Highlights

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- Globally, anisotropy is well predicted by the present-day flow field only.
- On the regional (1000 km) scale, past mantle flow is likely observable in seismic anisotropy of the lowermost mantle in key areas.
- The sensitivity of anisotropy in post-perovskite-rich rocks to the past mantle flow correlates well with the time any given pocket of mantle spends within the post-perovskite stability field.

The sensitivity of lowermost mantle anisotropy to past mantle convection

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Abstract

It is widely believed that seismic anisotropy in the lowermost mantle is caused by the flow-induced alignment of anisotropic crystals such as post-perovskite. What is unclear, however, is whether the anisotropy observations in the lowermost mantle hold information about past mantle flow, or if they only inform us about the present-day flow field. To investigate this, we compare the general and seismic anisotropy calculated using Earth-like mantle convection models where one has a time-varying flow, and another where the present-day flow is constant throughout time. To do this, we track a post-perovskite polycrystal through the flow fields and calculate texture development using the sampled strain rate and the visco-plastic self-consistent approach. As texture development also depends on the slip systems assumed, we compare the results of the flow fields under three ease-of-texturing slip system test cases. We compare the radial anisotropy parameters and the anisotropic components of the elastic tensors produced by the flow field test cases at the same location. We find, under all ease-of-texturing cases, the radial anisotropy is very similar (difference $< 2\%$) in the majority of locations and in some regions, the difference can be very large ($> 10\%$). The same is true when comparing the elastic tensors directly. Varying the ease-of-texture

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development in the crystal aggregate suggests that easier-to-texture material may hold a stronger signal from past flow than harder-to-texture material. Our results imply that broad-scale observations of seismic anisotropy such as those from seismic tomography, 1-D estimates and normal mode observations, will be mainly sensitive to present-day flow. Shear-wave splitting measurements, however, could hold information about past mantle flow. In general, mantle memory expressed in anisotropy may be dependent on path length in the post-perovskite stability field. Our work implies that, as knowledge of the exact causative mechanism of lowermost mantle anisotropy develops, we may be able to constrain both present-day and past mantle convection.

Keywords:

1. Introduction

Mantle convection has played a critical role in shaping the present-day surface environment and its evolution through time. It remains unclear, however, how mantle convection varies spatially and evolves, particularly in the lowermost mantle. Seismic anisotropy offers a unique probe into the convective patterns of the lowermost mantle and has been observed nearly ubiquitously in the enigmatic D'' region (e.g. Wookey et al., 2005; Cottaar and Romanowicz, 2013; Nowacki et al., 2010, 2011; Wolf et al., 2023a). As seismic anisotropy is widely believed to be caused by the gradual alignment of anisotropic crystals during mantle flow (Nowacki and Cottaar, 2021), it may hold information about past and present-day flow.

Several studies have shown the alignment of $MgSiO_3$ post-perovskite (ppv) crystals in D'' from flow-induced strain can cause an Earth-like anisotropy signal (e.g. Wenk et al., 2006; Walker et al., 2011; Wenk et al., 2011; Nowacki et al., 2013; Cottaar et al., 2014; Chandler et al., 2021). These studies calculate their anisotropy from the flow field in approximately the same way. Strain rates experienced along a path through a mantle flow field are measured and used to model texture development in a polycrystal of a particular composition such as $MgSiO_3$ post-perovskite (Hirose et al., 2015) or periclase (Park et al., 2022). This texture is then combined with single-crystal anisotropy elastic tensors to estimate the elastic tensor for the whole polycrystal at the end of the pathline. This modelling approach has been a powerful tool to investigate the cause and controls of anisotropy in the lowermost mantle. Some have used this to study anisotropy in local regions where subducting material is impinging on the core-mantle boundary (Wenk et al., 2011; Cottaar et al., 2014; McNamara et al., 2002, 2003). Others aimed to produce a map of radial seismic anisotropy for comparison with tomographic observations (Walker et al., 2011) and explored the effects of topotaxy (Walker et al., 2018; Chandler et al., 2021). Other studies have predicted the shear-wave splitting (Silver and Chan, 1991) signal from these ppv textures to compare with real observations(Nowacki et al., 2013; Nowacki and Cottaar, 2021). What remains an open question, however, is to what extent seismic anisotropy in the lowermost mantle holds information about past mantle flow, and it is this question we investigate here. In line with the previous studies, we assume lowermost mantle anisotropy is caused by the alignment of ppv crystals but other mechanisms such as melt inclusions or layering can also cause seismic anisotropy.

Constraining the influence of past flow on present-day anisotropy will allow us to better use anisotropy to constrain the Earth's mantle convection. If anisotropy is mainly impacted by present-day flow, then current flow may one day be inverted from seismic tomography. On the other hand, if anisotropy is sensitive to past flow, then observations of anisotropy may offer unique sensitivity to past mantle convection. To infer the sensitivity of seismic anisotropy to past flow, we compare the anisotropy in D$''$ calculated with two flow field test cases. In one case, we use the full dynamic flow field history where the flow is allowed to vary with time. In the other case, the present-day flow snapshot is kept constant throughout time. Note both flow fields have the same present-day mantle convection pattern. Previous studies differ in how the texture was generated from the flow fields. Wenk et al. (2011) traced particles to keep track of strain rates experienced along a pathline during forward modelling of the scenario in question such as a subducting slab impinging onto the core-mantle boundary. This approach has the advantage of a higher flow field resolution than a global flow inversion used by other studies (Walker et al., 2011). When tracing particles during forward modelling the final locations of the particles can not be controlled, leaving regions in the model unsampled. In contrast, when tracing the particles backwards in time the final location can be defined, but previously this has required a time-invariant flow field (Walker et al., 2011). In our approach, we get the best of both of these approaches; we use modern mantle convection simulations to create high-resolution global flow fields with Earth-like parameters (Davies et al., 2012a) and have control over where we measure the anisotropy by tracing particles back in time. For this study, a sufficiently Earth-like mantle convection field will have realistic flow velocities, flow velocity gradients and temperatures in the lower mantle. As the model we use has a surface plate motion model, a reasonable viscosity profile and a reasonable core temperature, we argue this model is sufficient for this study.

In line with previous studies (Walker et al., 2011; Nowacki et al., 2010; Walker et al., 2018), we assume anisotropy is created in D″ by the crystallographic alignment of $MgSiO_3$ post-perovskite as several studies have suggested its presence and anisotropic nature (Merkel et al., 2007; Miyagi et al., 2010; Hirose et al., 2015; Kuwayama et al., 2022). As anisotropy is affected by both the strain rates sampled along the particle path and the slip systems of the material being textured, the sensitivity of anisotropy to past flow is also controlled by these mechanisms. Therefore, we not only vary the flow field but also the slip systems of post-perovskite. We do this by varying the ease-of-texturing of post-perovskite to infer its effect on the 'memory' of the material.

Our results provide a conservative estimate of the extent to which past flow is observable in seismic anisotropy. We find that global, present-day mantle convection dominates anisotropic signal in D″, but in many regions past mantle flow is recorded. Therefore, localised observations such as shear-wave splitting (Silver and Chan, 1991) and body wave waveform studies may be able to discriminate between models of mantle convection history. Broader scale observations such as from seismic tomography will mostly be sensitive to present-day flow and could be used to invert for mantle flow.

2. Methods

This study aims to test the sensitivity of present-day anisotropy (the full elastic tensor) to past mantle flow in D″ assuming it is caused by texturing of post-perovskite-rich material. To test the memory of seismic anisotropy, we use a fully-dynamic model of mantle convection and create an Earth-like mantle flow field history (Section 2.1). From this, we create two flow field cases: one where mantle flow changes with time and the other where the flow at the present day is kept constant through time. Note the flowfield we use as the 'present-day' flowfield is that at the end of the mantle convection simulation. As anisotropy is also sensitive to slip systems of the material being textured, the impact of past flow on present-day anisotropy may also be affected by these slip systems. Therefore, we also vary the slip systems of post-perovskite and create three ease-of-texturing test cases. The resulting anisotropy is analysed to determine the effect of past flow on present-day anisotropy and whether an easily textured material dampens or enhances this effect.

2.1. Mantle convection model

We use TERRA (Baumgardner, 1985; Bunge et al., 1997; Davies et al., 2012b; Panton et al., 2023), a three-dimensional mantle convection code, to solve the governing equations with the Boussinesq approximation and assume an incompressible mantle (McKenzie et al., 1974). Driving parameters for the simulation are listed in Table 1. The model domain is discretised into 129 radial layers with an average radial spacing of $\sim$22.5 km. In each of these layers, we form a grid by projecting a regular icosahedron projected onto a sphere. The grid is equally discretised at each layer resulting in an average lateral grid spacing of $\sim$16 km at the core-mantle-boundary (CMB) and $\sim$30 km at the surface. The surface boundary is isothermal (300 K) and has lateral velocities applied from plate motion reconstructions since the beginning of the Neoproterozoic (Merdith et al., 2020). As such, the model features hot ridges, plumes and cool subduction zones where surface material is recycled into the mantle. The CMB boundary is also isothermal (3000 K) and is free-slip. The CMB boundary temperature is lower than current seismological and mineral physics estimates for CMB temperature (Kim et al., 2020; Lobanov et al., 2021; Deschamps and Cobden, 2022) due to the incompressible equation of state that we use. A theoretical adiabat is added to account for compressibility when using the temperature field to calculate post-perovskite stability. The adiabat is calculated using a linear increase in temperature in the upper mantle (until 660 km depth) and then fit to a quadratic increase in the lower mantle.

As well as heating from the bottom boundary, the model is internally heated via the decay of radioactive isotopes, concentrations of which are tracked using tracer particles. A depth and composition-dependent solidus controls melting (van Heck et al., 2016), which occurs at ridges and plume heads, causing heat-producing elements to be fractionated. We employ a depth-dependent viscosity with a $\sim$100 km thick lithosphere which is 100 times more viscous than the reference. Note that there is no temperature dependence in the viscosity. Upper mantle viscosity is equal to the reference and a 30-fold jump in viscosity occurs across the bottom of the mantle transition zone at 660 km depth (van Keken and Ballentine, 1998). Viscosity

Table 1: Driving parameters for the simulation. Reference viscosity is equal to the viscosity of the upper mantle.

Symbol	**Parameter**	**Value**	**Unit**
T_S	Surface temperature	300	K
T_{CMB}	CMB temperature	3000	K
η_0	Reference Viscosity	3×10^{21}	Pa s
ρ_0	Reference Density	4500	kg m^{-3}
k	Thermal conductivity	4	W m^{-1} K^{-1}
α	Thermal expansivity	2.5×10^{-5}	K^{-1}
C_p	Specific heat capacity	1100	J kg^{-1} K^{-1}

drops off in the bottom 150 km of the mantle to simulate the drop in viscosity across the post-perovskite transitions which occur there (Li et al., 2014).

For the purposes of our study, it is important that we have features in our simulated mantle which are of a similar scale to those found in Earth. The mixed heating Rayleigh number for the simulation is 8.8×10^8, which is in line with estimates for Earth's mantle (Bunge et al., 1997). In our simulation, the mantle cools at a rate of 70 K Gyr^{-1} which is in good agreement with estimates of Earth's mantle cooling rate (Labrosse and Jaupart, 2007). At the present day, the surface heat flux in the model is 40.5 TW, only slightly higher than current estimates for Earth's mantle heat flux (Davies and Davies, 2010). All of this gives us confidence that our simulation is thermally behaving in a similar way to the Earth and so should produce thermal features which are recognisably Earth-like. Figure 1 shows the temperature and radial flow fields in the lower mantle as well as the predicted post-perovskite thickness. Although Earth-like, it is unlikely that this model will perfectly capture the finest properties of mantle convection. As we are comparing the flow field models to each other, a mantle convection model with the properties described above is suitable for our purposes.

