Nature Geoscience*, 2021, 10.1038/s41561-021-00761-w . hal-03252777

**HAL Id: hal-03252777**

**<https://hal.science/hal-03252777v1>**

Submitted on 7 Jun 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Title:** Dynamic history of the inner core constrained by seismic anisotropy

2  
3 **Author list:** Daniel A. Frost<sup>1\*</sup>, Marine Lasbleis<sup>2,3</sup>, Brian Chandler<sup>1</sup>, Barbara Romanowicz<sup>1,4,5</sup>

4  
5 **Affiliations:**

6 <sup>1</sup>Department of Earth & Planetary Science, University of California, Berkeley, CA, USA.

7 <sup>2</sup> Laboratoire de Planétologie et Géodynamique, UMR 6112, Université de Nantes, CNRS,  
8 France

9 <sup>3</sup>Earth-Life Science Institute, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan

10 <sup>4</sup> Collège de France, Paris, France.

11 <sup>5</sup> Université de Paris, Institut de Physique du Globe de Paris, Paris, France.

12  
13 \*Correspondence to: dafrost@berkeley.edu

14  
15 **Abstract**

16 **Progressive crystallisation of Earth's inner core drives convection in the outer core and**  
17 **magnetic field generation. Determining the rate and pattern of inner core growth is thus crucial**  
18 **to understanding the evolution of the geodynamo. The growth history of the inner core is likely**  
19 **recorded in the distribution and strength of its seismic anisotropy, which arises from**  
20 **deformation texturing constrained by conditions at the inner-core solid-fluid boundary. Here**  
21 **we show from analysis of seismic body wave travel times that the strength of seismic**  
22 **anisotropy increases with depth within the inner core, and the strongest anisotropy is offset**  
23 **from Earth's rotation axis. Then, using geodynamic growth models and mineral physics**  
24 **calculations, we simulate the development of inner core anisotropy in a self-consistent**  
25 **manner. From this we find that an inner core composed of hexagonally close-packed iron-nickel**  
26 **alloy, deformed by a combination of preferential equatorial growth and slow translation, can**  
27 **match the seismic observations without requiring hemispheres with sharp boundaries. Our**  
28 **model of inner core growth history is compatible with external constraints from outer core**  
29 **dynamics, and supports arguments for a relatively young inner core (~0.5–1.5 Ga) and a**  
30 **viscosity >10<sup>18</sup> Pa-s.**

31  
32 **Main text**

33 The presence of seismic anisotropy - the dependence of seismic wavespeed on direction of  
34 propagation - in the inner core (IC) was proposed over 30 years ago to explain the early  
35 arrival times of IC sensitive seismic body waves (PKP<sub>df</sub>) travelling on paths parallel to the  
36 Earth's rotation axis<sup>1,2</sup> and anomalous splitting of core-sensitive free oscillations<sup>3</sup>. This  
37 anisotropy is thought to result from alignment of iron crystals caused by deformation in a  
38 flow field induced by the evolution of the core, i.e. deformation texturing. Previously,  
39 different geodynamic<sup>4</sup> and plastic deformation mechanisms<sup>5</sup> were explored to explain the  
40 variation of PKP<sub>df</sub> travel times with angle of the ray path with respect to the rotation axis.  
41 Here, we combine geodynamic modelling of flow in the IC, allowing for slow lateral  
42 translation, with present knowledge on the mineralogy and deformation mechanisms  
43 proposed for the IC to explain spatial patterns of observed seismic travel times in an updated  
44 dataset.

45

46 Indeed, early models of seismic anisotropy based on measurements of PKP<sub>df</sub> travel times  
47 featured constant cylindrical anisotropy, with the fast axis parallel to Earth's rotation axis.  
48 Further work on IC structure has revealed increasing complexity. Recent IC models comprise  
49 two quasi-hemispheres of differing strengths of anisotropy, ~4.8% on average in the quasi-  
50 western hemisphere (WH), and ~1.4% in the quasi-eastern hemisphere (EH)<sup>6-8</sup>. Anisotropy  
51 strength increases with depth in the IC up to 8.8% at the centre of the IC<sup>9</sup>. However, past  
52 models suffer from the poor data coverage on polar paths, due to the limited distribution of  
53 earthquakes and stations.

54

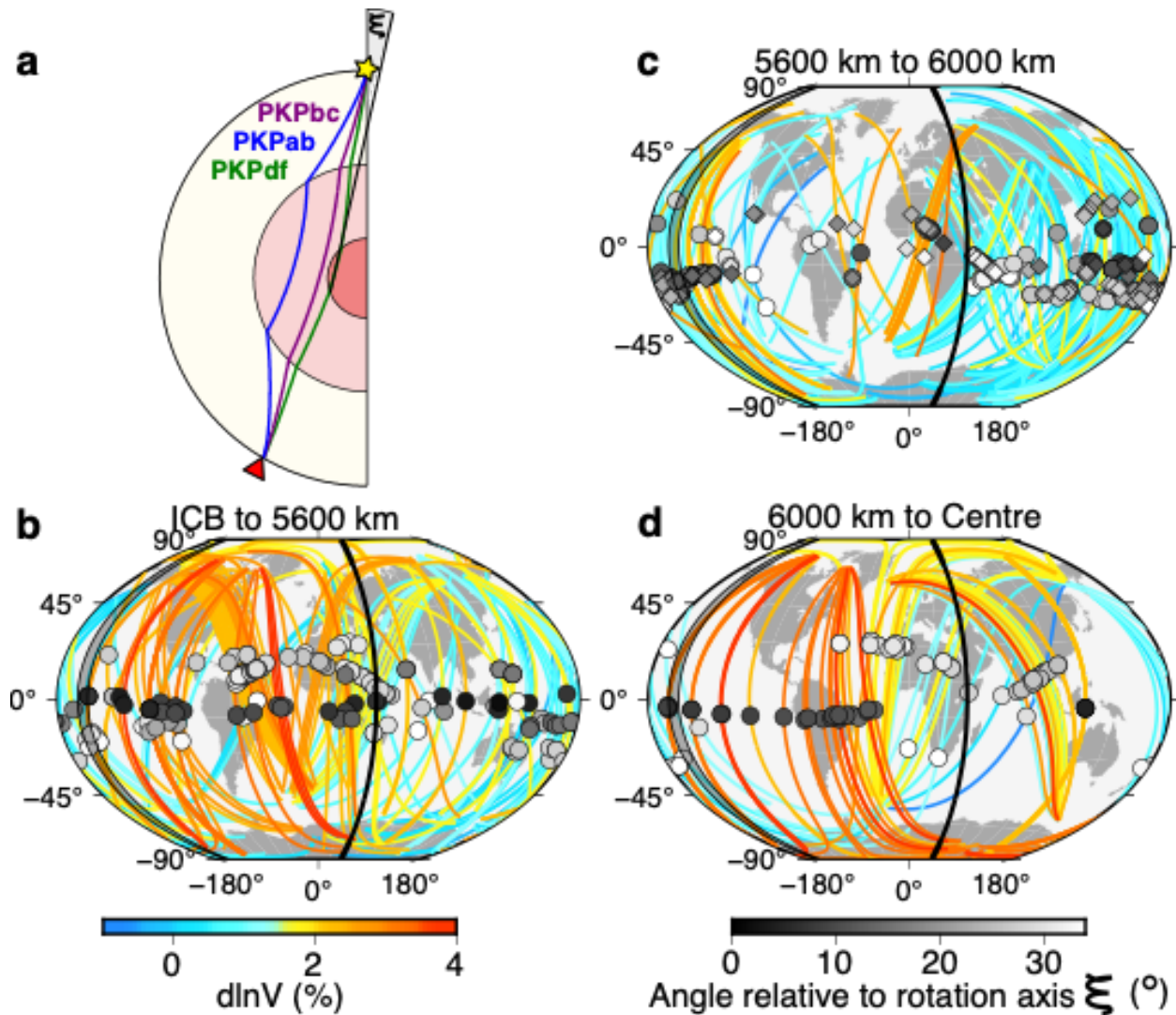
### 55 **Seismic analysis of asymmetric anisotropy**

56 Aiming to address this issue, we have made new differential travel time measurements of  
57 PKP<sub>ab-df</sub> and PKP<sub>bc-df</sub> from recent seismic deployments (Fig. 1 and Extended Data Fig. 1),  
58 increasing sampling of the IC along polar directions at a large range of depths, and added  
59 them to our existing global collection (See Methods). The updated dataset samples the IC  
60 close to Earth's rotation axis: from the inner core boundary (ICB) to within 35 km of the  
61 centre of the Earth.

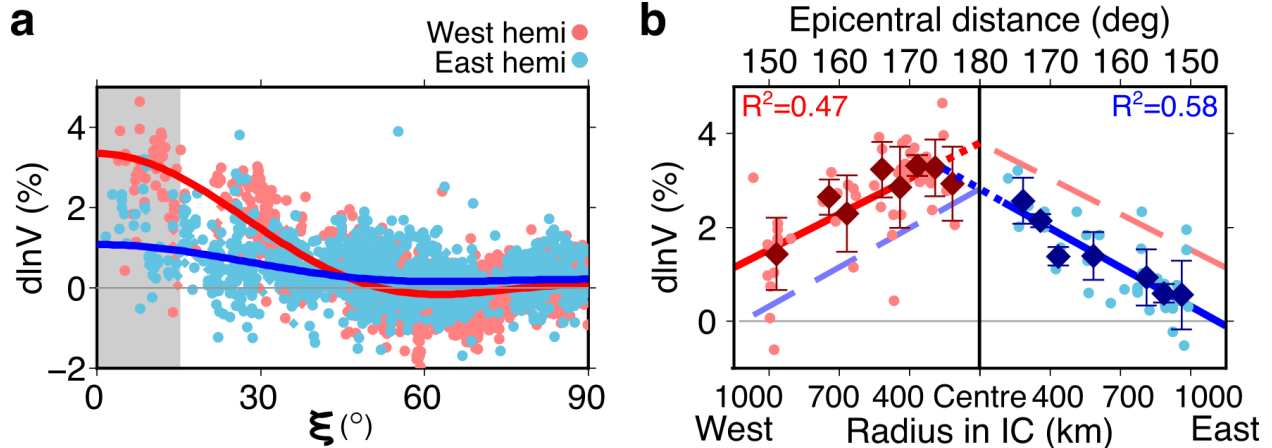
62

63 Differential travel time anomalies, expressed as the effective P-velocity anomaly within the  
64 IC ( $d\ln V = -\frac{dT}{T_{ic}}$ , where  $T_{ic}$  is the travel time through the IC) exhibit a strong dependence  
65 on  $\xi$ , the angle of the path within the IC relative to the rotation axis (Fig. 1a), with residuals  
66 of up to 9.9 s at the largest distances for polar paths, and  $\pm 2$  s for more equatorial paths  
67 (Extended Data Fig. 2). Furthermore, the residuals depend on both the longitude and depth  
68 of the turning point of the ray (Fig. 1b,c,d). To first order, as found previously<sup>6-9</sup>, the data  
69 exhibit hemispherical differences (Fig. 1 and Extended Data Fig. 4). Assuming a linear  
70 dependence of anisotropy on depth in each hemisphere, we determine the best fitting  
71 western boundary of the WH to be between -166°E and -159°E (Methods and Extended Data  
72 Fig. 5). However, sharp hemispherical boundaries are difficult to reconcile with geodynamic  
73 models of IC growth.