2.2. Predicting anisotropy from flow fields

We calculate anisotropy in the lowermost mantle from the flow fields in a similar way to Walker et al. (2011) with the addition of allowing for a time-varying flow field. We give a brief summary of the methodology and explain the addition of a time-varying flow field.

The flow field is taken from the mantle convection model outlined in Section 2.1. For each point of interest, we trace a particle backwards through

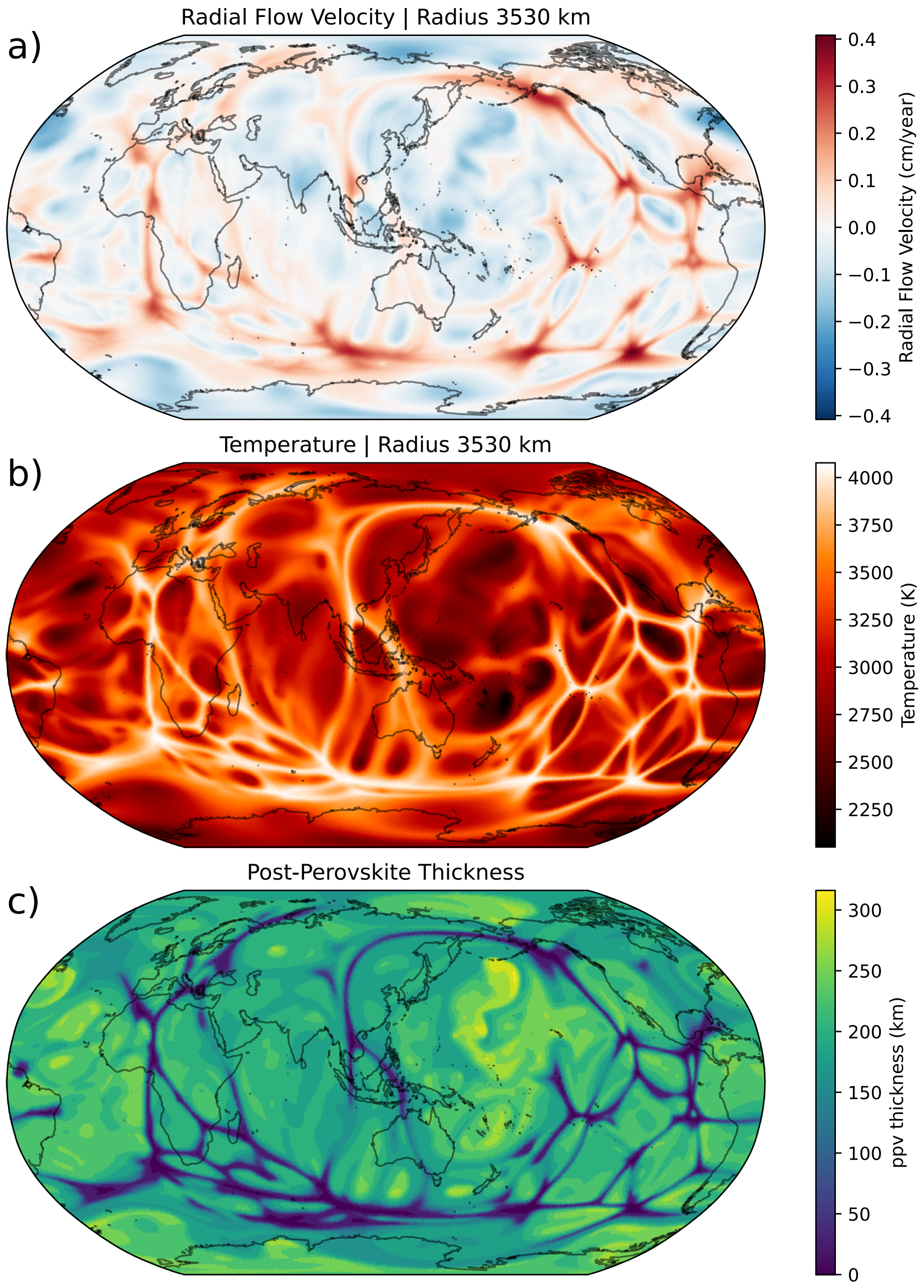

Figure 1: Present-day (end of mantle convection simulation, 0 Ma) summary snapshot of the mantle convection model used in this study showing (a) radial flow velocity, (b) temperature (with adiabat added), and (c) post-perovskite thickness. Notice that upwelling, high-temperature regions also have very thin or no post-perovskite and mark areas of convergent flow.

time in the flow field using 4th-order Runge-Kutta integration with a constant time step of 25,000 years. This timestep gives very similar results to that of a time step of 5000 years. Note that for a time-constant flow field, we will be tracing streamlines through the final flow field snapshot whereas in the time-varying case, we will be tracing path lines using multiple flow field time snapshots. The particle continues to be traced back through time until it reaches the phase transition between post-perovskite and perovskite. Whether there is a phase transition at that location is determined using the pressure and temperature at the location and a Clapeyron slope of 7.0×10^{-3} MPa K^{-1} and pressure intercept of 105.7 GPa. The predicted post-perovskite thickness in the model is shown in Figure 1c. The pressure is calculated using the density from 1-D Earth model ak135 (Kennett et al., 1995) and temperature from the model's temperature field.

At each step along the path, we extract the velocity gradient tensor and use this to calculate the textural evolution of a post-perovskite polycrystal. The evolution of the polycrystal needs to model the rotation and alignment of all the crystals in the aggregate. Rather than describing all interaction between adjacent crystals, we use the visco-plastic self-consistent (VPSC) approach (Lebensohn and Tomé, 1993). VPSC represents adjacent grain interactions by embedding each grain in a homogeneous medium which represents the other grains in the polycrystal. For the velocity gradients to be translated to the rotation and deformation of the polycrystal, we assume material properties of post-perovskite in the form of slip system activities. The slip systems impact the texture development along the path and also the final anisotropy. Therefore, to investigate the influence of past flow on anisotropy, we need to investigate the effect of different slip systems. This is done by varying the slip system activities such that the ease of texture development is varied.

To calculate the texture, we use 500 post-perovskite crystals which are randomly oriented at the beginning of each path. At the end of the pathline, the crystals have been rotated. From these orientations, we calculate the elastic tensor of the polycrystal by computing the Voigt-Reuss-Hill average over all crystal orientations and the single-crystal elastic tensor. Here, we use single-crystal properties found by Stackhouse et al. (2005) and Stackhouse and Brodholt (2007) interpolated in pressure-temperature space with the approach described by Ammann et al. (2010) using pressure derivatives from Wentzcovitch et al. (2006). We assume the effect of different pressure and temperature on the single-crystal anisotropy is small relative to other actors in the model affecting the anisotropy such as the flowfield or slip system activities in line with previous studies (Walker et al., 2011). From this elastic tensor, the radial anisotropy parameters $\xi = V_{SH}^2/V_{SV}^2$ and $\phi = V_{PV}^2/V_{PH}^2$ can be calculated and compared. Alternatively, the elastic tensors between the time-constant and time-varying cases can be compared directly. This approach means the final anisotropy is an accumulation of texturing along the whole path but, crucially, the importance of past texturing is uncertain.

To allow the flow field to vary with time, we take flow field snapshots at 10 Ma intervals and linearly interpolate between them for intervening times. We use 4th-order Runge-Kutta integration to find the new location of the particle based on the flow velocities at its current location and time. The spatial gradient of the flow field is calculated and a new particle location is found using the time-interpolated flow field. This process is repeated until the particle reaches the phase transition from post-perovskite to perovskite. Note that because the particle is being traced until it hits this phase transition, the time each particle travels will be very different with the longest paths have the particles travelling for 120 Ma. If the final location of the particle is not in the post-perovskite stability field, no anisotropy is calculated and plotted in grey later in Section 3.

2.3. Test setup

To explore the dependence of present-day anisotropy on past mantle flow, we perform the texture development calculation described above on an equal-area grid approximately 50 km above the core-mantle boundary. The grid was created using the healpix algorithm (Gorski et al., 2005). The resulting anisotropy, and therefore its sensitivity to past flow, is controlled both by the strain rates sampled along the path and the slip system activities of the material being textured.

We use the flow field from the model described in Section 2.1 and perform the analysis in two cases. In the first case, the flow field is time-constant and we trace particles as streamlines through the present-day flow field. In the other case, the flow field is time-varying and we trace the particles as path lines through the whole dynamic history. We use the present-day flow as the constant-through-time case because it is common for seismic anisotropy observations to be interpreted in the context of present-day flow only. To predict elastic anisotropy, we need to assume the ppv slip system activities which can impact the final anisotropy and therefore the impact of past flow on such anisotropy. We use three slip system cases where we vary how easily

	Ease of texture development		
Slip System	Hard	Medium	Easy
[100](110)	1	1	1
[010](001)	1	1	1
[001](100)	3	5	10
[010](100)	3	5	10
[001]{110}	3	5	10
⟨110⟩(001)	2	2	2
⟨110⟩{110}	3	5	10

Table 2: Table showing the relative critical resolved shear stress (CRSS) coefficients used in VPSC for the different ease-of-texture cases. Each of these accommodates strain along the 001 plane as observed by Miyagi et al. (2010). The different models represent different scenarios for how easily texture develops in the post-perovskite polycrystal. Slip systems with infinite CRSS cannot accommodate strain.

the ppv aggregate develops texture and allow the texture to develop on the 001 plane. The slip systems activities are listed in Table 2.

We first analyse differences between the flow fields using summary statistics of the paths such as path length and path tortuosity. This shows the difference a time-varying flow field can have on the paths and the sampled strain rates. Then, we compare the anisotropy outputs between the flow fields for each of the ease-of-texturing scenarios. We do this both in terms of radial anisotropy parameters ξ and ϕ and the anisotropic components of the elastic tensor to infer the relative impacts on different observations. At present, lower mantle radial anisotropy is still challenging to constrain accurately with seismic tomography (Chang et al., 2014). Future tomography models may provide useful broad-scale observations of lowermost mantle anisotropy, therefore it is important to know if these observations are impacted by past mantle flow. Before calculating the misfit between elastic tensors, we remove the isotropic component (Browaeys and Chevrot, 2004) as we only want to compare the difference in anisotropy. We calculate the misfit with

$$\text{misfit} = \sqrt{\sum_{ij} (C_{ij}^{tv} - C_{ij}^{tc})^2}, \quad (1)$$

where C_{ij}^{tv} is the elastic tensor produced by the time-varying flow field and C_{ij}^{tc} is the time-constant flow field. We use Voigt matrix representations of the elastic tensors (a 6×6 matrix) where ij are the indices of the matrix notation we use. From the misfits for each texturing scenario, we can infer the influence of past flow on present-day anisotropy, the impact of ease-of-texturing, and what controls the size of the misfit.