74



75  
 76 **Fig. 1: Sampling of the inner core with polar PKP rays.** (a) Ray paths of PKP branches  
 77 used here. PKPdf samples the IC, while PKPbc and PKPab remain in the outer core.  $\xi$  is the  
 78 angle that the PKPdf path in the IC makes with Earth's rotation axis. (b-d): Only polar paths  
 79 ( $\xi < 35^\circ$ ) from source to receiver colour-coded by effective IC velocity anomaly (line colour)  
 80 and  $\xi$  (symbol colour) for paths turning between (b) 5200 and 5600 km depth, (c) 5600 km  
 81 and 6000 km, and (d) 6000 km and Earth's centre. 530 polar paths are shown. Turning points  
 82 for PKPbc-df and PKPab-df ray pairs are shown as diamonds and circles, respectively. We  
 83 exclude the South Sandwich Islands (SSI) to Alaska paths. Grey region marks best fitting WH  
 84 boundaries determined in this study and solid line marks the EH boundary<sup>10</sup>.  
 85



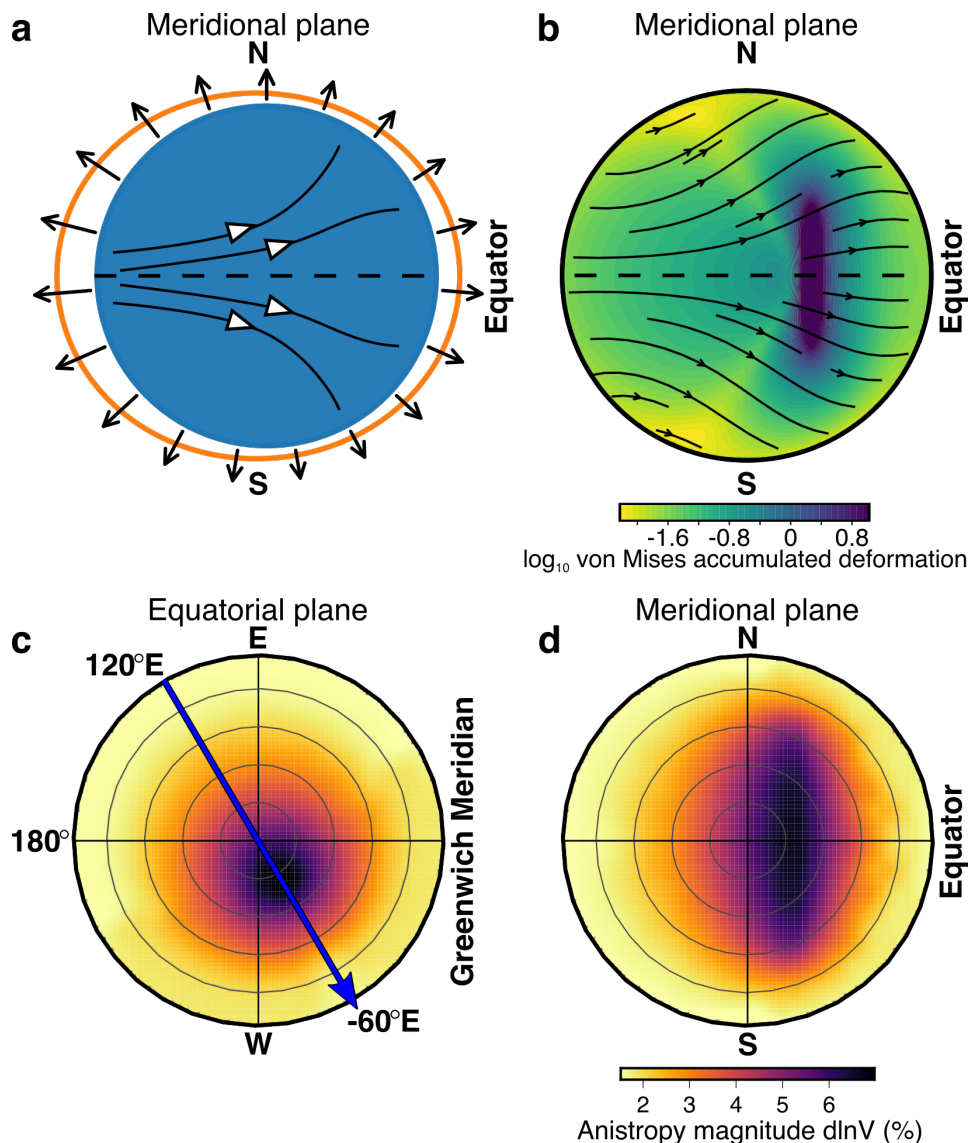
86  
87 **Fig. 2: Effective velocity anomaly in the inner core from PKPab-df and PKPbc-df travel**  
88 **time observations as a function of  $\xi$  and epicentral distance. (a)** Effective velocity  
89 anomalies as a function of  $\xi$  display a hemispherical pattern implying stronger anisotropy in  
90 the WH (red) than in the EH (blue). Data from the SSI to Alaska are excluded (Extended Data  
91 Figure 3). **(b)** IC velocity anomaly as a function of epicentral distance, and thus bottoming  
92 radius of the ray in the WH (left) and EH (right), for data with  $\xi \leq 15^\circ$  (shaded region in (a)).  
93 Solid lines mark linear fits as a function of distance in the respective hemispheres with  
94 mirror images across the centre of the Earth (180°) shown as broken lines. Moving averages  
95 (diamonds) and standard deviations at 2.5° increments in distance highlight the robust  
96 trends. The EH trend is extended to meet the WH trend (at 400 km radius) with a dotted blue  
97 line.

98  
99 Examining the data more closely, we find that the effective velocity anomaly linearly  
100 increases with distance, i.e. turning point radius in the IC, in both hemispheres (Fig. 2b). The  
101 gradient with distance is approximately equal in both hemispheres, but with an offset to  
102 larger anomalies in the WH. This gradient is dependent on  $\xi$  and is steepest and most  
103 robustly defined for polar paths ( $0 < \xi < 15^\circ$ ) (Extended Data Fig. 6). The largest effective  
104 velocity anomalies ( $\geq 3.5\%$   $d\ln V$ ) are recorded in the WH, for rays bottoming at around 400  
105 km radius (distances  $\geq 170^\circ$ ) with longitude  $\sim 60^\circ W$ , not at the centre of the IC. Our travel  
106 time data suggest a depth-dependence of anisotropy that, to first order, is smooth and  
107 asymmetric with respect to the centre of the Earth, rather than a hemispherical pattern with  
108 sharp boundaries between the hemispheres.

### 109 Growing anisotropic texture in the inner core

110 In order to interpret the seismological observations, we consider that the core likely grows  
111 preferentially at the equator due to Taylor column convection in the outer core, which  
112 induces more efficient heat transport in the cylindrically radial direction<sup>11,12</sup>. Isostatic  
113 adjustment would cause the oblate IC to flow inwards from the equator and up towards the  
114 poles<sup>11,13</sup>. Such a flow would be confined to the uppermost layer if a strong density  
115 stratification existed, and would induce deformation at depth if not<sup>13</sup>. Any asymmetry to the  
116 heat extraction from the IC in the plane of the equator would cause asymmetric growth<sup>12,14</sup>  
117 resulting in lateral advection of the growing IC and thus slow net translation. Previous  
118 studies attempted to explain the depth dependence of anisotropy by degree 2 flow<sup>11,14</sup> on the  
119 one hand, and the hemispherical dichotomy by degree 1 flow<sup>15,16</sup> on the other. However,  
120

121 these hemispherical studies considered fast convective instabilities resulting in a degree 1  
122 flow that, alone, could not produce the observed seismic anisotropy pattern and strength.  
123 Guided by our seismic observations, we combine the processes of preferred equatorial  
124 growth and hemispherically asymmetric growth and analytically model the flow pattern in  
125 a neutrally stratified IC (Fig. 3; see Methods). Advection of strained crystals along the  
126 translation axis shifts the pattern of high deformation laterally from the axis of rotation, with  
127 lateral offset of the high deformation zone from the rotation axis depending on the chosen  
128 translation rate. A key assumption here is that the translation rate is slower than the rate of  
129 growth, resulting from differential growth<sup>14</sup>, and not from simultaneous melting and  
130 freezing on opposite hemispheres<sup>15,16</sup>. Given the limited constraints, the age of the IC and the  
131 translation velocity are both free parameters of such a model. The differential growth rate of  
132 the IC between the equator and the poles is described by the parameter  $S_2$ , which controls  
133 the magnitude and pattern of strain experienced.  $S_2$  is loosely constrained to between 0 and  
134 1 from dynamical arguments<sup>11</sup>, while geodynamical models of the outer core<sup>12,14</sup> argue for a  
135 value of  $\sim 0.4$ . Constraints on  $S_2$  are not strong, however additional information can be  
136 brought in from mineral physics, which provides constraints on strain rate dependent  
137 development of anisotropy.  
138



139  
 140 **Fig. 3: Inner core growth, strain and anisotropy.** (a) Sketch combining preferential  
 141 equatorial growth (driven by Taylor column convection in the outer core) and asymmetric  
 142 growth rate, with imposed IC growth rate at the boundary and internal flow shown by black  
 143 and white arrows, respectively. (b) Asymmetric growth and movement in from the equator  
 144 and towards the poles causing lateral and vertical advection of the strongest deformation.  
 145 Both (a) and (b) show the meridional plane along the axis of translation with dashed line  
 146 showing the equator. The strain field aligns iron grains, producing strong anisotropy in the  
 147 deep IC that is offset from the rotation (N-S) axis in (c) the equatorial plane, and elongated  
 148 parallel to the rotation axis in (d) the meridional plane along the direction of translation  
 149 shown by the arrow in (c). Calculated with IC age of 0.5 Ga, S2 of 0.6, translation rate of 0.3,  
 150 and translation direction from 120°E to -60°W.

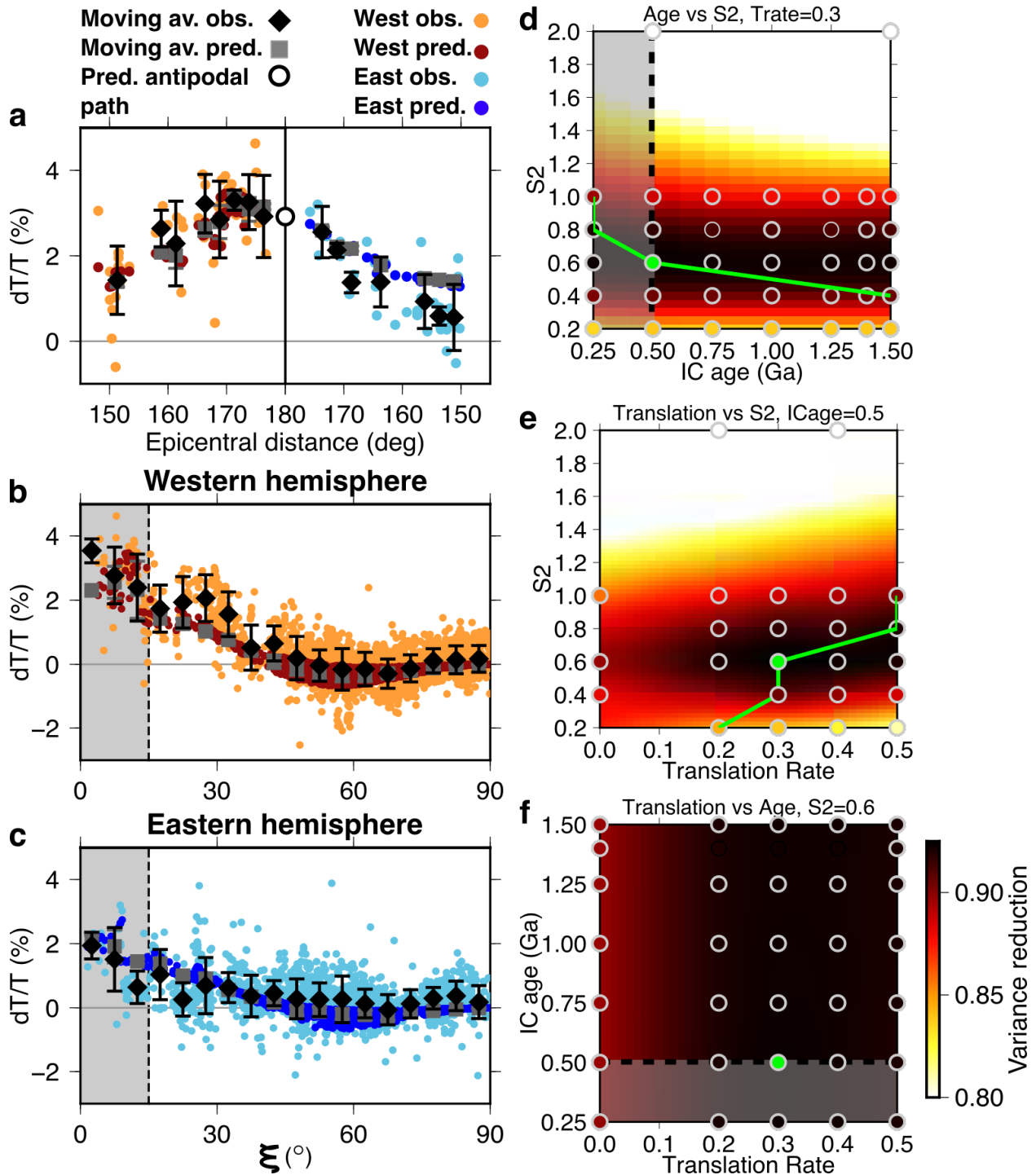
151  
 152 In our model, the present-day IC seismic anisotropy is a function of the initial single crystal  
 153 anisotropy, the slip planes of crystal deformation, and the flow field. Crystallographic  
 154 alignment of a polycrystal is necessary to generate significant anisotropy on the length scale

155 of the IC. Using Visco-Plastic Self-Consistent modelling (VPSC)<sup>17</sup> we calculate the anisotropy  
156 resulting from dislocation creep in the strain field produced by our geodynamic models, for  
157 different IC ages, translation rates, and single crystal structures. Despite body-centred cubic  
158 (bcc) iron having strong single crystal anisotropy<sup>18</sup>, we find that it cannot produce strong  
159 polycrystal anisotropy, nor can face-centered cubic iron, as also previously shown<sup>19</sup>. In  
160 contrast, plastic deformation of a hexagonally close packed (hcp) iron-nickel alloy  
161 ( $\text{Fe}_{93.75}\text{Ni}_{6.25}$ )<sup>20</sup>, compatible with cosmo-chemical constraints<sup>21</sup>, with slip on the  $\langle c+a \rangle$   
162 pyramidal planes<sup>22,23</sup> produces an anisotropic IC with up to 6.6% anisotropy (Fig. 3d) that  
163 can fit the seismic data well. In this model, the fast direction of anisotropy becomes aligned  
164 with the rotation axis and the slow direction varies with depth (Extended Data Fig. 7),  
165 matching observations<sup>24</sup>. Pure hcp iron does not produce as strong a match to our  
166 observations (Extended Data Figs. 8 and 9).