3. Results and interpretation

In this section, we first compare the path length and path tortuosity to analyse the effect a time-varying flow field can have on particle paths. Then, for each of the ease-of-texturing scenarios, we compare the anisotropy between the flow field scenarios. To compare the anisotropy, we analyse the difference between the anisotropic components of the elastic tensors to infer the impact of past flow on measurements that are sensitive to different parts of the elastic tensor such as shear-wave splitting. Then, we use the radial seismic anisotropy values to infer the sensitivity of seismic tomography observations to past mantle flow.

3.1. Path differences

The paths taken by particles through a flow field have a direct impact on the anisotropy at the end of the path. If the path line through a time-varying flow field is different to a streamline through the present-day flowfield, it motivates exploring whether the anisotropy is also different. Here, we explore how different, if at all, the path properties are between the different flow field cases. The properties we compare are the total path length and the tortuosity. Tortuosity is defined as a ratio between the path length and the linear distance between the start and end points of the path. Essentially it is a measure of how non-linear the path is. Figure 2 shows the path length in the time-constant and time-varying cases as well as their difference. It shows, for the majority of locations, the path lengths are very similar (<500 km). In some regions, a time-varying flow field can lead to significantly longer or shorter paths with some differences going up to 6000 km. Analysing the tortuosity tells a similar story (Figure 3) with the majority of locations showing negligible differences and some locations having very large differences. The difference in tortuosity shows that not only are the paths longer or shorter but also that the linearity of the paths changes. This comparison shows that a time-varying flow field can significantly affect the paths taken by particles. In the next section, we present the differences in general and seismic anisotropy for the different flow fields.

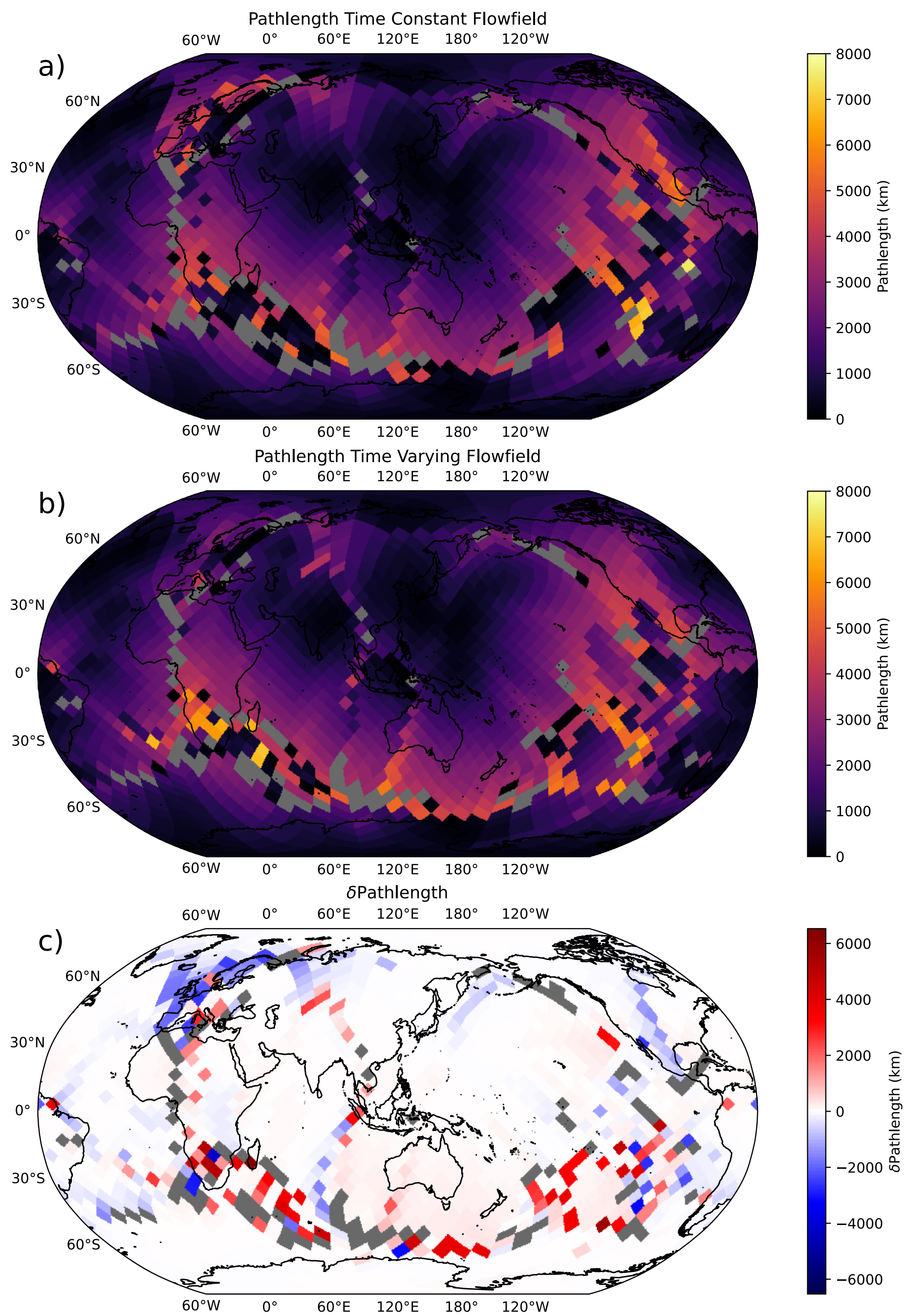

Figure 2: Maps comparing the path lengths in the ppv stability field ending at each location at 3530 km radius for (a) the time-constant flow field, (b) time-varying flow field and (c) the difference in the length of paths.

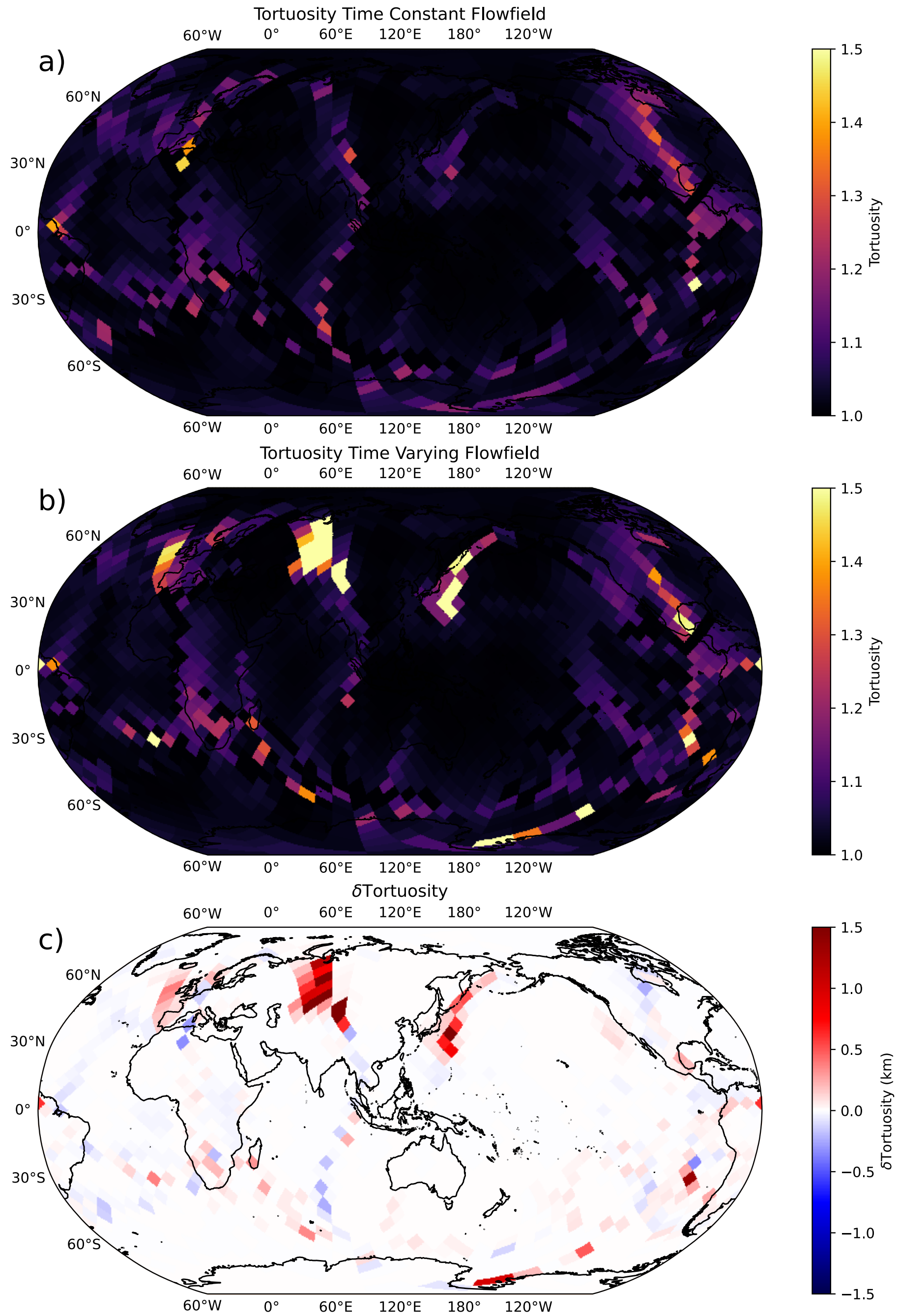

Figure 3: Maps comparing the tortuosity in the ppv stability field ending at each location at 3530 km radius for (a) the time-constant flow field, (b) time-varying flow field and (c) the difference in the length of paths.

3.2. Anisotropy comparison

As shown, a time-varying flow field can significantly alter the paths of particles. To predict the anisotropy from these paths, we need to assume the slip system activities of ppv which may also impact the sensitivity of such anisotropy to past flow. In this section, we investigate the spatial distribution of the differences in general and radial anisotropy of the flow fields for each of the ease-of-texturing models.

3.2.1. General anisotropy

As described in Section 2.3, we compare the general anisotropy between the flow field test cases by taking the misfit between the elastic tensors at the same locations. Figure 4 shows a map of the misfits for the three ease-of-texturing cases. In the majority of locations, for all ease-of-texturing cases, the difference is small (< 50 GPa), however, in some local regions, there are very large differences (> 300 GPa). For context, a 50 GPa difference is equivalent to the misfit between two ppv crystals with properties from Stackhouse et al. (2005) where one is rotated by less than 15 ° around the b axis. A 300 GPa difference is equivalent to comparing the two ppv crystals where one is rotated by approximately 45 °.

Visual inspection of Figures 2, 3, and 4 suggests a relationship between the differential path measures earlier (path length and tortuosity) and general anisotropy misfit. We quantitatively investigate this possible relation by plotting the misfit and the path parameters and calculating the Spearman correlation coefficient (Figure 5). We also investigate the possible contribution of temperature at the end of the path and the influence of past flow.

We find a positive correlation between the difference in path length and the misfit values (0.54). The same is true for the difference in tortuosity (0.55). This reinforces our suggestion that the differences in the paths contribute to the differences in anisotropy between the flow fields. There is also a weak but positive correlation between the misfits and temperature (0.27) suggesting some relationship between hotter regions and the impact of past flow exists, but it is not as important as differences in path properties. We also test how predictable the differential anisotropy between time-varying and time-constant flow fields is using only the path length (Figure 5d). We find a positive correlation (0.49) between path length and misfit suggesting the longer paths tend to also be more sensitive to past flow.