167  
168 The pattern and strength of the flow field induced by IC growth impacts the strain that  
169 crystals experience, and is controlled by the IC age, S2, translation rate, and the direction of  
170 translation. The IC age trades off linearly with strain rate and duration, but the dislocation  
171 creep has a non-linear relation between stress and strain rate (see Methods), implying that  
172 the degree and pattern of crystal alignment - and therefore the pattern and strength of the  
173 resulting seismic anisotropy varies with duration, and so IC age. The total strain is controlled  
174 by the parameter S2; thus, the strain rate is controlled by both IC age and S2. We constrain  
175 the IC growth history by running models with a range of ages, translation rates, and values  
176 of S2 and compare predicted anisotropy from these models with our seismic observations  
177 (Figure 4). The data is best fit by models with  $0.4 \leq S2 \leq 0.8$ . Within the range of acceptable IC  
178 ages<sup>23-25</sup> (see Methods), we find  $S2=0.6$  and IC age of 0.5 Ga to best fit both the seismic  
179 observations and geodynamic constraints, although the constraint on age is not strong (Fig.  
180 4d-f; See Methods). Translation at a rate of 0.3 IC radii over the 0.5 Ga IC lifetime along an  
181 axis oriented in the equatorial plane from 120°E towards -60°W matches the geographic  
182 pattern of anisotropy, achieving a 93% variance reduction for the polar data compared with  
183 89% for a model with no translation. Our model shows increasing anisotropy strength with  
184 depth. The model also displays weak anisotropy near the ICB that is stronger in the WH than  
185 the EH, which is qualitatively compatible with models of hemispherically distinct isotropy in  
186 the upper IC from measurements of PKiKP<sup>25</sup> and P'P'df<sup>26</sup> travel times, and with constraints  
187 on the magnitude and distribution of anisotropy from normal modes<sup>27,28</sup>.

188





189  
 190  
 191  
 192  
 193  
 194  
 195  
 196

**Fig. 4: Predicted versus observed PKP velocity anomalies for hcp Fe<sub>93.75</sub>Ni<sub>6.25</sub> at 5500 K and 360 GPa<sup>20</sup> and trade-offs between IC age, S<sub>2</sub>, and translation rate. (a-c): Predicted (dark blue and red dots and with mean as grey squares) and observed (light blue and orange dots and with mean as black diamonds) effective velocity anomalies as a function of (a) epicentral distance for data with  $\xi \leq 15^\circ$ , marked by shaded region in (b) and (c), and as a function of  $\xi$  in the (b) western and (c) eastern hemispheres for IC growth model in Fig. 3. The open circle in (a) marks the predicted effective velocity anomaly for a path along the**

197 rotation axis. Error bars for the data show the mean and one standard deviation at 2.5° and  
198 5° increments for panels **(a)**, and **(b)** and **(c)**, respectively. **(d-f)**: Variance reduction of the  
199 model relative to the data illustrating the trade-offs between **(d)** IC age and S2, **(e)** S2 and  
200 translation rate, and **(f)** translation rate and IC age. Grey circles mark tested values, and the  
201 green circle marks the best-fitting parameters, corresponding to the model in **(a-c)** and at  
202 which the 3D space is sampled. The green line tracks the best x-value at any given y-value.  
203 Models in the shaded region have too young IC ages based on core conductivity. Surface is  
204 interpolated with a “minimum curvature” spline.

205  
206 Remaining discrepancies between observations and predictions may result from  
207 contamination of the observations by mantle structure and small-scale structure in the IC.  
208 While differential measurements remove some of the effect of upper mantle heterogeneity  
209 on the PKP travel times, even modest 3D velocity structure deeper in the mantle can  
210 influence them<sup>29</sup>. The largest travel time anomalies that we observe (9.9 s) are for PKPab-df  
211 measurements between 170° and 175° distance, where there is large lateral separation  
212 between the two ray paths such that they could experience significantly different velocities  
213 in the deep mantle. Still, mantle velocity anomalies such as Ultra Low Velocity Zones (ULVZ)  
214 and the Large Low Shear Velocity Provinces (LLSVPs) could generate at most 1-2s travel time  
215 delays. Furthermore, the data with large travel time anomalies pierce the core-mantle  
216 boundary at distinctly different locations (Fig. 1b,c,d), and no ULVZs have yet been reported  
217 in these regions<sup>30</sup>. Thus, mantle structure would mostly introduce scatter and not  
218 significantly obscure the first-order IC anisotropic pattern that we model.

219  
220 **Implications for core and mantle evolution**  
221 Within the limits of the assumptions made, particularly the assumption of dislocation creep,  
222 the proposed model has implications for the physical properties of the IC. Assuming Yoshida-  
223 style deformation restricts the range of possible IC viscosities ( $\eta > 10^{18}$  Pas), and the IC age  
224 to be larger than the diffusive time scale, which may range from 0.2 to 1.5 Ga<sup>4</sup>, depending on  
225 the chosen core conductivity. This constraint places the viscosity at the upper end of the  
226 range recently obtained by density function theory<sup>31</sup>.

227  
228 Our model suggests that the seismic structure of the IC records the large-scale pattern of the  
229 heat flux at the ICB, which is controlled by the dynamics of the outer core and the heat flux  
230 variations at the CMB<sup>12</sup>. Our preferred model has a translation rate of 0.3 and a ratio of polar  
231 to equatorial growth (S2) of 0.6. This corresponds to a growth rate that is 40% lower at the  
232 poles and 130% larger at the equator compared to the global average. Growth rate at the  
233 equator varies between the eastern and western hemispheres from 100% to 160% of the  
234 global average rate, respectively. This pattern is similar to that obtained when forcing the  
235 geodynamo with heat fluxes at the top of the core based on present-day lower mantle  
236 structure<sup>12</sup> and suggests that the asymmetry in heat extraction has been stable in the outer  
237 core for times similar to the age of the IC. This agrees with indications that the currently  
238 observed LLSVPs separated by a ring of high seismic velocities at the base of the mantle may  
239 have been stable for at least 200-300 Ma<sup>32-34</sup>, and with the potential existence of structures  
240 in the mantle stabilizing the convection pattern<sup>35</sup>. In contrast, geomagnetic observations of  
241 outer core patterns that imply forcing by bottom-up interactions<sup>36</sup> may indicate either a  
242 recent change in IC dynamics from passive to active dynamics or complex interactions

243 between the inner and outer core that may be described at smaller scales than are  
244 considered here. Our modeling supports a relatively high core conductivity, as it favors a  
245 young IC age ( $\sim 0.5$  Ga) and requires the absence of convective instabilities. Preventing the  
246 development of thermal instabilities with an IC age of 0.5 Ga requires IC thermal conductivity  
247  $> 120$  W/m/K<sup>4</sup>. Better resolving 3D patterns of seismic anisotropy in the IC may help  
248 document further the uneven growth history of the IC, providing a record of the global scale  
249 pattern of outer core dynamics. While our model does not consider the smaller-scale seismic  
250 structure of the inner core<sup>37</sup>, we provide the first holistic model of IC growth capable of  
251 matching the observed seismic anisotropy and consistent with available paleomagnetic  
252 observations and mineral physics data<sup>38,39</sup>.

253

## 254 **References**

- 255 Poupinet, G., Pillet, R. & Souriau, A. Possible heterogeneity of the Earth's core deduced from  
256 PKIKP travel times. *Nature* **305**, 294–206 (1983).
- 257 2. Morelli, A., Dziewonski, A. M. & Woodhouse, J. H. Anisotropy of the inner core  
258 inferred from PKIKP travel times. *Geophys. Res. Lett.* **13**, 1545–1548 (1986).
- 259 3. Woodhouse, J. H., Giardini, D. & Li, X. -D. Evidence for inner core anisotropy from free  
260 oscillations. *Geophys. Res. Lett.* **13**, 1549–1552 (1986).
- 261 4. Lasbleis, M. & Deguen, R. Building a regime diagram for the Earth's inner core. *Phys.*  
262 *Earth planet. Int.* **247**, 80–93 (2015).
- 263 5. Lincot, A., Cardin, P., Deguen, R. & Merkel, S. Multiscale model of global inner-core  
264 anisotropy induced by hcp alloy plasticity. *Geophys. Res. Lett.* **43**, 1084–1091 (2016).
- 265 6. Tanaka, S. & Hamaguchi, H. Degree one heterogeneity and hemispherical variation of  
266 anisotropy in the inner core from PKP (BC)- PKP (DF) times. *J. Geophys. Res.* **102**,  
267 2925–2938 (1997).
- 268 7. Creager, K. C. Large-scale variations in inner core anisotropy. *J. Geophys. Res.* **104**,  
269 23127–23139 (1999).
- 270 8. Irving, J. C. E. & Deuss, A. Hemispherical structure in inner core velocity anisotropy. *J.*  
271 *Geophys. Res.* **116**, 1–17 (2011).
- 272 9. Lythgoe, K. H., Deuss, A., Rudge, J. F. & Neufeld, J. A. Earth's inner core: Innermost  
273 inner core or hemispherical variations? *Earth Planet. Sci. Lett.* **385**, 181–189 (2014).
- 274 10. Irving, J. C. E. Imaging the inner core under Africa and Europe. *Phys. Earth planet. Int.*  
275 **254**, 12–24 (2016).
- 276 11. Yoshida, S., Sumita, I. & Kumazawa, M. Growth model of the inner core coupled with  
277 the outer core dynamics and the resulting elastic anisotropy. *J. Geophys. Res.* **101**,  
278 28085–28103 (1996).
- 279 12. Aubert, J., Amit, H., Hulot, G. & Olson, P. Thermochemical flows couple the Earth's  
280 inner core growth to mantle heterogeneity. *Nature* **454**, 758–761 (2008).
- 281 13. Deguen, R., Cardin, P., Merkel, S. & Lebensohn, R. A. Texturing in Earth's inner core  
282 due to preferential growth in its equatorial belt. *Phys. Earth planet. Int.* **188**, 173–184  
283 (2011).
- 284 14. Deguen, R., Alboussière, T. & Labrosse, S. Double-diffusive translation of Earth's inner  
285 core. *Geophys. J. Int.* **214**, 88–107 (2018).
- 286 15. Alboussière, T., Deguen, R. & Melzani, M. Melting-induced stratification above the  
287 Earth's inner core due to convective translation. *Nature* **466**, 744–747 (2010).
- 288 16. Monnereau, M., Calvet, M., Margerin, L. & Souriau, A. Lopsided growth of Earth's

- 289 inner core. *Science (80-. )*. **328**, 1014–1017 (2010).
- 290 17. Lebensohn, R. A. & Tomé, C. N. A self-consistent anisotropic approach for the  
291 simulation of plastic deformation and texture development of polycrystals:  
292 Application to zirconium alloys. *Acta Met. Mater.* **41**, 2611–2624 (1993).
- 293 18. Belonoshko, A. B. *et al.* Origin of the low rigidity of the earth's inner core. *Science (80-.*  
294 *)*. **316**, 1603–1605 (2007).
- 295 19. Lincot, A., Merkel, S. & Cardin, P. Is inner core seismic anisotropy a marker for plastic  
296 flow of cubic iron? *Geophys. Res. Lett.* **42**, 1326–1333 (2015).
- 297 20. Martorell, B., Brodholt, J., Wood, I. G. & Vočadlo, L. The effect of nickel on the  
298 properties of iron at the conditions of Earth's inner core: Ab initio calculations of  
299 seismic wave velocities of Fe-Ni alloys. *Earth Planet. Sci. Lett.* **365**, 143–151 (2013).
- 300 21. McDonough, W. F. & Sun, S. s. The composition of the Earth. *Chem. Geol.* **120**, 223–  
301 253 (1995).
- 302 22. Miyagi, L. *et al.* In situ phase transformation and deformation of iron at high pressure  
303 and temperature. *J. Appl. Phys.* **104**, (2008).
- 304 23. Merkel, S., Gruson, M., Wang, Y., Nishiyama, N. & Tomé, C. N. Texture and elastic  
305 strains in hcp-iron plastically deformed up to 17.5GPa and 600K: Experiment and  
306 model. *Model. Simul. Mater. Sci. Eng.* **20**, (2012).
- 307 24. Frost, D. A. & Romanowicz, B. On the orientation of the fast and slow directions of  
308 anisotropy in the deep inner core. *Phys. Earth Planet. Inter.* **286**, 101–110 (2019).
- 309 25. Garcia, R. & Souriau, A. Inner core anisotropy and heterogeneity level. *Geophys. Res.*  
310 *Lett.* **27**, 3121–3124 (2000).
- 311 26. Frost, D. A. & Romanowicz, B. Constraints on Inner Core Anisotropy Using Array  
312 Observations of P'P'. *Geophys. Res. Lett.* **44**, 10,878-10,886 (2017).
- 313 27. Romanowicz, B., Li, X. D. & Durek, J. Anisotropy in the inner core: Could it be due to  
314 low-order convection? *Science (80-. )*. **274**, 963–966 (1996).
- 315 28. Irving, J. C. E. & Deuss, A. Stratified anisotropic structure at the top of Earth's inner  
316 core: A normal mode study. *Phys. Earth planet. Int.* **186**, 59–69 (2011).
- 317 29. Bréger, L., Romanowicz, B. & Rousset, S. New constraints on the structure of the  
318 inner core from P'P'. *Geophys. Res. Lett.* **27**, 2781–2784 (2000).
- 319 30. Yu, S. & Garnero, E. J. Ultralow Velocity Zone Locations: A Global Assessment.  
320 *Geochem. Geophys. Geosyst.* **19**, 396–414 (2018).
- 321 31. Ritterbex, S. & Tsuchiya, T. Viscosity of hcp iron at Earth's inner core conditions from  
322 density functional theory. *Sci. Rep.* **10**, 2–5 (2020).
- 323 32. Torsvik, T. H., Smethurst, M. A., Burke, K. & Steinberger, B. Large igneous provinces  
324 generated from the margins of the large low-velocity provinces in the deep mantle.  
325 *Geophys. J. Int.* **167**, 1447–1460 (2006).
- 326 33. Dziewonski, A. M., Lekic, V. & Romanowicz, B. A. Mantle Anchor Structure: An  
327 argument for bottom up tectonics. *Earth Planet. Sci. Lett.* **299**, 69–79 (2010).
- 328 34. Greff-Lefftz, M. & Besse, J. Paleo movement of continents since 300Ma, mantle  
329 dynamics and large wander of the rotational pole. *Earth Planet. Sci. Lett.* **345–348**,  
330 151–158 (2012).
- 331 35. Ballmer, M. D., Houser, C., Hernlund, J. W., Wentzcovitch, R. M. & Hirose, K.  
332 Persistence of strong silica-enriched domains in the Earth's lower mantle. *Nat.*  
333 *Geosci.* **10**, 236–240 (2017).
- 334 36. Aubert, J., Finlay, C. C. & Fournier, A. Bottom-up control of geomagnetic secular