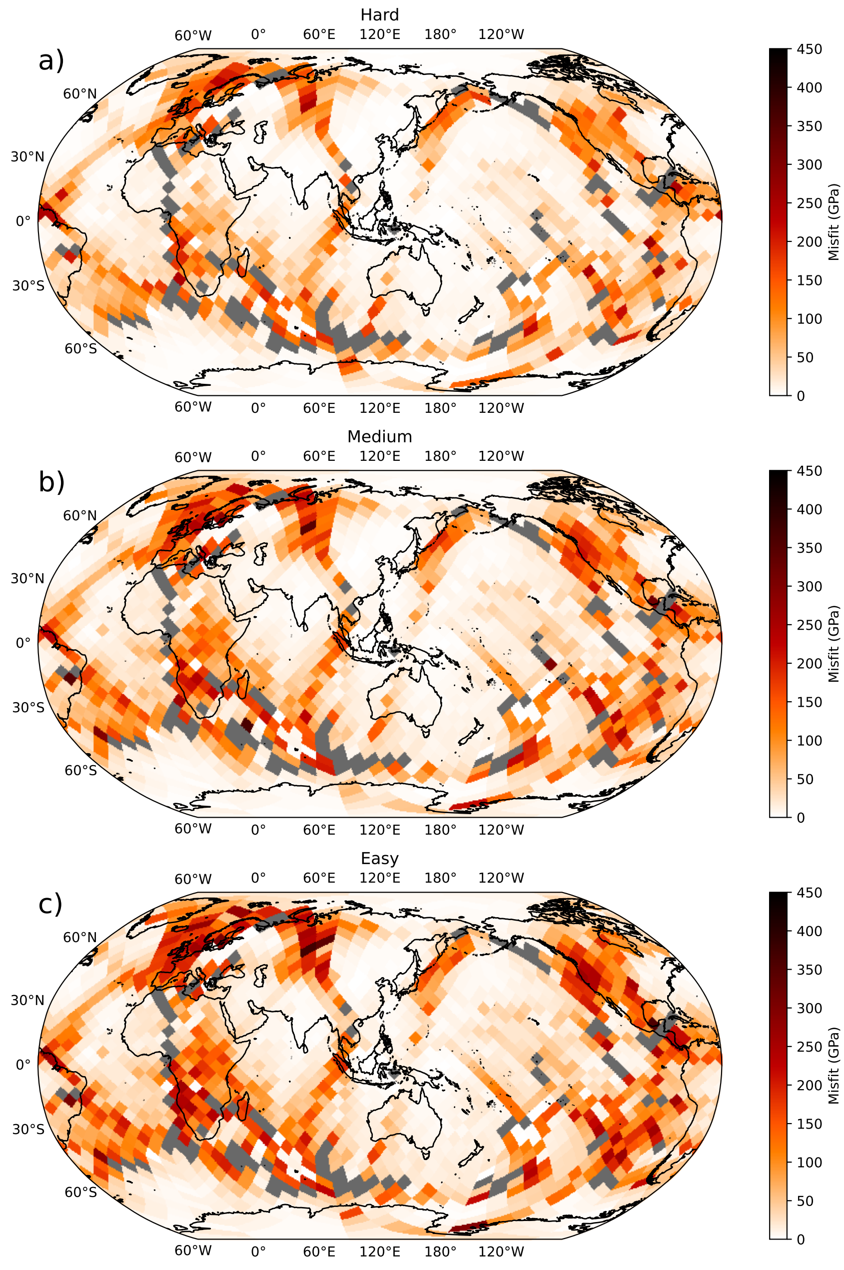

Figure 4: Maps showing the distribution of misfit values between the elastic tensors calculated with a time-constant and with a time-varying flow field for the three ease-of-texturing scenarios at 3530 km radius. The regions in grey show where post-perovskite is not stable. Notice the easier-to-texture case has more locations with a very high misfit (>350).

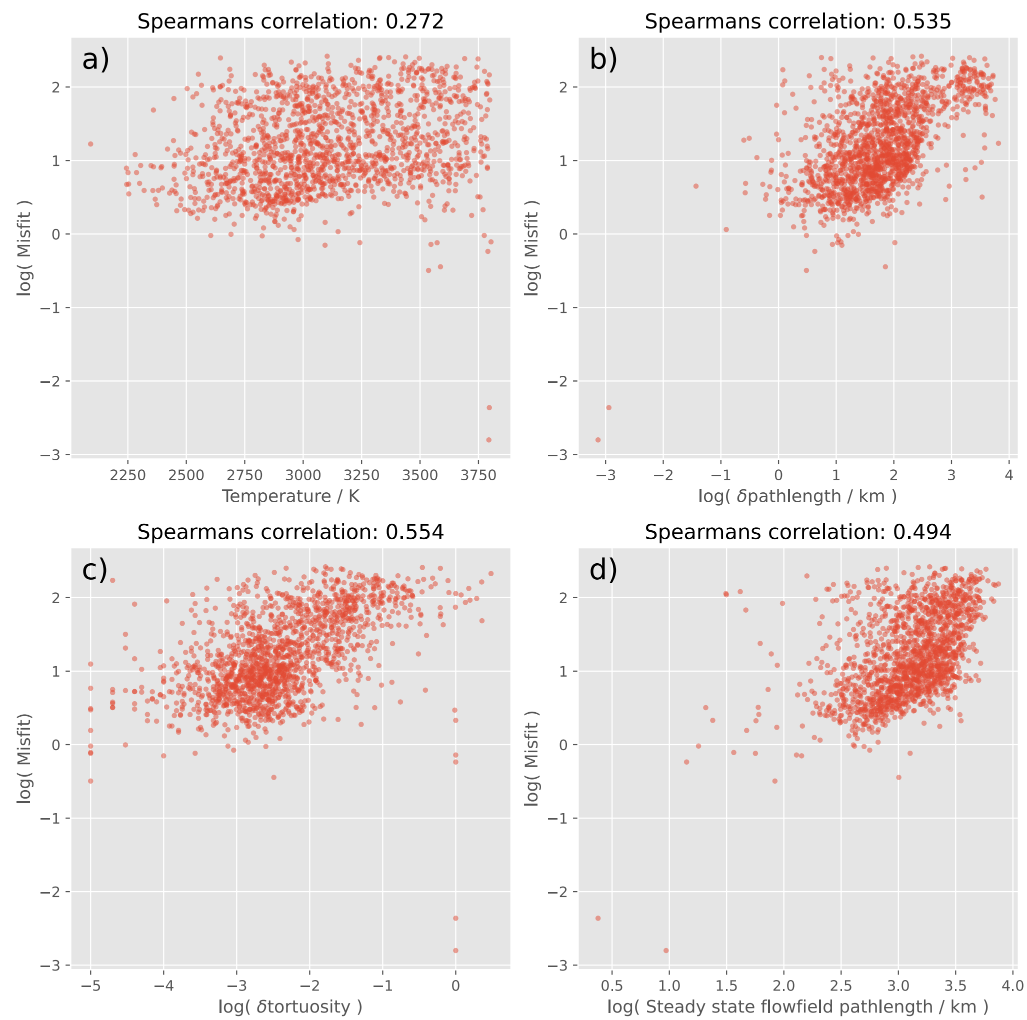

Figure 5: Scatter plots of the misfit between elastic tensors and parameters which may impact how much past flow affects the anisotropy at a location, for the hard-to-texture case. Panel (a) compares misfit with the temperature, (b) with the difference in path length, (c) with the difference in tortuosity, and (d) with the path length in the time-constant model. In panels (b), (c), and (d) we take the logarithm of the model parameters. The Spearman correlation value is shown in the title.

3.2.2. Radial anisotropy

In addition to comparing the elastic tensors directly, we compare the radial seismic anisotropy predicted by the flow fields for the different ease-of-texturing cases. We do this to test whether observations of radial anisotropy such as those derived from seismic tomography hold information about past flow. A map of the difference in radial anisotropy parameter ξ between the flow models is shown in Figure 6 for each of the texturing cases. The predicted S and P wave radial anisotropy for the flow field cases and their differences for each ease-of-texturing case are shown in supplementary figures A.10 to A.15. As with the general anisotropy, the majority of locations have small differences ($< 1\%$), however, in some local regions, there are very large differences ($> 10\%$). We define the percentage anisotropy as (ξ - 1)%. As with our interpretation of the general anisotropy, we hypothesise the large differences are caused by differences in the particle paths (Figure 2). The distribution of the difference in ϕ tells a similar story (see supplementary Figure A.9).

The distributions of radial anisotropy for the flow fields are very similar (Figure 7). Furthermore, the mean values are very similar where ξhas a difference of 0.14 % and ϕ a difference of 0.03 % for the hard-to-texture case (Table 2). The distributions for the other ease of texturing cases show the same pattern. Both the mean ξ (~ 2.8 %) and ϕ (~ -7.3 %) indicate horizontally polarised P and S waves travel faster in D$''$ in our models. Because of the free slip boundary condition, we expect flow near the core-mantle-boundary to be near horizontal. This then textures the post-perovskite aggregate to be broadly horizontal also for the 001 slip system and therefore, on average, to cause horizontally polarised waves to travel faster.

The similar mean radial anisotropy in the models, in the context of the spatial similarity also, suggests that in most of the lowermost mantle, radial seismic anisotropy measurements are sensitive to present-day flow only.

3.3. The effect of ease-of-texturing on past flow influence

In addition to exploring the effects of particle path differences, we explore how the ease of texturing of the crystal aggregate affects the impact of past flow on present-day anisotropy. We do this by comparing the distributions of the elastic tensor misfit (Section 3.2.1) between the ease-of-texturing cases.