- 335 variation by the Earth's inner core. *Nature* **502**, 219–223 (2013).  
336 37. Tkalčić, H. Large variations in travel times of mantle-sensitive seismic waves from  
337 the South Sandwich Islands: Is the Earth's inner core a conglomerate of anisotropic  
338 domains? *Geophys. Res. Lett.* **37**, 1–6 (2010).  
339 38. Biggin, A. J. *et al.* Palaeomagnetic field intensity variations suggest Mesoproterozoic  
340 inner-core nucleation. *Nature* **526**, 245–248 (2015).  
341 39. Bono, R. K., Tarduno, J. A., Nimmo, F. & Cottrell, R. D. Young inner core inferred from  
342 Ediacaran ultra-low geomagnetic field intensity. *Nat. Geosci.* **12**, 143–147 (2019).  
343  
344

### 345 Corresponding author

346 For correspondence and requests for material please contact Daniel A Frost at  
347 dafrost@berkeley.edu.  
348

### 349 Acknowledgements

350 The authors acknowledge the following funding sources: NSF grants EAR-1135452 and EAR-  
351 1829283 to DAF and BR; European Union's Horizon 2020 research and innovation program  
352 under the Marie Skłodowska-Curie Grant Agreement No. 795289 to ML; and NSF grant EAR  
353 1343908 and DOE grant DE-FG02-05ER15637 to BC.  
354

### 355 Author contributions

356 All authors contributed to project design, methodology development, model  
357 conceptualization and manuscript preparation. DAF was responsible for seismic data  
358 curation and formal analysis and wrote the first draft of the paper. ML contributed to the  
359 geodynamic modeling and BC provided the mineral physics input. DAF and BR coordinated  
360 the project.  
361

### 362 Competing interests

363 No authors have any known competing interests.  
364

### 365 Figure Legends

366 **Fig. 1: Sampling of the inner core with polar PKP rays.** (a) Ray paths of PKP branches  
367 used here. PKP<sub>df</sub> samples the IC, while PKP<sub>bc</sub> and PKP<sub>ab</sub> remain in the outer core.  $\xi$  is the  
368 angle that the PKP<sub>df</sub> path in the IC makes with Earth's rotation axis. (b-d): Only polar paths  
369 ( $\xi < 35^\circ$ ) from source to receiver colour-coded by effective IC velocity anomaly (line colour)  
370 and  $\xi$  (symbol colour) for paths turning between (b) 5200 and 5600 km depth, (c) 5600 km  
371 and 6000 km, and (d) 6000 km and Earth's centre. 530 polar paths are shown. Turning points  
372 for PKP<sub>bc</sub>-<sub>df</sub> and PKP<sub>ab</sub>-<sub>df</sub> ray pairs are shown as diamonds and circles, respectively. We  
373 exclude the South Sandwich Islands (SSI) to Alaska paths. Grey region marks best fitting WH  
374 boundaries determined in this study and solid line marks the EH boundary<sup>10</sup>.  
375

376 **Fig. 2: Effective velocity anomaly in the inner core from PKP<sub>ab</sub>-<sub>df</sub> and PKP<sub>bc</sub>-<sub>df</sub> travel**  
377 **time observations as a function of  $\xi$  and epicentral distance.** (a) Effective velocity  
378 anomalies as a function of  $\xi$  display a hemispherical pattern implying stronger anisotropy in  
379 the WH (red) than in the EH (blue). Data from the SSI to Alaska are excluded (Extended Data  
380 Figure 3). (b) IC velocity anomaly as a function of epicentral distance, and thus bottoming

381 radius of the ray in the WH (left) and EH (right), for data with  $\xi \leq 15^\circ$  (shaded region in (a)).  
382 Solid lines mark linear fits as a function of distance in the respective hemispheres with  
383 mirror images across the centre of the Earth ( $180^\circ$ ) shown as broken lines. Moving averages  
384 (diamonds) and standard deviations at  $2.5^\circ$  increments in distance highlight the robust  
385 trends. The EH trend is extended to meet the WH trend (at 400 km radius) with a dotted blue  
386 line.

387  
388 **Fig. 3: Inner core growth, strain and anisotropy.** (a) Sketch combining preferential  
389 equatorial growth (driven by Taylor column convection in the outer core) and asymmetric  
390 growth rate, with imposed IC growth rate at the boundary and internal flow shown by black  
391 and white arrows, respectively. (b) Asymmetric growth and movement in from the equator  
392 and towards the poles causing lateral and vertical advection of the strongest deformation.  
393 Both (a) and (b) show the meridional plane along the axis of translation with dashed line  
394 showing the equator. The strain field aligns iron grains, producing strong anisotropy in the  
395 deep IC that is offset from the rotation (N-S) axis in (c) the equatorial plane, and elongated  
396 parallel to the rotation axis in (d) the meridional plane along the direction of translation  
397 shown by the arrow in (c). Calculated with IC age of 0.5 Ga, S2 of 0.6, translation rate of 0.3,  
398 and translation direction from  $120^\circ\text{E}$  to  $-60^\circ\text{W}$ .

399  
400 **Fig. 4: Predicted versus observed PKP velocity anomalies for hcp Fe<sub>93.75</sub>Ni<sub>6.25</sub> at**  
401 **5500 K and 360 GPa<sup>20</sup> and trade-offs between IC age, S2, and translation rate. (a-c):**  
402 Predicted (dark blue and red dots and with mean as grey squares) and observed (light blue  
403 and orange dots and with mean as black diamonds) effective velocity anomalies as a function  
404 of (a) epicentral distance for data with  $\xi \leq 15^\circ$ , marked by shaded region in (b) and (c), and  
405 as a function of  $\xi$  in the (b) western and (c) eastern hemispheres for IC growth model in Fig.  
406 3. The open circle in (a) marks the predicted effective velocity anomaly for a path along the  
407 rotation axis. Error bars for the data show the mean and one standard deviation at  $2.5^\circ$  and  
408  $5^\circ$  increments for panels (a), and (b) and (c), respectively. (d-f): Variance reduction of the  
409 model relative to the data illustrating the trade-offs between (d) IC age and S2, (e) S2 and  
410 translation rate, and (f) translation rate and IC age. Grey circles mark tested values, and the  
411 green circle marks the best-fitting parameters, corresponding to the model in (a-c) and at  
412 which the 3D space is sampled. The green line tracks the best x-value at any given y-value.  
413 Models in the shaded region have too young IC ages based on core conductivity. Surface is  
414 interpolated with a “minimum curvature” spline.

415  
416

417 **Methods for:** Seismic evidence of slow translation and preferential equatorial growth of the  
418 inner core

419  
420 **Authors:** Daniel A. Frost<sup>1\*</sup>, Barbara Romanowicz<sup>123</sup>, Marine Lasbleis<sup>45</sup>, Brian Chandler<sup>1</sup>

421  
422

### 423 **Seismology**

424 We collect PKPab-df and PKPbc-df differential travel time measurements to determine inner  
425 core structure (Fig. 1). Differential travel time anomalies, calculated with respect to a 1D  
426 reference model, can thus be attributed to the IC, at least to first order.

427

428 Our dataset comprises the existing Berkeley (UCB) PKP travel time data collection<sup>24,40-42</sup>  
429 with additional data<sup>43</sup>. This collection includes 2944 and 1170 PKPab-df and PKPbc-df  
430 differential travel time measurements, respectively. Here, we have added a total of 614  
431 PKPab-df and 416 PKPbc-df measurements from both recent events in the South Sandwich  
432 Islands between 23/10/2015 and 15/09/2017 observed in Alaska and other nearby stations  
433 in the northern hemisphere, and from events of  $m > 5.5$  at latitudes greater than  $50^\circ\text{N}$   
434 between 1/1/2008 and 31/06/2017 observed at distances beyond  $150^\circ$  and stations in the  
435 southern hemisphere, collected using the SOD mass-downloader tool and IRIS Wilber3 tool  
436 (289 observations from South Sandwich Islands to Alaska and 741 observations from other  
437 high latitude events observed in Antarctica). These events were recorded at networks: YT07,  
438 ZM07, 2C, AI, AU, ER, G, GE, II, IU, PS, SY, C, 9G, ID.

439

440 Locations and arrival times for events before and after 2009 are from the EHB<sup>44</sup> and ISC  
441 catalogues, respectively. We removed the linear trend and mean from vertical component  
442 data, deconvolved the instrument response to velocity. Data were bandpass filtered between  
443 0.4-2.0 Hz, and the Hilbert transform was applied to take account of the phase shift between  
444 PKPab and PKPdf. We manually picked phase onsets relative to predicted times from the 1D  
445 reference model ak135<sup>45</sup> after applying ellipticity corrections<sup>46</sup>. PKPdf and PKPbc are picked  
446 on the untransformed data, while PKPab is picked on the Hilbert transformed data. We  
447 classified picks based on the clarity of the signal onset, and the prominence of the signal in  
448 the unfiltered trace. Following picking and classification, we retained 614 and 416 highest  
449 quality differential PKPab-df and PKPbc-df travel times, respectively, measured with respect  
450 to ak135 (all data are shown, split by quality, in Extended Data Fig. 2). These new  
451 measurements, combined with the existing catalogues mentioned above yield 3558 and  
452 1586 high quality PKPab-df and PKPbc-df measurements, respectively. We only use the high-  
453 quality data for all plots and calculations in this paper.

454

455 Attributing the entire travel-time anomaly to structure in the IC, we convert travel times to  
456 velocity anomalies relative to 1D model ak135<sup>45</sup> as:  $-\frac{dT}{T_{ic}} = \frac{dv}{v}$ , where  $T_{ic}$  and  $v$  are reference  
457 travel times and velocities in the IC, respectively. This accounts for the difference in path  
458 length between the shallow and more deeply travelling waves. We construct cylindrically  
459 symmetric models of anisotropy, in which the perturbation to a spherically symmetric  
460 model<sup>47</sup> is expressed as:

461

462 
$$\frac{\delta v}{v} = a + b \cos^2 \xi + c \cos^4 \xi \quad (\text{S1})$$

463

464 where  $v$  and  $\delta v$  represent the reference velocity and velocity perturbations, respectively and  
465  $\xi$  is the angle of the ray path direction at the bottoming point of the ray with respect to Earth's  
466 rotation axis. We determine the coefficients  $a$ ,  $b$ , and  $c$  (which can depend on depth and  
467 location, depending on the model considered) by fitting our data with an L1-norm to account  
468 for outliers. The apparent IC velocity anomaly will be the integrated effect of the velocity  
469 anomalies along the raypath in the inner core.

470

471 In order to best illustrate the hemispherical differences, we update hemisphere boundaries  
472 by grid searching for the location of the western boundary of the western hemisphere. We  
473 hold the eastern boundary fixed to that previously found<sup>10</sup> as our dataset has limited  
474 coverage in this region, while the previous study was designed to sample the eastern  
475 boundary. Seeking to test the model of an IC with hemispherical and depth dependent  
476 anisotropy, we split the data into two hemispheres described by the candidate boundaries  
477 and fit models of velocity anomaly as a function of distance to the polar data ( $\xi \leq 15^\circ$ ). Only  
478 the polar data shows significant hemisphericity, thus we exclude higher  $\xi$  data to avoid  
479 biasing the fit with data with little resolving power. We seek to minimise the combined misfit  
480 to the two straight lines (Extended Data Fig. 6). Hemispheres are assigned based on the  
481 longitude of the turning point of the ray, an approximation that works well for polar data,  
482 but for equatorial data leads to smearing of hemispherical differences. However, since  
483 equatorial data do not show significant differences between hemispheres this  
484 approximation is not problematic. The western boundary of the western hemisphere  
485 produces equal fits to the data when located between  $-166^\circ$  E and  $-159^\circ$  E, with a very sharp  
486 falloff in  $R^2$  at locations  $< -166^\circ$  E or  $> -153^\circ$  E. While we simplify the boundary to a line of  
487 constant longitude, we cannot rule out a bent western boundary<sup>48</sup>. When we repeat this test  
488 with the less-polar data,  $\xi < 35^\circ$ , the best fitting hemisphere locations are similar with a sharp  
489 falloff at  $< -153^\circ$  E.

490

491 To determine the robustness of the resolved gradients of velocity with depth in each  
492 hemisphere we perform an interaction effect analysis using the data shown in Fig. 2b. We  
493 find that to 95% confidence we cannot reject the null hypothesis that the gradient of the two  
494 hemispheres is the same, i.e. the gradient of the two hemispheres is statistically the same. To  
495 determine the robustness of the offset in intercept between the two gradients we perform a  
496 bootstrap resampling of the same data. We find that the second standard deviations about  
497 the bootstrapped means do not overlap between the two hemispheres. We conclude that the  
498 trends of velocity with depth in the two hemispheres have statistically distinct intercepts but  
499 statistically very similar gradients.

500

### 501 **South Sandwich Islands to Alaska anomaly**

502 PKPbc-df and PKPab-df data recorded at stations in Alaska show a spread of travel time  
503 anomalies that do not match the global pattern as a function of  $\xi$  (Extended Data Fig. 3), as  
504 previously reported<sup>37,49,50</sup>. This is especially clear for PKPbc-df measurements that show  
505 travel time anomalies of up to 6 s, in contrast to measurements outside of Alaska of less than  
506 3 s on the most polar paths. This data may be contaminated by the Alaska slab<sup>49</sup>. We thus



507 remove data recorded in Alaska from the analysis presented here, but we keep data from  
508 events in Alaska, which are not affected by the slab and fit the global trends (Extended Data  
509 Fig. 3).

510

### 511 **Geodynamics**

512 It has previously been proposed by different groups that viscous relaxation of topography at  
513 the inner core boundary, caused by differential growth rate of the inner core, may orientate  
514 crystals in the inner core and explain the inner core bulk anisotropy (Extended Data Fig.  
515 10)<sup>11</sup>. Flows in the inner core induced by preferential growth at the equator have a vertical  
516 cylindrical axis of symmetry and tend to align the crystals along this axis close to the center  
517 of the inner core. However, such a model cannot explain the observation of hemispherical  
518 differences in IC anisotropy. Meanwhile, lateral translation caused by either simultaneous  
519 melting and crystallisation on opposite sides of the IC<sup>15,16</sup> or an unstable compositional  
520 gradient<sup>12,14</sup> has been proposed to explain the hemispherical dichotomy in the IC.

521 Here we consider the flows induced by differential growth rate at the inner core boundary,  
522 where the differential growth rate is a sum of two previously studied patterns: preferential  
523 equatorial growth and hemispherical asymmetric growth (Supplementary Information Fig.  
524 1). We consider neutral density stratification of the inner core, as it is the only regime in  
525 which deformation occurs at depth<sup>4</sup>. This drastically reduces the parameter space where  
526 such a flow could be observed, as a slightly unstable density stratification develops large-  
527 scale convection<sup>51</sup> and a stable density stratification inhibits radial flows and layers of high  
528 deformation develop near the inner core boundary<sup>13</sup>. As discussed before<sup>4</sup>, preferential  
529 growth at the equator would still develop large-scale flows for stable stratification for large  
530 viscosity values ( $\eta > 10^{18}$  Pa.s) and an age of inner core larger than the diffusive time scale  
531 (0.2-1.5 Ga). The assumption of Yoshida-style convection thus restricts the range of possible  
532 viscosities for the IC.

533 We solve the conservation of momentum equation for an incompressible fluid of constant  
534 viscosity  $\eta$  and constant density  $\rho$  in a spherical shell whose radius increases with time as  
535  $R_{ic}(t) = R_{ic}(\tau_{ic})\sqrt{t/\tau_{ic}}$  from time 0, representing the nucleation of the inner core, to  
536 time  $\tau_{ic}$ , today. The assumption of neutral stratification allows for a complete analytical  
537 solution for the flow for both the equatorial<sup>11</sup> and hemispherical patterns.

538

539 To determine the trajectory of a particle in the inner core, we fix the position of the particle  
540 today (at  $\tau_{ic}$ ) and integrate the trajectory backward in time using GrowYourIC<sup>52</sup>. The  
541 intersection of the trajectory and the ICB in the past corresponds to the time of crystallisation  
542 of the material.

543

544 We output the positions, velocity components, and velocity gradients of the particles with  
545 time and use this to calculate crystal orientations. To obtain a first idea of the deformation  
546 experienced by the particle, we calculate the vonMises equivalent strain rate and its average  
547 over the trajectory for  $t_{\text{crystallisation}} > 0$ .

548

549 In modelling the growth and resulting strain in the inner core, we also test the dependence  
550 of S2 on the preferred IC age and translation rate. We explore translation rates between 0

551 and 0.5 in increment of 0.1 radii of the IC over the age of the IC, IC ages between 0.25 and 1.5  
552 in increments of 0.25, and S2 between 0.2 and 1.0 in increments of 0.2, searching for the  
553 model that best matches the observed anisotropy. Such slow translation rates, which are  
554 lower than the crystallisation rate, require only differential freezing and no melting, unlike  
555 models of fast translation<sup>15,16</sup>. We calculate the core growth and translation for non-  
556 dimensionalised time and IC size. We then scale the model using the radius of the inner core  
557 at the present day (1217.5 km) and the chosen age of the inner core. Thus, we scale the  
558 instantaneous strain rate by the inverse of the IC age ( $1/\tau_{ic}$ ) and the time step ( $dt$ ) by the IC  
559 age ( $dt * \tau_{ic}$ ). Inner core age linearly affects the strain rate, but the maximum total  
560 accumulated strain for all IC ages is equal to S2, thus the value of S2 affects the total  
561 accumulated strain and the strain rate, while IC age only affects the strain rate. For each inner  
562 core age, S2, and translation rate, we use VPSC to calculate the resulting deformation. We  
563 model deformation by dislocation-creep, thus strain-rate and time step have a non-linear  
564 influence on the generation of anisotropy. Comparison of the resultant anisotropy models  
565 with our seismic observations suggest best-fitting ages between 0.5 and 1.5 Ga, depending  
566 on S2, with a translation rate of 0.3 radii over the age of the IC. Since models with  $S2 < 0.4$   
567 generate too little anisotropy to match the data and models with  $S2 \geq 0.8$  require an IC age of  
568 0.25 Ga (which is likely too young<sup>53-55</sup>), we determine reasonable bounds for S2 of  
569  $0.4 \leq S2 \leq 0.6$ , with the age trading off accordingly between 1.5 and 0.5 Ga, respectively.  
570 External constraints on the parameter S2 are poor, but previous work based on outer core  
571 geodynamics considerations<sup>12</sup> has preferred  $S2 = 0.4$ , which is consistent with our preferred  
572 range. The data can be fit by models with ages that are consistent with the range suggested  
573 from paleomagnetic constraints (between 0.5 Ga and 1.3 Ga<sup>38,39</sup>).

574  
575 Anisotropy strength depends on IC age and S2 thus by matching the observed strength of  
576 anisotropy for a given S2 we can estimate IC age. Models with  $S2 = 0.4$  and inner core ages  
577  $> 0.5$  Ga generate strong and localised anisotropy capable of matching our observations.  
578 Models run with inner core ages  $< 0.5$  Ga have maximum anisotropies of less than 6.0%, and  
579 the volume of the IC with maximum anisotropy is very small. These models predict weaker  
580 anisotropy and lower gradients of anisotropy with depth than what we observe. In contrast,  
581 for older inner cores the maximum anisotropy reaches  $\sim 7.0\%$  in places, thus achieves nearly  
582 full alignment of crystals, for which anisotropy would be 7.5%. For  $S2 = 0.6$  inner core ages  
583  $\geq 0.5$  predict strong anisotropy with a maximum anisotropy of  $\sim 7.0\%$  in places, equivalent  
584 to the models with  $S2 = 0.4$  and IC age  $\geq 1.0$  Ga. In fact, for  $S2 = 0.6$  and IC ages  $> 1.0$  Ga, the  
585 models begin to predict anisotropy that is stronger than the observations. Age of the IC also  
586 depends on IC viscosity through its influence on strain rate, but the viscosity is fixed to  $> 10^{18}$   
587 Pa-s by our assumption of Yoshida-style deformation<sup>4</sup>. Alternative solutions to fit the large  
588 anisotropy would be either easier deformation of hcp iron-nickel alloy than in our VPSC  
589 simulation, stronger single crystal anisotropy, or pressure dependence of the single crystal  
590 anisotropy (Extended Data Figure 9). However, both the deformation behaviour and precise  
591 anisotropic pattern of iron and iron alloys at high pressures and temperatures are not well  
592 constrained.

593  
594 We rotate the resulting model of anisotropy about the rotation axis and in the equatorial  
595 plane through  $360^\circ$  in  $10^\circ$  increments and compare the misfit with the data. We thus find  
596 that the best fitting growth direction is from  $120^\circ\text{E}$  towards  $60^\circ\text{W}$ , placing the points of

597 fastest and slowest growth under the Banda Sea and Brazil, respectively. Interestingly, these  
598 are very similar to the foci of growth and melting modelled by <sup>16</sup>, albeit with the opposite  
599 direction of growth.

600

### 601 **Mineral physics**

602 We calculate the anisotropy that would result from a deformation of an IC of a given  
603 composition in the presence of the strain field described above. An important component is  
604 the composition chosen, as anisotropy of the single crystal controls the anisotropy of the  
605 bulk model after deformation. Experimental studies indicate that hexagonally close packed  
606 (hcp) iron is stable at IC conditions<sup>56</sup>, but this is complicated by the presence of lighter  
607 elements in the IC. The body centred cubic (bcc) iron phase may also be stable<sup>57</sup>, depending  
608 on the strain field<sup>58</sup>. First principles calculations estimate the anisotropy of pure single iron  
609 crystals to range from 4.9-7.9% for hcp iron (given as the total range from minimum to  
610 maximum  $d\ln V$ ), and up to 14.7% for bcc iron<sup>18,42,59</sup>, and potentially up to 20% near the  
611 melting point of hcp iron<sup>60</sup>, although there is debate over the trends of anisotropy as a  
612 function of pressure and temperature<sup>59,61-64</sup>. The pattern of anisotropy for iron near its  
613 melting point<sup>60</sup> is very different from the observed IC anisotropy. Alloys of iron with  
614 plausible light elements modify the character of anisotropy, but the limited number of  
615 experiments leaves the dependence on pressure and temperature uncertain<sup>20,65-69</sup>. We select  
616 hcp iron-nickel alloy ( $\text{Fe}_{93.75}\text{Ni}_{6.25}$ )<sup>20</sup> as its pattern of single crystal anisotropy  
617 (Supplementary Information Fig. 11) is most similar to the observed anisotropy (Extended  
618 Data Figs. 3 and 4) and it is consistent with cosmo-chemical calculations of the core's  
619 composition<sup>21</sup>.

620

621 We calculate the development of Crystal Preferred Orientation (CPO) in the presence of the  
622 strain field resulting from our above inner core growth models using the Visco-Plastic Self-  
623 Consistent modelling code (VPSC)<sup>17</sup>. Groups of 1500 particles, representing crystals of hcp  
624 iron-nickel alloy ( $\text{Fe}_{93.75}\text{Ni}_{6.25}$ ) are generated at the Inner Core Boundary throughout the  
625 growth history of the inner core. Crystal growth at the ICB may cause pre-texturing<sup>70</sup>. We  
626 model particles with an initial solidification pre-texture in which the c-axes of the hcp iron  
627 crystals are oriented in the plane of the ICB, as in previous work<sup>5</sup>. The group of particles  
628 deforms as it is subject to the strain along the tracer path. The deformation is controlled by  
629 the crystal slip systems, for which we use those of hcp iron. Following from a previous study<sup>5</sup>,  
630 we allow slip along the  $\langle c+a \rangle$  pyramidal planes of hcp iron and lock the remaining slip  
631 systems and we set the normalized critically resolved shear stresses to  $\infty$  for the basal  $\langle a \rangle$ ,  
632 prismatic  $\langle a \rangle$ , and pyramidal  $\langle a \rangle$  plane slip systems, and 0.5 for the pyramidal  $\langle c+a \rangle$  plane  
633 slip system. We measure the resultant CPO at the present day.

634

635 CPO developed at each step of the growth model is combined with its respective elastic  
636 tensor to determine the resultant anisotropy. We incorporate estimates of the elastic tensors  
637 resulting from *ab initio* molecular dynamic simulations. For our chosen hcp FeNi alloy,  
638 elastic tensors are only available at 0 K and 360 GPa, and 5500 K and 360 GPa<sup>20</sup>. The  
639 temperature range of the inner core is likely very small – on the order of 30 K<sup>71</sup>. We thus  
640 neglect the pressure and temperature dependence of the elastic constants and calculate the  
641 resultant CPO for  $\text{Fe}_{93.75}\text{Ni}_{6.25}$  alloy at 5500 K and 360 GPa (Supplementary Information Fig.  
642 11). The discrepancy between the observed and predicted anisotropy in the eastern

643 hemisphere (Figure 4a) may result from the single crystal anisotropy being fixed with  
644 respect to pressure, thus not allowing weak enough anisotropy to match the data.