In Figure 8a, we show the distribution of all the misfit values for each of the three texturing cases. We observe the easy-to-texture case having larger misfits than the hard-to-texture case suggesting sensitivity to time variations

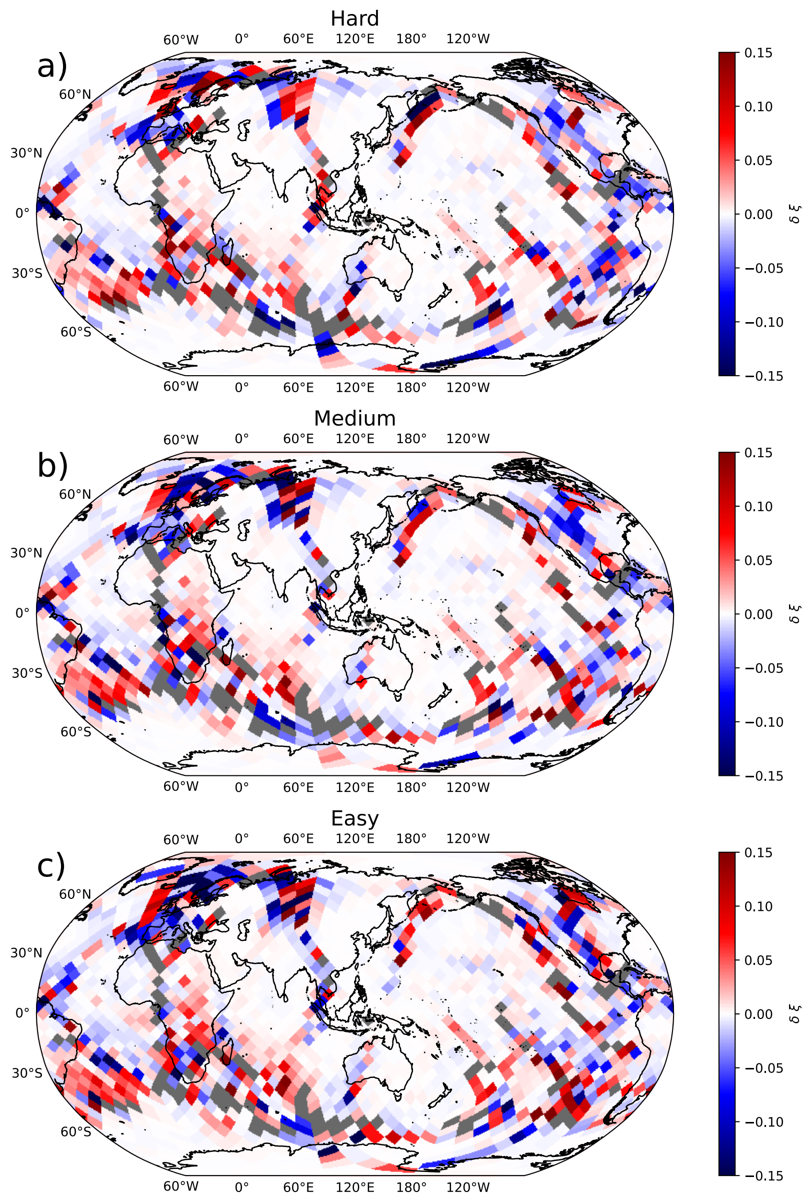

Figure 6: Maps showing the difference between shear-wave radial anisotropy at 3530 km radius (50 km above the core–mantle boundary) for the different flow fields with the different ease-of-texturing cases. The regions in grey show where post-perovskite is not predicted to be stable at this depth.

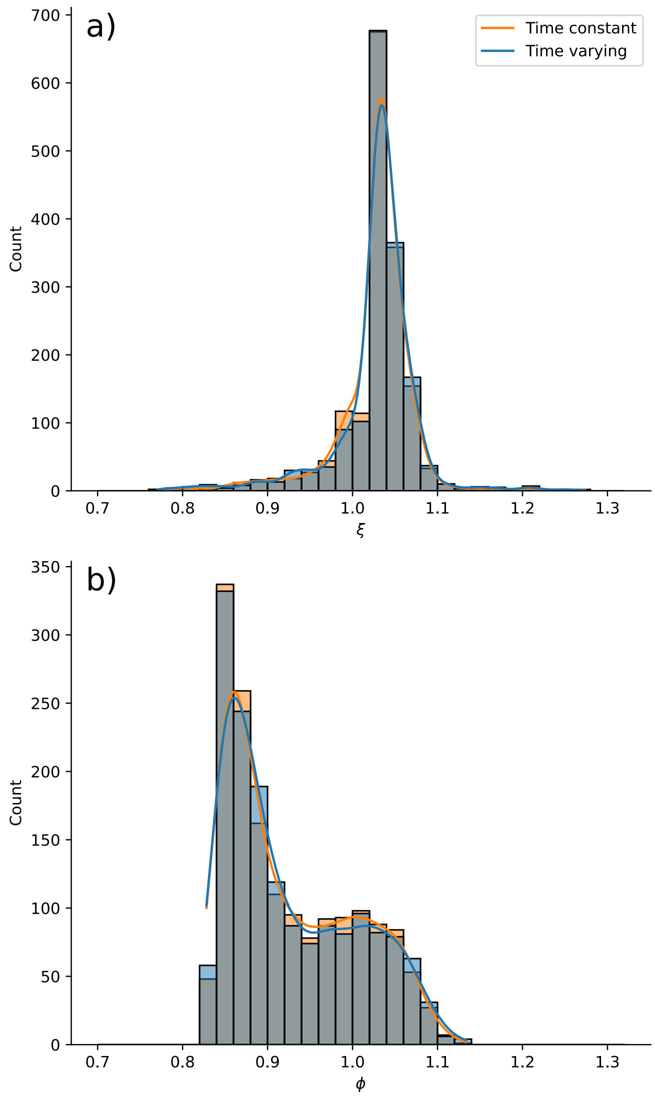

Figure 7: Histograms of S-wave (a) and P-wave (b) radial anisotropy coloured by whether the flow field was time-dependent or -independent. Here we can see very little difference between the two for either P- or S-wave radial anisotropy. The lines show the kernel density estimates for the distribution of radial anisotropy for the time-varying and time-constant cases. Note this is for the hard-to-texture case and other texturing cases show equally similar distributions between time-varying and time-constant flow fields.

in flow is affected by the material being textured. Specifically, an easy-to-texture crystal aggregate will hold more texturing from past flow than a hard-to-texture crystal aggregate. This is supported by Figure 8(b) where there are significantly more misfits in the <10 GPa bin in the hard-to-texture case. Analysing the radial anisotropy (see supplementary Figures A.16 and A.17), shows the same pattern and therefore has the same implications for interpreting observations such as seismic tomography.

We suggest easier-to-texture polycrystals hold more texturing from past flow in our setup because of the difficulty to re-texture a heavily shear-strained polycrystal. If the polycrystal experiences high strain rates early in its path, an easy-to-texture material will be heavily textured and geometric hardening, where the material hardness increases with plastic deformation (Hansen et al., 2012; Mameri et al., 2019), will make new texturing more difficult.

4. Discussion

As the previous sections show, for most locations in the lower mantle of an Earth-like mantle convection model, seismic anisotropy is mostly sensitive to the present-day flow field. In this section, we discuss the implications of these results both for those making observations and also for those investigating the material properties of post-perovskite. Then, we highlight limitations in our modeling approach.

4.1. Implications for seismic anisotropy studies

We have shown in the majority of locations in the lower mantle, seismic anisotropy is sensitive primarily to the present-day flow field, but in small regions, the past flow has a strong influence. Therefore, the implications our findings will have depend on the resolution and location of the seismic anisotropy. Global-scale observations such as 1-D seismic anisotropy observations (De Wit and Trampert, 2015), current body-wave seismic tomography (e.g. Simmons et al., 2021; Auer et al., 2014) or normal-mode observations (Restelli et al., 2023) should be sensitive mainly to present-day flow only in the lower mantle. Note that in the case of seismic tomography improvements in resolution may lead to sensitivity to past flow. Regional-scale observations from shear-wave splitting (e.g. Nowacki et al., 2010; Asplet et al., 2020; Wolf et al., 2023a; Wookey et al., 2005) may be sensitive to present-day flow but potentially could have information about past mantle flow. To investigate

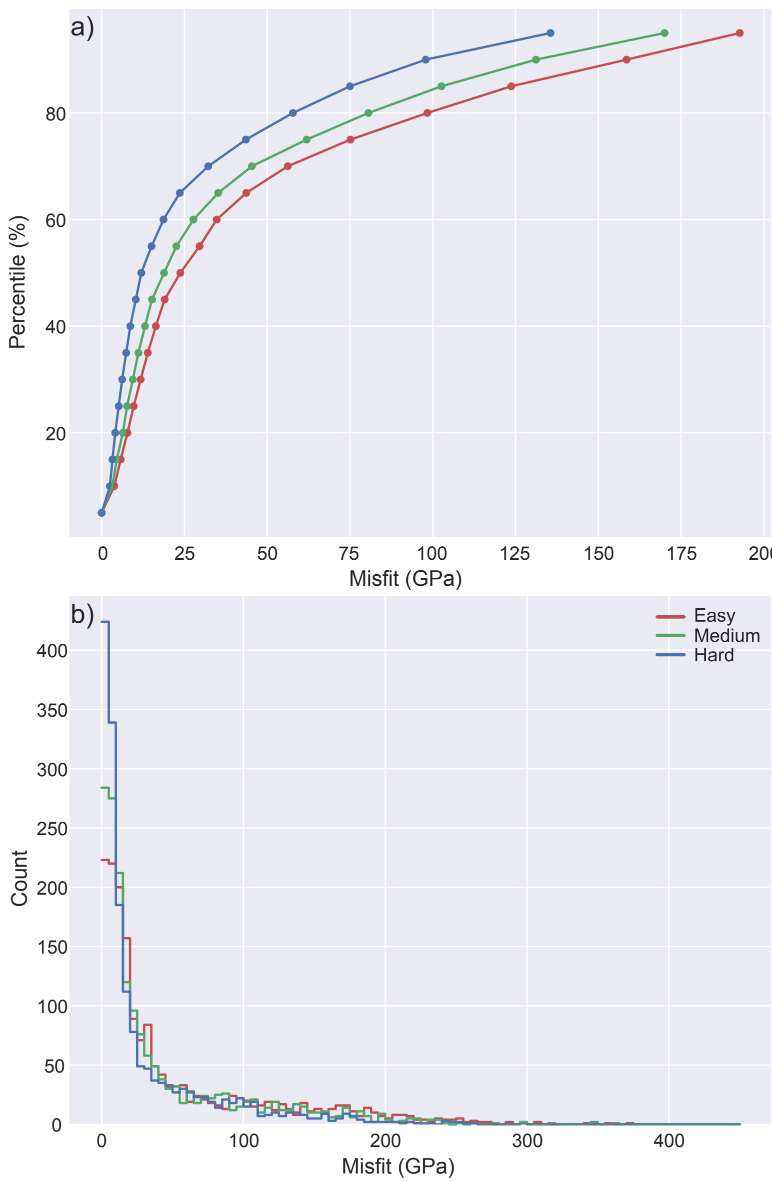

Figure 8: The effect of slip system activities on sensitivity to past flow. a) shows the different percentile misfit values coloured by the slip system label from Table 2. b) shows overlapping histograms for misfit data, also coloured by the slip system activities. The orange and blue lines are the kernel-density estimates for the time-constant and time-varying cases.

whether shear wave splitting observations have information about past flow, future studies can compare the observations to those made from flowfield test cases with time-varying and time-constant flowfields. This could potentially constrain what historic flow was like. Future studies could also take existing databases of splitting observations in D″ (e.g. Wolf et al., 2023b) and compare them to predictions of different global flowfields to constrain what past flow fields may have been like in the lower mantle.

We found a positive but weak correlation between temperature and elastic tensor misfit (Figure 5), suggesting seismic anisotropy measurements in hot regions may hold more information about past flow. We believe this weak correlation is caused by differences in path lengths (Figure 2). The hot regions have different path lengths because of the thin post-perovskite present. Therefore, some paths may be very short and paths between the time-varying and time-constant flowfields could be significantly different and have different texturing history. Stronger correlations with other metrics such as path length show multiple factors contribute to the sensitivity to past flow.

The longer paths in the time-constant flow field tend to also be more affected by a time-varying flow field than the shorter paths (Figure 5). This may be because there is more opportunity for the particle paths in the different flow fields to deviate, and thus the histories of strain rates likewise tend to diverge. When interpreting regional observations such as those using shear-wave splitting, it is most likely that a time-varying flow field must be considered, with particular caution being taken with longer paths.

We have shown that to be able to interpret lower mantle seismic anisotropy observations in terms of a time-varying flow field, it is vital to know how easily lowermost mantle minerals are textured. We found that harder-to-texture crystal aggregates hold less information about past mantle flow than easier-to-texture crystal aggregates.