645  
646 We seek to understand the influence of the physical state with depth in the IC on the elastic  
647 tensors. As above, we neglect the temperature dependence given its small impact on elastic  
648 tensors but consider the influence of pressure. Given the limited data for FeNi alloys, we  
649 assess the effects of the pressure dependence of anisotropy using pure Fe, for which there  
650 are data at a range of pressures from *ab initio* calculations<sup>20,59</sup>. Pressure as a function of  
651 radius was extracted from the Preliminary Reference Earth Model (PREM)<sup>72</sup> where the  
652 pressure ranges from 330 GPa at the inner core boundary (ICB) to 364 GPa at the centre of  
653 the Earth. A reference point of 360 GPa and 5500 K was chosen, and the derivatives of  
654 pressure at a constant temperature were determined by a middle difference method using  
655 results from the above-mentioned studies. Elastic constants from the reference point were  
656 then interpolated using a Taylor expansion to the 2<sup>nd</sup> derivative of pressure from the  
657 reference point to the pressure at each location along the geodynamic streamline (Extended  
658 Data Fig. 9). We find that at pressures of the ICB, pure hcp Fe would show weaker anisotropy  
659 of 5% and stronger anisotropy of 7% at the centre of the IC.

660  
661 To predict travel time anomalies generated by the modelled anisotropy, we trace rays  
662 through 1D velocity model ak135 between the ICB piercing points for each of our  
663 observations using TauP<sup>73</sup>, assuming propagation along the theoretical raypath in the 1D  
664 model. We interpolate the anisotropy model to a 50×50×50 km grid spacing and interpolate  
665 the ray to increase spatial sampling. For each ray segment, we find the anisotropy at the  
666 nearest model location, measure the  $\xi$  angle of the ray segment, calculate the velocity  
667 anomaly for that  $\xi$  angle using Christoffel's equation, and calculate the resulting travel time  
668 anomaly given the length of the ray segment. We sum the travel time anomalies over the ray  
669 to find the total predicted anomaly for each path through the anisotropy model. We calculate  
670 the variance reduction between the observed and predicted travel time anomalies for the  
671 most polar data,  $\xi < 15^\circ$ , without separating hemispheres.

## 672 673 **References**

- 674 40. Tkalčić, H., Romanowicz, B. & Houy, N. Constraints on D'' structure using PKP (AB-  
675 DF), PKP (BC-DF) and PcP-P traveltimes data from broad-band records. *Geophys. J.*  
676 *Int.* **148**, 599–616 (2002).
- 677 41. Cao, A. & Romanowicz, B. Test of the innermost inner core models using broadband  
678 PKIKP travel time residuals. *Geophys. Res. Lett.* **34**, 1–5 (2007).
- 679 42. Romanowicz, B. *et al.* Seismic anisotropy in the Earth's innermost inner core: testing  
680 structural models against mineral physics predictions. *Geophys. Res. Lett.* 93–100  
681 (2015). doi:10.1002/2015GL066734
- 682 43. Tkalčić, H., Young, M., Muir, J. B., Davies, D. R. & Mattesini, M. Strong, Multi-Scale  
683 Heterogeneity in Earth's Lowermost Mantle. *Sci. Rep.* **5**, 1–8 (2015).
- 684 44. Robert Engdahl, E., Van Hilst, R. Der & Buland, R. Global teleseismic earthquake  
685 relocation with improved travel times and procedures for depth determination. *Bull.*  
686 *Seismol. Soc. Am.* **88**, 722–743 (1998).
- 687 45. Kennett, B. L. N., Engdahl, E. R. & Buland, R. Constraints on seismic velocities in the  
688 Earth from traveltimes. *Geophys. J. Int.* **122**, 108–124 (1995).

- 689 46. Kennett, B. L. N. & Gudmundsson, O. Ellipticity corrections for seismic phases.  
690 *Geophys. J. Int.* **127**, 40–48 (1996).
- 691 47. Creager, K. C. Anisotropy of the inner core from differential travel times of the  
692 phases\nPKP and PKIKP. *Nature* **356**, 309–314 (1992).
- 693 48. Yu, W. che *et al.* The inner core hemispheric boundary near 180 °W. *Phys. Earth*  
694 *planet. Int.* **272**, 1–16 (2017).
- 695 49. Romanowicz, B., Tkalčić, H. & Bréger, L. On the Origin of Complexity in PKP Travel  
696 Time Data. *Earth's Core Dyn. Struct. Rotat.* 31–44 (2003). doi:10.1029/GD031p0031
- 697 50. Romanowicz, B. & Wenk, H. R. Anisotropy in the deep Earth. *Phys. Earth planet. Int.*  
698 **269**, 58–90 (2017).
- 699 51. Deguen, R., Olson, P. & Reynolds, E. F-layer formation in the outer core with  
700 asymmetric inner core growth. *Comptes rendus - Geosci.* **346**, 101–109 (2014).
- 701 52. Lasbleis, M., Waszek, L. & Day, E. A. GrowYourIC: A Step Toward a Coherent Model of  
702 the Earth's Inner Core Seismic Structure. *Geochem. Geophys. Geosyst.* **18**, 4016–4026  
703 (2017).
- 704 53. Pozzo, M., Davies, C., Gubbins, D. & Alfè, D. Thermal and electrical conductivity of iron  
705 at Earth's core conditions. *Nature* **485**, 355–358 (2012).
- 706 54. Dobson, D. Earth's core problem. *Nature* **534**, 45 (2016).
- 707 55. Ohta, K., Kuwayama, Y., Hirose, K., Shimizu, K. & Ohishi, Y. Experimental  
708 determination of the electrical resistivity of iron at Earth's core conditions. *Nature*  
709 **534**, 95–98 (2016).
- 710 56. Tateno, S., Hirose, K., Ohishi, Y. & Tatsumi, Y. The Structure of Iron in Earth's Inner  
711 Core. *Science (80-. ).* **330**, 359–362 (2010).
- 712 57. Belonoshko, A. B. *et al.* Stabilization of body-centred cubic iron under inner-core  
713 conditions. *Nat. Geosci.* **10**, 312–316 (2017).
- 714 58. Vočadlo, L. *et al.* The stability of bcc-Fe at high pressures and temperatures with  
715 respect to tetragonal strain. *Phys. Earth planet. Int.* **170**, 52–59 (2008).
- 716 59. Vočadlo, L., Dobson, D. P. & Wood, I. G. Ab initio calculations of the elasticity of hcp-Fe  
717 as a function of temperature at inner-core pressure. *Earth Planet. Sci. Lett.* **288**, 534–  
718 538 (2009).
- 719 60. Martorell, B., Vočadlo, L., Brodholt, J. & Wood, I. G. Strong premelting effect in the  
720 elastic properties of hcp-Fe under inner-core conditions. *Science (80-. ).* **342**, 466–  
721 468 (2013).
- 722 61. Steinle-Neumann, G., Stixrude, L., Cohen, R. E. & Gülseren, O. Elasticity of iron at the  
723 temperature of the Earth's inner core. *Nature* **413**, 57–60 (2001).
- 724 62. Gannarelli, C. M. S., Alfè, D. & Gillan, M. J. The particle-in-cell model for ab initio  
725 thermodynamics: Implications for the elastic anisotropy of the Earth's inner core.  
726 *Phys. Earth planet. Int.* **139**, 243–253 (2003).
- 727 63. Gannarelli, C. M. S., Alfè, D. & Gillan, M. J. The axial ratio of hcp iron at the conditions  
728 of the Earth's inner core. *Phys. Earth planet. Int.* **152**, 67–77 (2005).
- 729 64. Antonangeli, D., Merkel, S. & Farber, D. L. Elastic anisotropy in hcp metals at high  
730 pressure and the sound wave anisotropy of the Earth's inner core. *Geophys. Res. Lett.*  
731 **33**, 1–5 (2006).
- 732 65. Wu, X., Mookherjee, M., Gu, T. & Qin, S. Elasticity and anisotropy of iron-nickel  
733 phosphides at high pressures. *Geophys. Res. Lett.* **38**, 10–13 (2011).
- 734 66. Mookherjee, M. Elasticity and anisotropy of Fe<sub>3</sub>C at high pressures. *Am. Mineral.* **96**,

- 735 1530–1536 (2011).
- 736 67. Mookherjee, M. *et al.* High-pressure behavior of iron carbide (Fe<sub>7</sub>C<sub>3</sub>) at inner core  
737 conditions. *Geophys. J. Int.* **116**, (2011).
- 738 68. Martorell, B., Wood, I. G., Brodholt, J. & Vočadlo, L. The elastic properties of hcp-  
739 Fe1 – xSixat Earth’s inner-core conditions. *Earth Planet. Sci. Lett.* **451**, 89–96 (2016).
- 740 69. Li, Y., Vočadlo, L., Alfè, D. & Brodholt, J. Mg partitioning between solid and liquid iron  
741 under the Earth’s core conditions. *Phys. Earth planet. Int.* **274**, 218–221 (2018).
- 742 70. Bergman, M. I. Measurements of electric anisotropy due to solidification texturing  
743 and the implications for the Earth’s inner core. *Nature* **389**, 60–63 (1997).
- 744 71. Stacey, F. D. & Davis, P. M. High pressure equations of state with applications to the  
745 lower mantle and core. *Phys.* **142**, 137–184 (2004).
- 746 72. Dziewonski, A. M. & Anderson, D. L. Preliminary reference Earth model. *Phys.* **25**,  
747 297–356 (1981).
- 748 73. Crotwell, H. P., Owens, T. J. & Ritsema, J. The TauP Toolkit: Flexible Seismic Travel-  
749 time and Ray-path Utilities. *Seismol. Res. Lett.* **70**, 154–160 (1999).
- 750 74. Waszek, L., Irving, J. & Deuss, A. Reconciling the hemispherical structure of Earth’s  
751 inner core with its super-rotation. *Nat. Geosci.* **4**, 264–267 (2011).
- 752 75. Wessel, P., Luis, J. F., Uieda, L., Scharroo, R., Wobbe, F., Smith, W. H. F., & Tian, D. (2019).  
753 The Generic Mapping Tools version 6. *Geochemistry, Geophysics, Geosystems*, 20, 5556–  
754 5564. <https://doi.org/10.1029/2019GC008515>
- 755 76. MarineLasbleis/GrowYourIC: v0.6 (Version v0.6). Zenodo  
756 <http://doi.org/10.5281/zenodo.4560747>
- 757

#### 758 **Data availability statement**

759 The seismic travel time measurements that support the findings of this study (Figures 1, 2,  
760 4, and Extended Data Figures 2, 3, 4, 6 and 8) are available in the supplements and at  
761 <https://doi.org/10.5281/zenodo.4721364>. Raw seismic waveform data and metadata are  
762 accessible through the facilities of IRIS Data Services, and specifically the IRIS Data  
763 Management Center. The EHB On-line Bulletins are available from the International  
764 Seismological Centre (ISC), for access to the EHB see <https://doi.org/10.31905/PY08W6S3>

765

#### 766 **Code availability statement**

767 VPSC7 code is available on request from Dr. Ricardo A. Lebensohn. Information about  
768 accessing the code can be found at: <https://public.lanl.gov/lebenso/>  
769 GrowYourIC code is available at <https://github.com/MarineLasbleis/GrowYourIC> and this  
770 work uses the v0.6 (Marine Lasbleis. (2021, February 24). MarineLasbleis/GrowYourIC:  
771 v0.6 (Version v0.6). Zenodo. <http://doi.org/10.5281/zenodo.4560747>)  
772 Plots were produced using Generic Mapping Tools (Wessel et al., 2019;  
773 <https://doi.org/10.1029/2019GC008515>).