4.2. Modelling assumptions

Our results suggest broad-scale observations of seismic anisotropy in the lower mantle such as those from current seismic tomography or 1-D estimates should be sensitive to present-day flow only. On the other hand, higher resolution observations such as shear-wave splitting may hold information about past flow depending on the region sampled. Our model setup is built upon several assumptions and limitations which we discuss here.

A significant assumption we make is assuming deformation in D″ is accommodated solely by dislocation creep everywhere. In lowermost mantle conditions, it is likely that other deformation mechanisms are taking place which may or may not result in the texturing of a crystal aggregate. It is unclear what deformation mechanisms are present in the lower mantle, what effect they have on texturing and where they occur. It is commonly believed diffusion creep is present in hot regions, but whether this leads to texture loss (McNamara et al., 2001, 2002), texture preservation (Wheeler, 2009) or continued texture development (Dobson et al., 2019) is debated. Other mechanisms such as pure dislocation climb creep (Boioli et al., 2017; Reali et al., 2019) may be present and result in no texture development, but again, where this happens in the lower mantle and what proportion of deformation is accommodated by this remains uncertain. These will certainly affect the sensitivity of seismic anisotropy to time-varying flow. Our approach means we have essentially maximised the sensitivity of texturing to flow and therefore also maximised the influence of past flow. In light of this, our setup maximises how much past flow influences present-day anisotropy observations. The likely effect of considering other deformation mechanisms is a reduction in the time-sensitivity of seismic anisotropy. To properly account for other deformation mechanisms, more information about the conditions where they dominate and the effect they have on texturing is needed.

Another limitation is there is no cap on texture strength such as that expected to occur from dynamic recrystallisation as dislocation density increases. Not limiting texture strength in our model may lead to geometric hardening where high CPO intensity becomes harder to texture further as has been previously shown in olivine (Hansen et al., 2012; Mameri et al., 2019), which could limit the formation of future texture. Capping texture strength with some form of dynamic recrystallisation or in an ad-hoc way by reducing the velocity gradient magnitude at each step along the path (e.g. Wenk et al., 2011; Cottaar and Romanowicz, 2013) most likely will reduce the sensitivity to past flow and reduce the number of locations where there are large differences between a time-constant and time-varying flow field. As we observe differences between the flow field of up to 15 % radial anisotropy we do not expect reducing the strain rates in an ad-hoc way will greatly change our conclusions.

In our setup, we assume deformation occurs in pure post-perovskite and there is no texture inheritance from deformation outside of the post-perovskite stability field. Therefore, the particle path lengths and strain rates sampled are affected by the Clapeyron slope and pressure intercept we chose. We used a Clapeyron slope which is within the range of estimates from experiments and calculations (Hirose et al., 2015; Kuwayama et al., 2022). By assuming pure post-perovskite, we do not account for any additional phases such as ferropericlase or bridgmanite which may strengthen or weaken the anisotropy depending on if and how texture may develop. Furthermore, effects such as those from strain localisation are not accounted for.

5. Conclusion

We tested the sensitivity of present-day lowermost mantle anisotropy to past mantle flow by comparing the anisotropy predicted from two mantle flow field models: one where the flow field varies with time and another where the flow is constant. As texture and anisotropy are controlled by both the flow field and slip system activities we create three test cases where we vary the ease-of-texturing to test for its impact. We find, in all ease-of-texturing cases, low-resolution observations such as 1-D radial anisotropy observations and seismic tomography are likely sensitive to present-day flow only. High-resolution regional observations, such as those from shear-wave splitting, may hold some information about past mantle flow. If the resolution of seismic tomography improves, it may also have some sensitivity to past flow. Varying the ease-of-texturing of the crystal aggregate leads to a similar spatial distribution but the easier-to-texture material leads to greater differences in the anisotropy between the flow field cases at some locations. We investigate what could contribute to the impact of past flow on present-day anisotropy. We find path properties such as differences in path length and tortuosity between the flow fields show the strongest correlation with anisotropy difference. We also find the temperature at the endpoint may also have an effect with hotter temperatures leading to larger differences between the predicted anisotropy from a time-varying and constant flow field. From this, we conclude there is no one dominant predictor of sensitivity to past flow. Ultimately, we show that low-resolution observations of lower mantle anisotropy such as those from current seismic tomography or 1D radial anisotropy estimates are sensitive to present-day flow alone. This implies that inversions of flow from such observations may give promising estimates of present-day convection patterns. Regional, high-resolution observations such as those from shear-wave splitting may provide some sensitivity to historic flow. As constraints on mineral physics and deformation mechanisms in D$''$ are tightened in the future, our work gives us confidence that inversions for recent mantle flow from seismic anisotropy observations may become possible in time.

Acknowledgements

JW, AW and AN are supported by NERC large grant Mantle Circulation Constrained NE/T012684/1. JP and JHD are supported by NERC large grant Mantle Circulation Constrained NE/T012633/1. AN is partly funded by NERC standard grant NE/R001154/1 (REMIS: Reliable Earthquake Magnitudes for Induced Seismicity). Figures were made using Matplotlib (Hunter, 2007) and cartopy (Met Office, 2010 - 2015). Code to perform the seismic anisotropy calculation from flow is available upon request.

Appendix A. Supplementary material

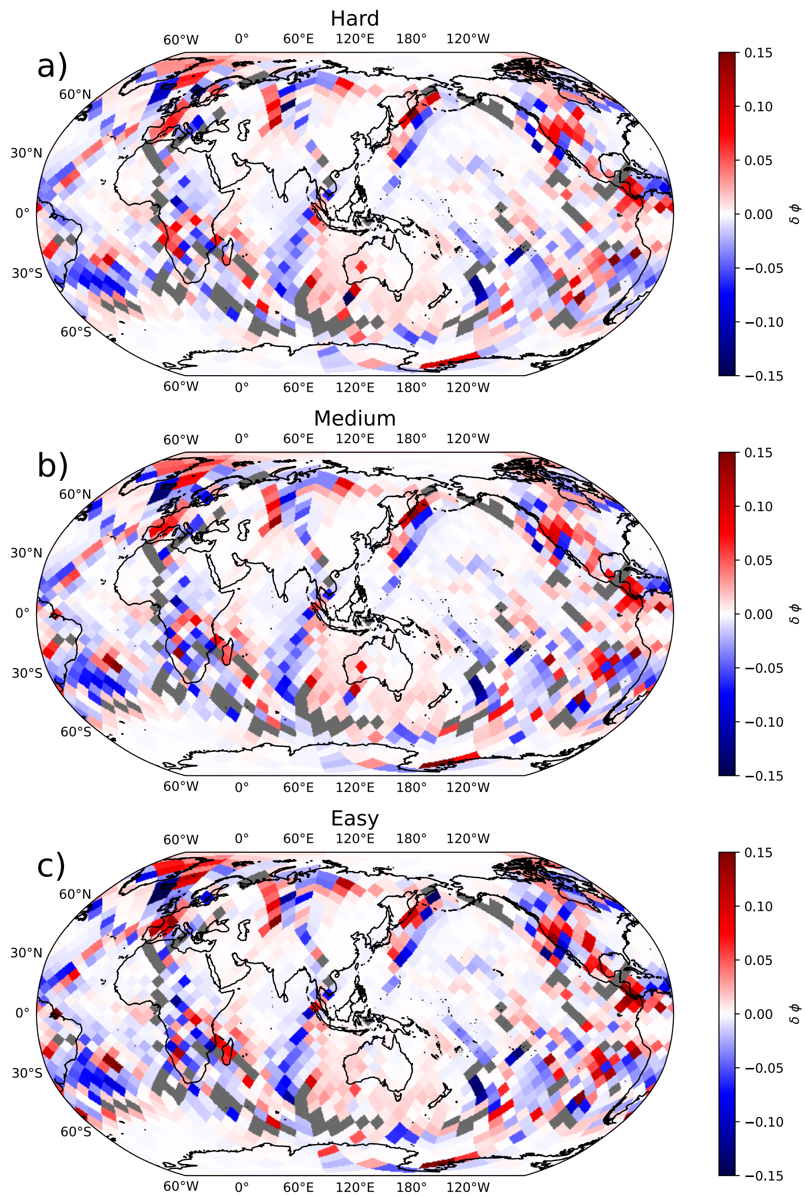

Figure A.9: Maps showing the difference between P-wave radial anisotropy (ϕ) at 3530 km radius (50 km above the core–mantle boundary) for the different flow fields with the different ease-of-texturing cases. The regions in grey show where post-perovskite is not predicted to be stable at this depth.

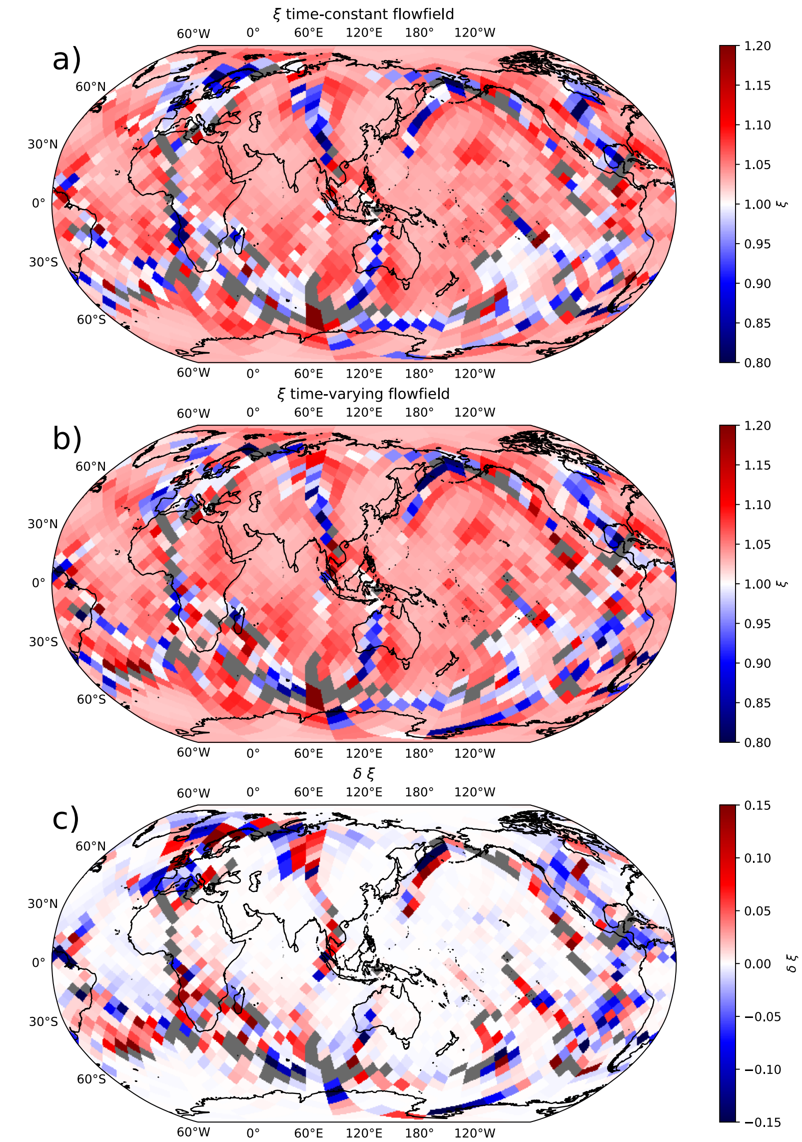

Figure A.10: Maps of S-wave radial anisotropy (ξ) at 3530 km radius (50 km above the core–mantle boundary) for the hard-to-texture case. We show ξ calculated with the time-constant flowfield (a), the time-varying flowfield (b) and the difference between the two (c).

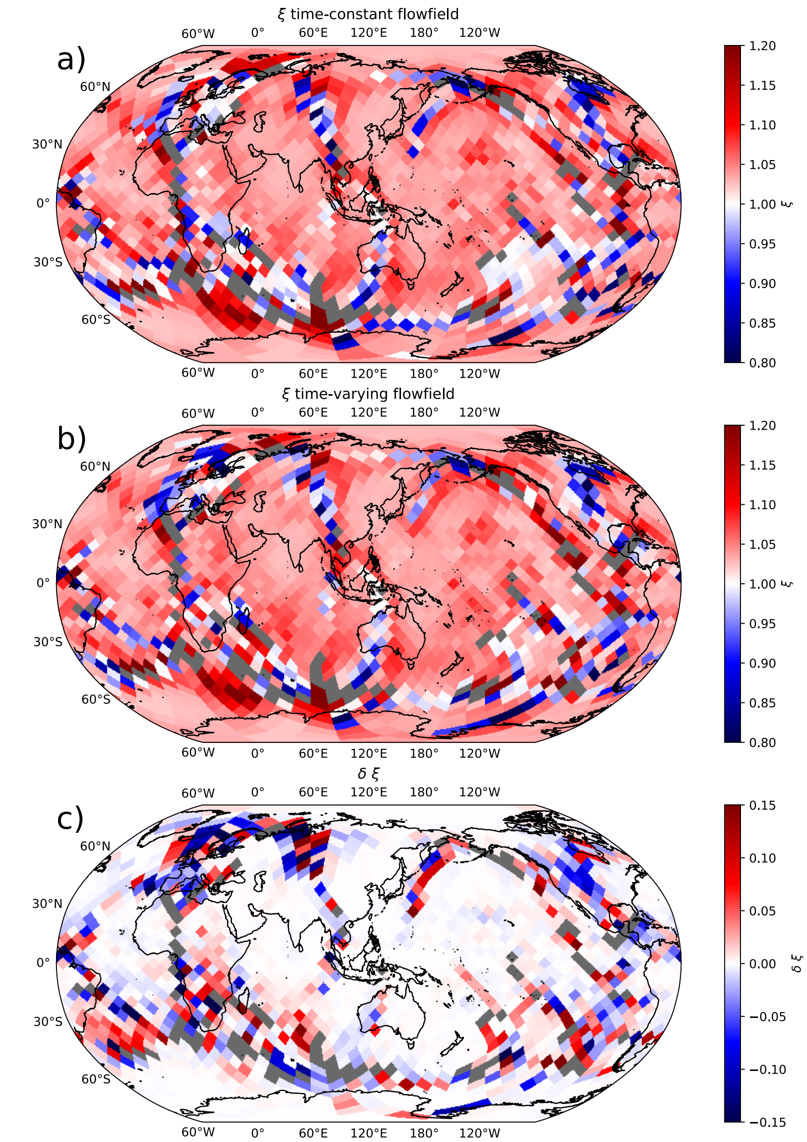

Figure A.11: Maps of S-wave radial anisotropy (ξ) at 3530 km radius (50 km above the core–mantle boundary) for the medium texture case. We show ξ calculated with the time-constant flowfield (a), the time-varying flowfield (b) and the difference between the two (c).

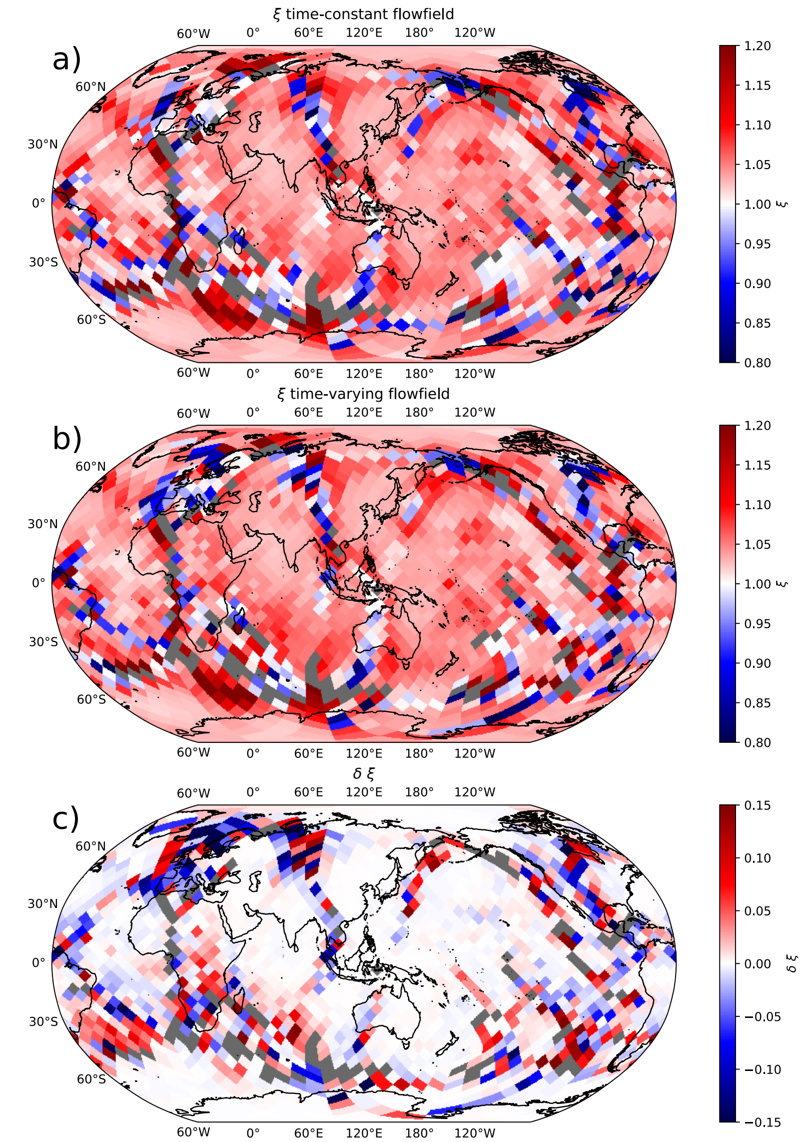

Figure A.12: Maps of S-wave radial anisotropy (ξ) at 3530 km radius (50 km above the core–mantle boundary) for the easy-to-texture case. We show ξ calculated with the time-constant flowfield (a), the time-varying flowfield (b) and the difference between the two (c).

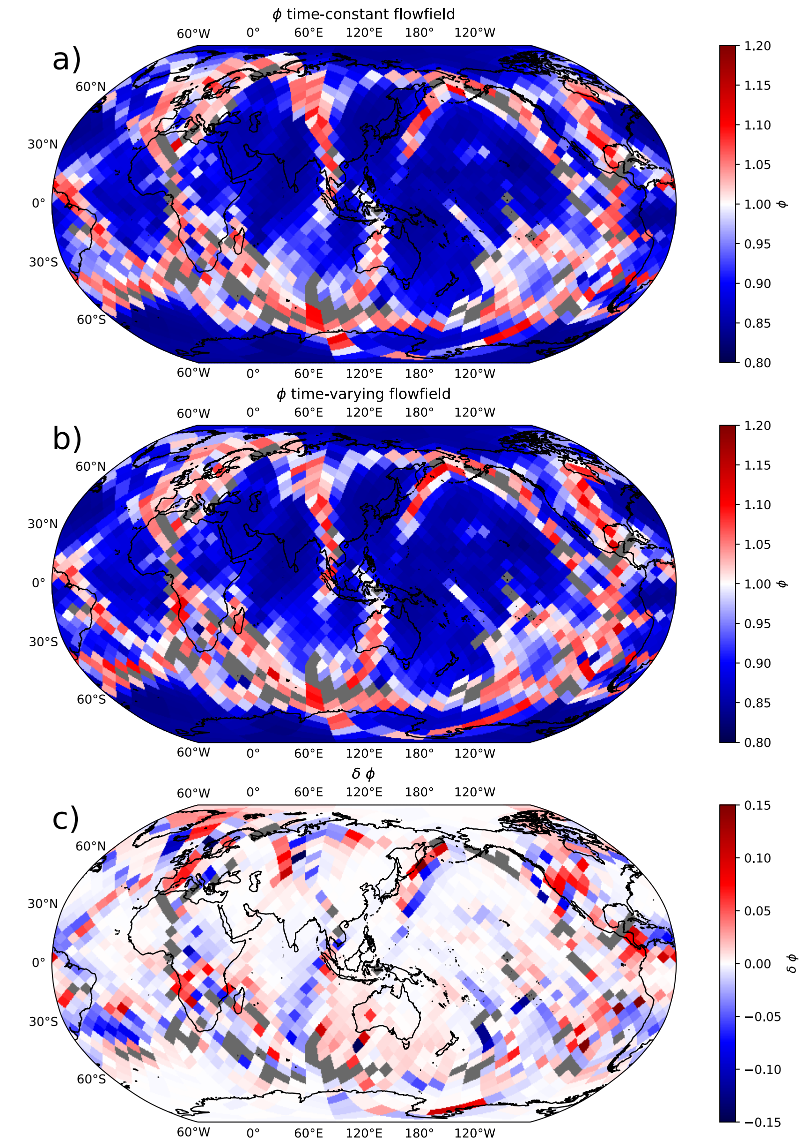

Figure A.13: Maps of P-wave radial anisotropy (ϕ) at 3530 km radius (50 km above the core–mantle boundary) for the hard-to-texture case. We show ϕ calculated with the time-constant flowfield (a), the time-varying flowfield (b) and the difference between the two (c).