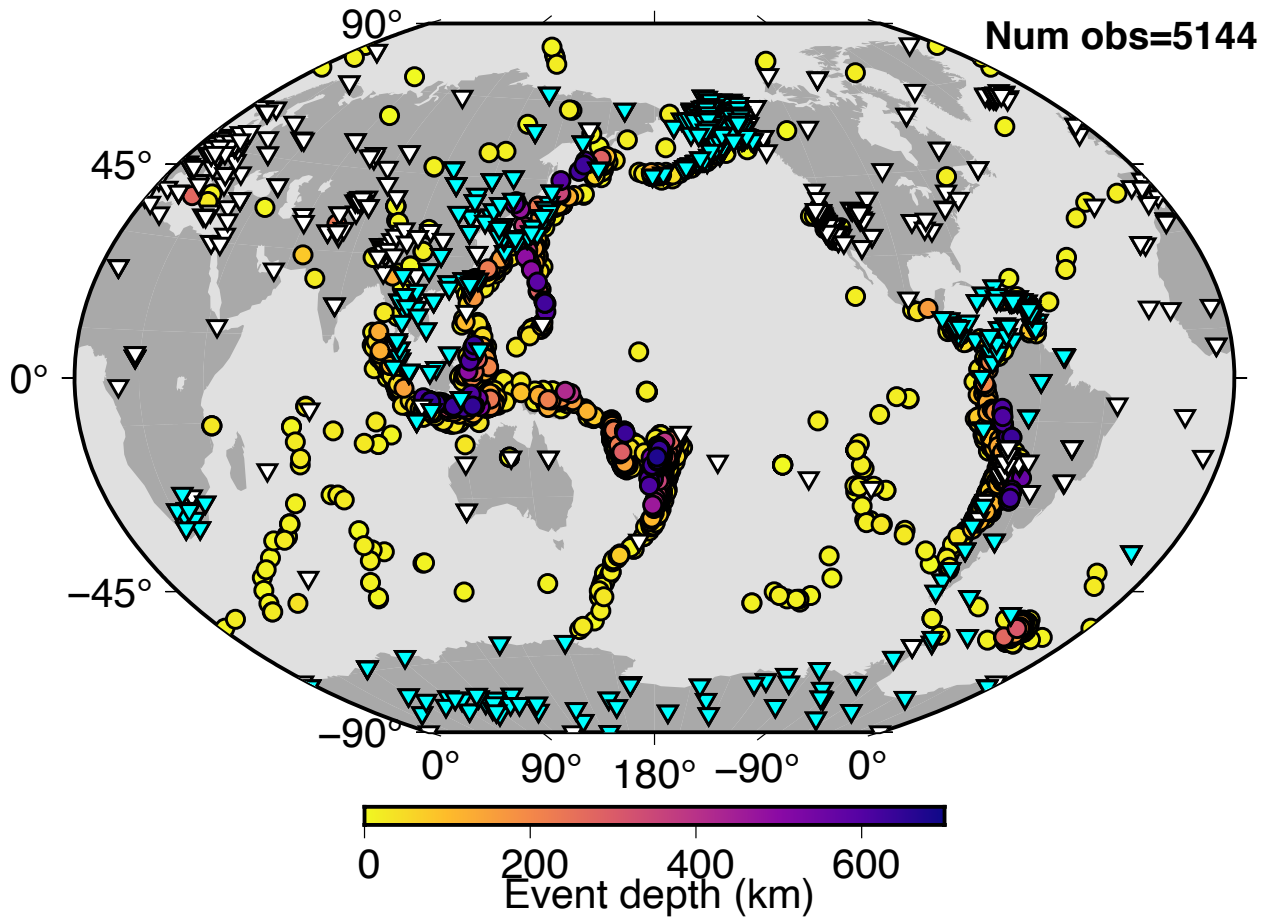
774

#### 775 **Extended Data**

##### 776 **List of Extended Data figures:**

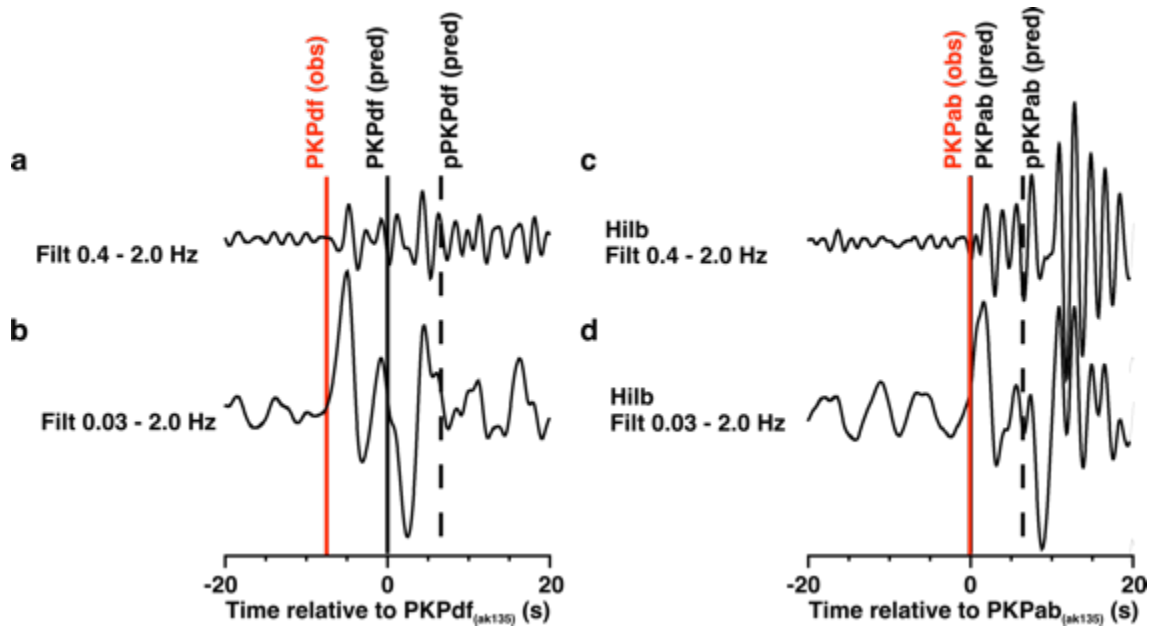
777 Extended Data Figures 1-9

778



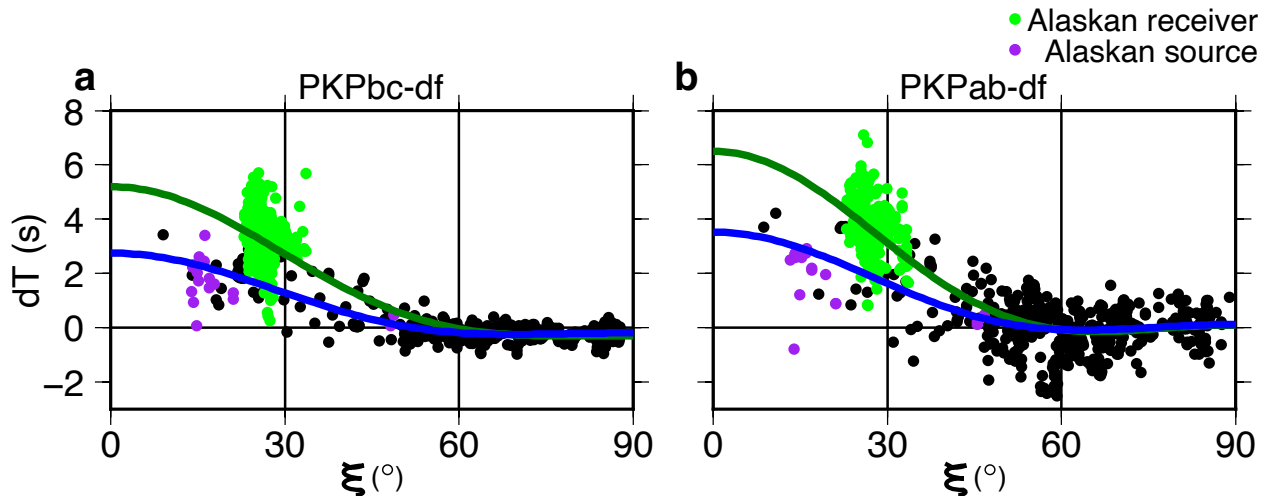
779  
780  
781  
782  
783

**Extended Data Figure 1: Distribution of sources of receivers.** Locations of sources (circles) and receivers (triangles) used in this study. Stations with newly acquired data are shown in cyan.



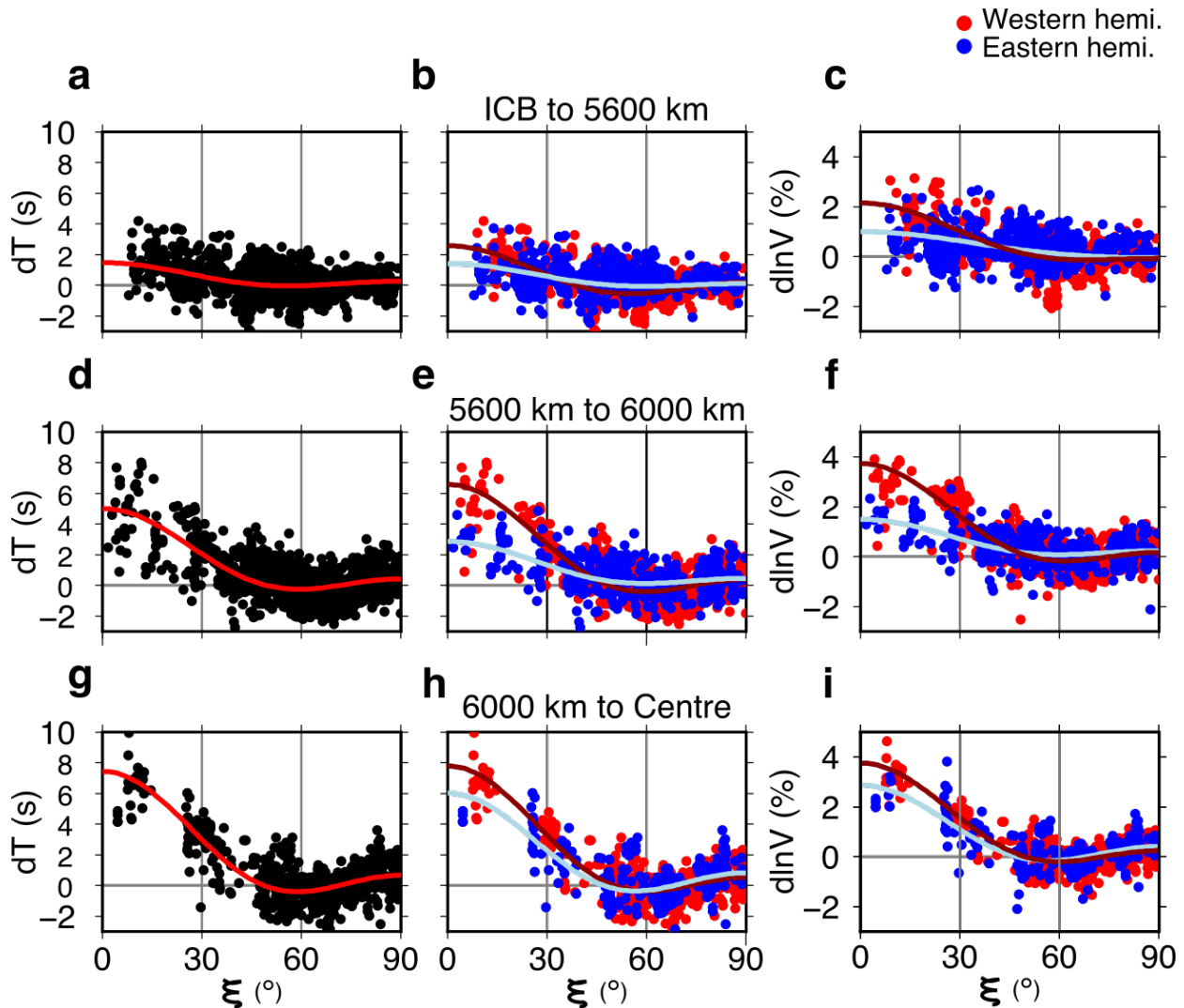
784

785 **Extended Data Figure 2: Measuring PKP differential travel times.** Example waveforms  
 786 of (left) PKPdf and (right) PKPab for a M6.0 event in Baffin Bay on 2009/07/07 observed at  
 787 station P124 in Antarctica. Waveforms are aligned on the predicted arrival time of the  
 788 respective phases. Waveforms are shown as (a-c) broadly filtered at 0.03-2 Hz, (b-d)  
 789 narrowly filtered at 0.4-2.0 Hz. In (c) and (d) waveforms have been Hilbert transformed.  
 790 Measured arrival times are shown as red lines. Predicted arrivals (in model ak135 with  
 791 ellipticity corrections) are shown by black solid and dashed lines for direct and depth phases,  
 792 respectively.  
 793



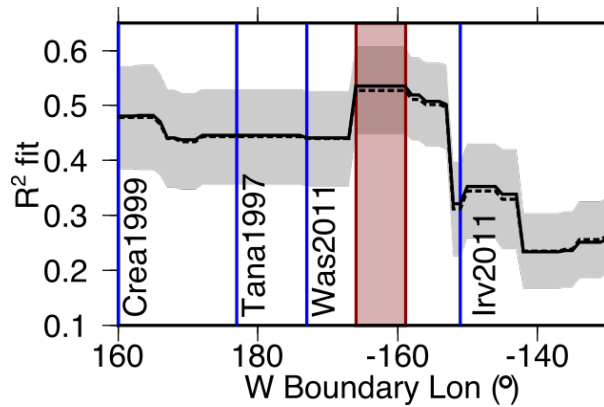
794 **Extended Data Figure 3: Differential travel time anomalies for western hemisphere**  
 795 **data turning within 450 km of the ICB with respect to model ak135, as a function of**  
 796 **angle to the rotation axis,  $\xi$ .** Travel time anomalies of (a) PKPbc-df and (b) PKPac-df phase  
 797 pairs showing that observations at stations in Alaska (green) do not fit the global pattern,  
 798 while observations from sources in Alaska (purple) do. Anisotropy curves are calculated  
 800 using equation S1, assuming constant cylindrical anisotropy through the inner core, for all  
 801 data (green curve) and all data except that recorded in Alaska (blue curve).  
 802  
 803