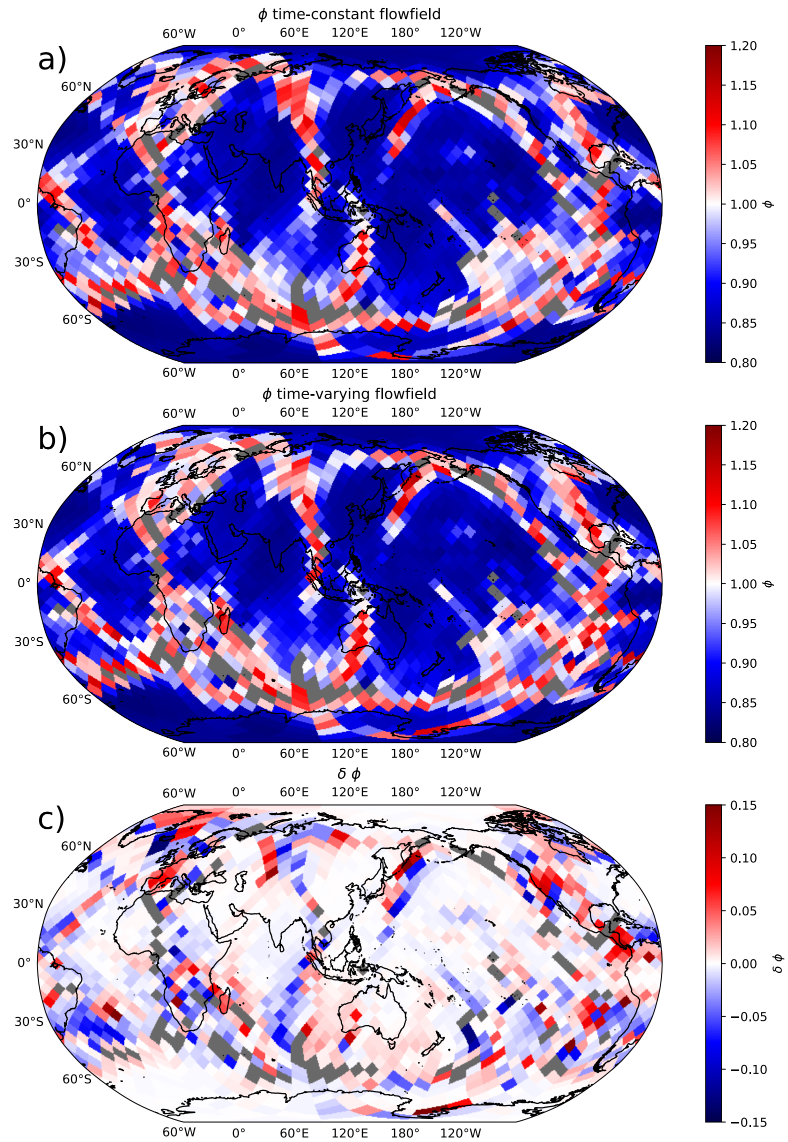

Figure A.14: Maps of P-wave radial anisotropy (ϕ) at 3530 km radius (50 km above the core–mantle boundary) for the medium texture case. We show ϕ calculated with the time-constant flowfield (a), the time-varying flowfield (b) and the difference between the two (c).

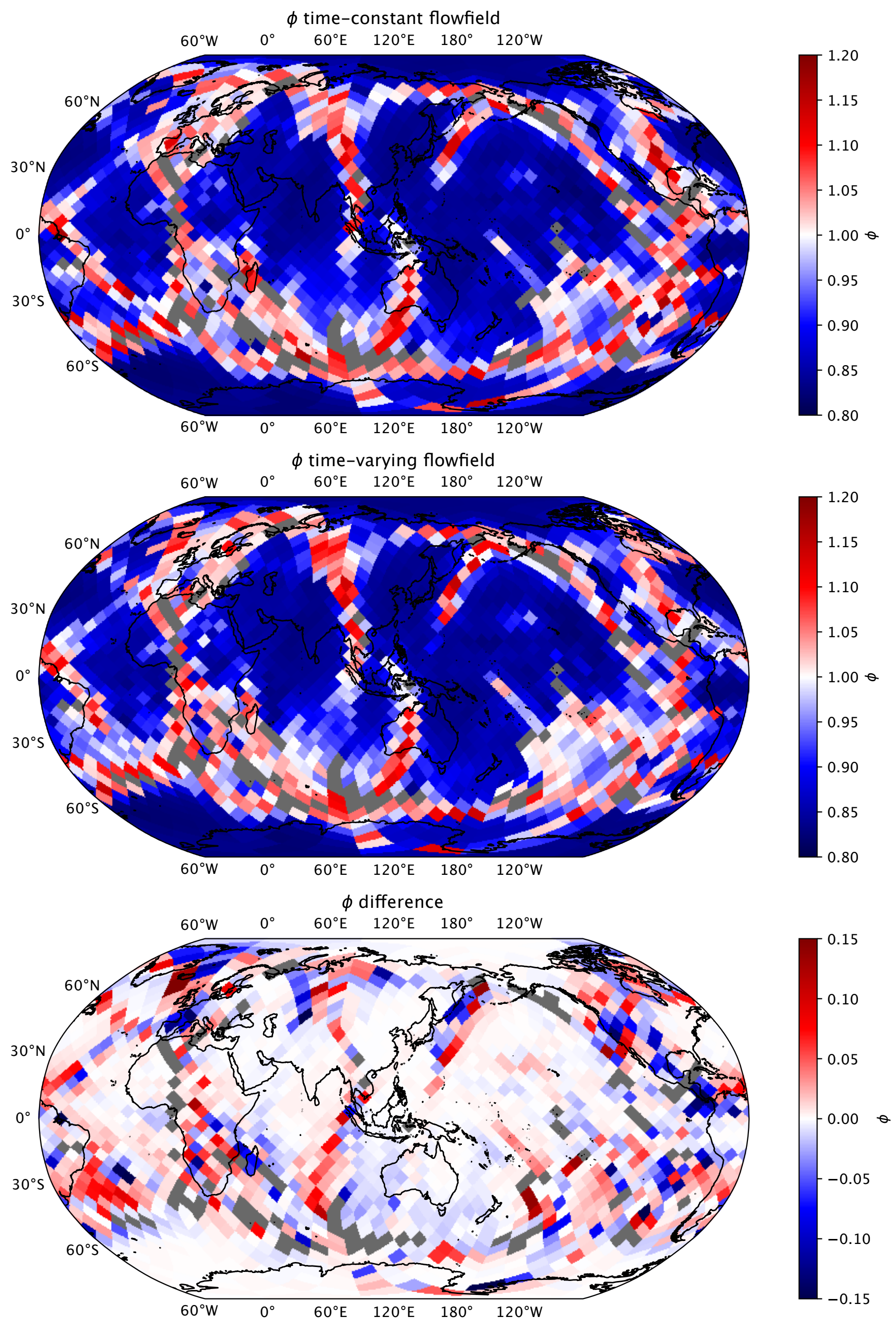

Figure A.15: Maps of P-wave radial anisotropy (ϕ) at 3530 km radius (50 km above the core–mantle boundary) for the easy-to-texture case. We show ϕ calculated with the time-constant flowfield (a), the time-varying flowfield (b) and the difference between the two (c).

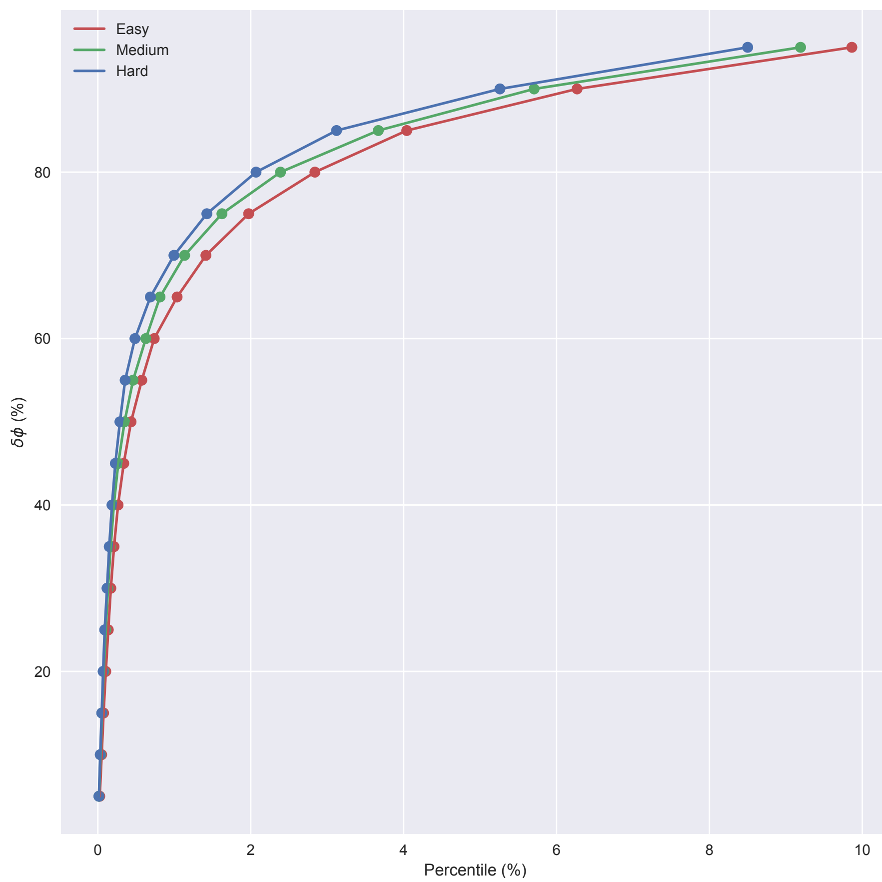

Figure A.16: The effect of slip system activities on the sensitivity of ξ observations to past flow in the lower mantle. This figure shows the different percentile ξ values coloured by the slip system label from Table 2. Notice at the larger percentiles the easy-to-texture case always has larger differences in ξ between the flow fields.

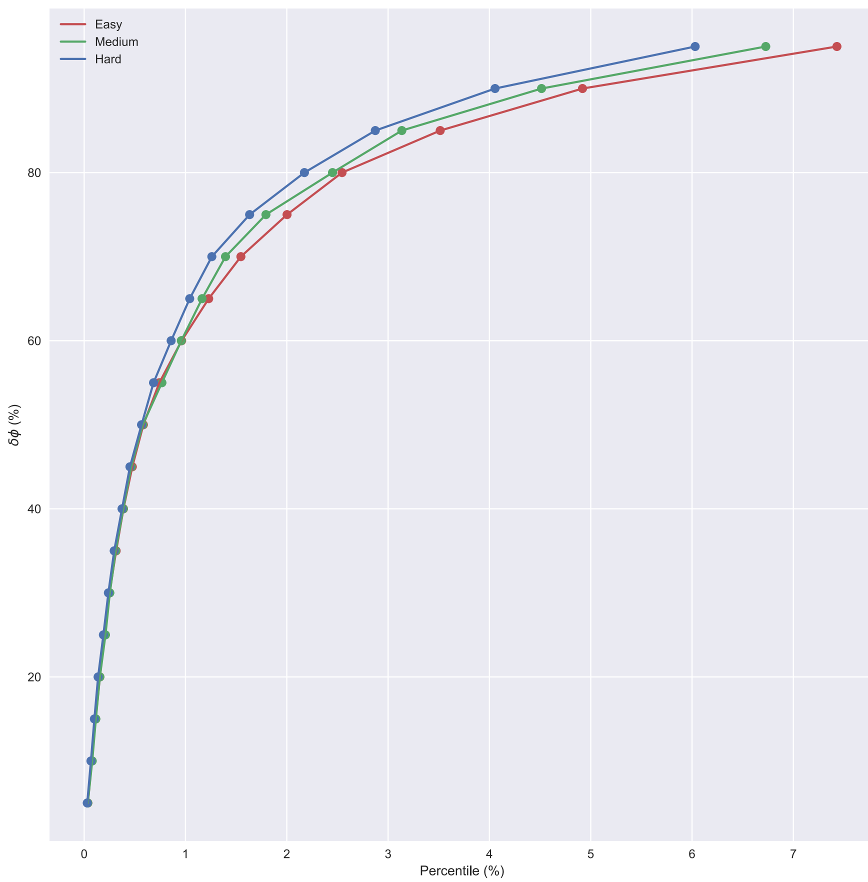

Figure A.17: The effect of slip system activities on the sensitivity of ϕ observations to past flow in the lower mantle. This figure shows the different percentile ϕ values coloured by the slip system label from Table 2. Notice at the larger percentiles the easy-to-texture case always has larger differences in ϕ between the flow fields.

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