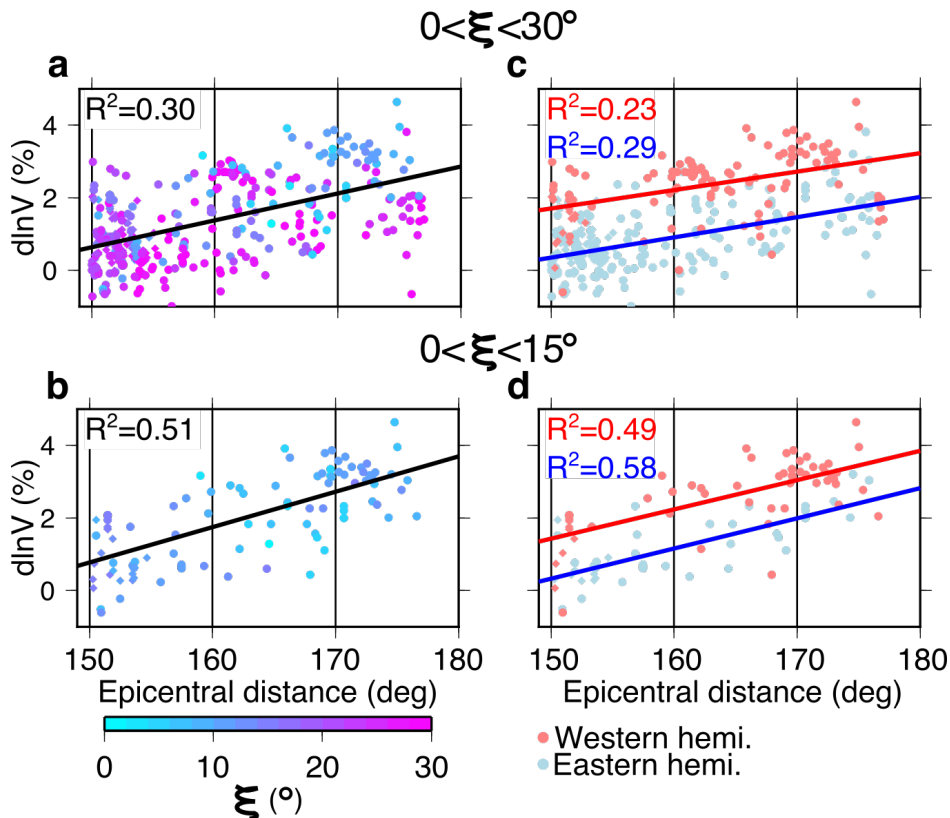
804  
805  
806  
807  
808  
809  
810  
811  
812  
813  
814

**Extended Data Figure 4: Differential travel times as a function of angle to the rotation axis,  $\xi$ , and depth.** PKPbc-df and PKPab-df travel time anomalies and effective velocity anomalies (excluding the data recorded at stations in Alaska) as a function of angle  $\xi$  with respect to the rotation axis, separated by ray turning depth for (a, b, and c) ICB to 5600 km, (d, e, and f) 5600 km to 6000 km, and (g, h, and i) 6000 km to Earth's centre. (a, d, g): All travel time anomalies. (b, e, h) Travel time anomalies split into data turning in the western (red) and eastern (blue) hemispheres. (c, f, i) Effective velocity anomalies in the IC split by hemisphere. The WH western boundary is set at  $-159^\circ$  E, and the WH eastern boundary is set at  $40^\circ$  E, as explained in Extended Data Figure 5.



815  
816  
817  
818  
819  
820  
821  
822  
823  
824  
825  
826

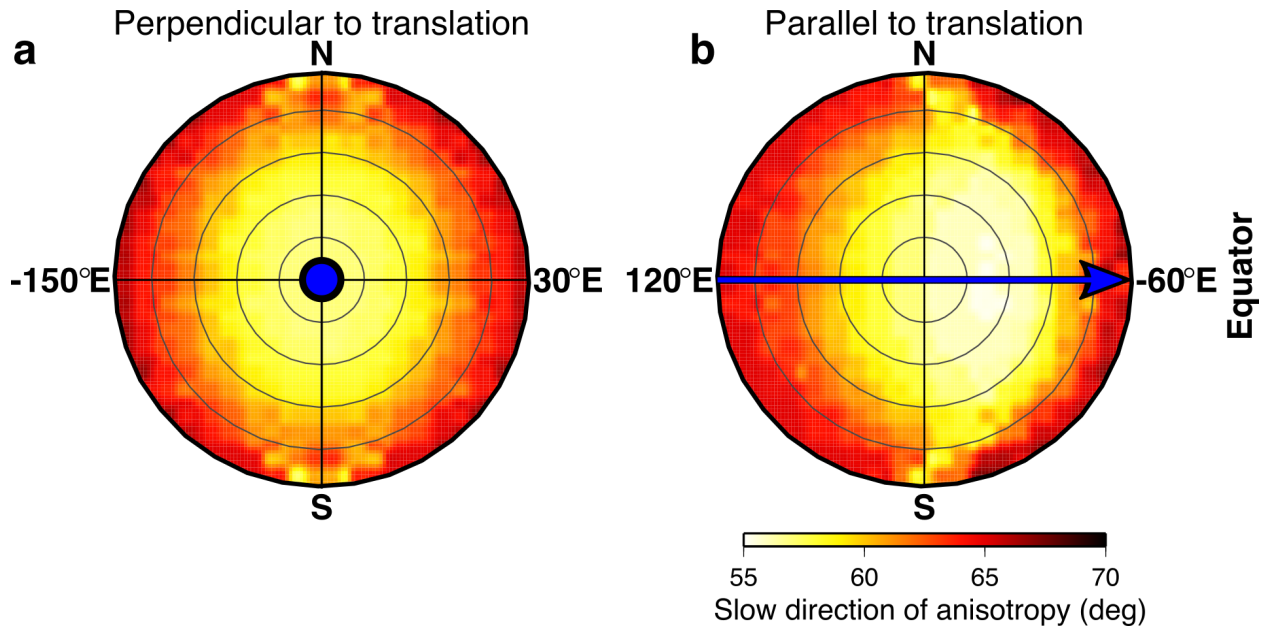
**Extended Data Figure 5: Locating the western boundary of the western hemisphere.** Best fit of WH western boundary locations calculated using polar data ( $\xi < 15^\circ$ ) and excluding data from stations in Alaska. Black solid line marks the  $R^2$  fit and red region describes the region of highest  $R^2$ , most likely containing the location of the boundary, which runs between  $-166^\circ$  E and  $-153^\circ$  E.  $R^2$  drops sharply at  $< -166^\circ$  E and  $> -153^\circ$  E. Black dashed line and grey shading show the mean and standard deviation of  $R^2$  values for 200 bootstrap resamples. The eastern boundary is fixed at  $40^\circ$  E, following the result of Irving (2016). Western boundary locations from previous studies are marked in blue: Tanaka & Hamaguchi 1997<sup>6</sup>; Creager 1999<sup>7</sup>; Waszek et al. 2011<sup>74</sup>; Irving & Deuss 2011<sup>8</sup>; while that of Lythgoe et al. 2014<sup>9</sup> plots outside of the region shown.



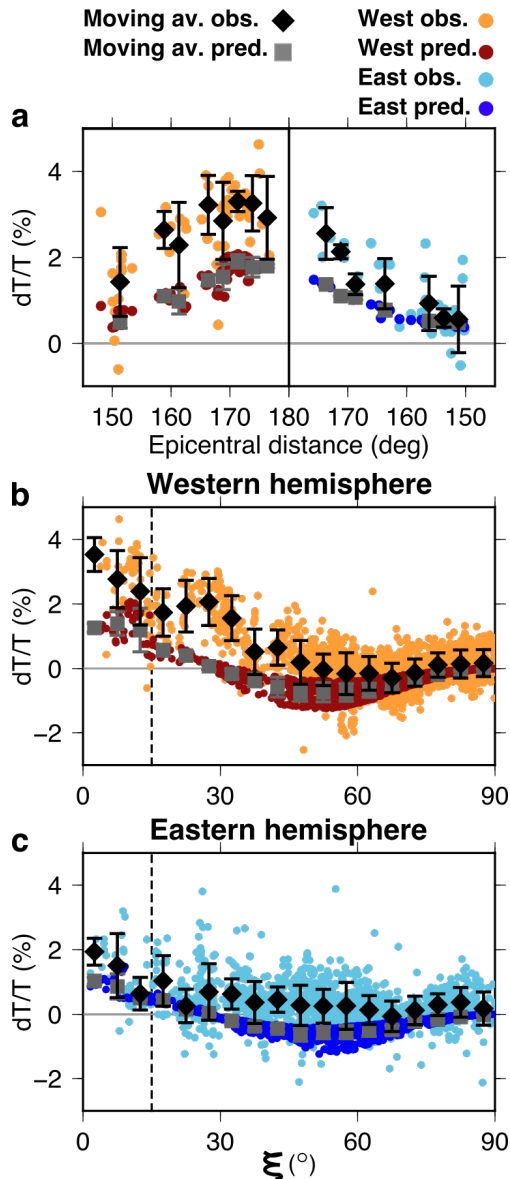
827  
828  
829

**Extended Data Figure 6: Pattern of effective velocity anomaly with depth.** Effective velocity anomaly in the IC as a function of epicentral distance for  $\xi$  in the range (a and c) 0 to

830 30°, and (b and d) 0 to 15°. Left panels show data coloured by  $\xi$ , and right panels show data  
 831 split into those turning in the eastern (blue) and western (red) hemispheres. The western  
 832 hemisphere is defined as between -159° E and 40° E, as explained in Extended Data Figure  
 833 5. The linear trend with distance, solid line, is particularly clear for the most polar data (c  
 834 and f), indicating increasing anisotropy with depth.  
 835  
 836

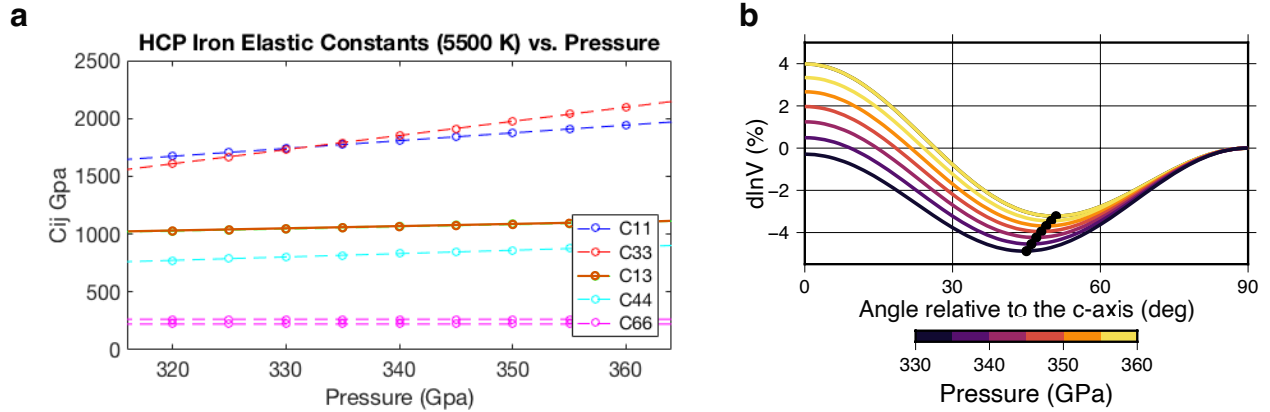


837 **Extended Data Figure 7. Distribution of slow axes of anisotropy.** Slow directions of  
 838 anisotropy in our final model (Fig. 3), measured relative to the rotation (N-S) axis in the (a)  
 839 plane perpendicular to the direction of translation (blue arrow coming out of plane), and (b)  
 840 plane parallel to the direction of translation (blue arrow) from the left (east) to right (west)  
 841 of the figure, respectively.  
 842  
 843  
 844



845  
846  
847  
848  
849  
850  
851  
852  
853  
854  
855

**Extended Data Figure 8: Predicted versus observed PKP velocity anomalies for pure hcp Fe.** Predicted (dark blue and red dots and with mean as grey squares) and observed (light blue and orange dots and with mean as black diamonds) effective velocity anomalies as a function of **(a)** epicentral distance for data with  $\xi \leq 15^\circ$ , marked by dashed line in **b** and **c**, and as a function of  $\xi$  in the **(b)** western and **(c)** eastern hemispheres. Error bars for the data show the mean and one standard deviation at  $2.5^\circ$  and  $5^\circ$  increments for panels **a**, and **b** and **c**, respectively. We use the elastic tensor for pure HCP Fe at 5500 K and 360 GPa<sup>68</sup>, an age of 0.5 Ga, and a translation rate of 0.3 radii over the age of the IC. Variance reduction for the data with  $\xi < 15^\circ$  is 73% compared to 93% for our model with Fe<sub>93.25</sub>Ni<sub>6.75</sub>.



856  
 857  
 858  
 859  
 860  
 861  
 862  
 863  
 864  
 865

**Extended Data Figure 9: The effect of pressure on anisotropy.** (a) Elastic constants for hcp iron as a function of pressure calculated from the reference position at 360 GPa and 5500 K, extrapolated using results from several calculations<sup>59,68</sup> at 5500 K and 316 GPa, and 5500 K and 360 GPa. (b) Resultant anisotropy across the pressure range of the inner core. Direction of minimum velocity anomaly is marked by black circles. The orientation of the minimum anisotropy moves towards higher  $\xi$  values (more equatorial) with increasing pressure.