# Evolving viscous anisotropy in the upper mantle and its geodynamic implications

3 Á. Király<sup>1</sup>, C.P. Conrad<sup>1</sup>, L.N. Hansen<sup>2</sup>

4 <sup>1</sup> Centre for Earth Evolution and Dynamics, University of Oslo, Norway

<sup>2</sup> Department of Earth and Environmental Sciences, University of Minnesota, Minneapolis,
MN, USA

7

#### 8 Key Points

We develop models of olivine texture evolution within deforming asthenosphere, and the associated directional variations in viscosity
The effective viscosity of textured olivine can vary by an order of magnitude, depending on which slip system dominates the deformation.
Anisotropic viscosity promotes faster plate motion & ridge-parallel subduction initiation, but impedes directional changes in plate motion

#### 16 Key words

Olivine, Anisotropic viscosity, LPO, Texture development, Plate motions, Asthenosphericdeformation

#### 20 Abstract

21 Asthenospheric shear causes some minerals, particularly olivine, to develop anisotropic 22 textures that can be detected seismically. In laboratory experiments, these textures are also 23 associated with anisotropic viscous behavior, which should be important for geodynamic processes. To examine the role of anisotropic viscosity for asthenospheric deformation, we 24 25 developed a numerical model of coupled anisotropic texture development and anisotropic viscosity, both calibrated with laboratory measurements of olivine aggregates. This model 26 27 characterizes the time-dependent coupling between large-scale formation of lattice-preferred 28 orientation (i.e., texture) and changes in asthenospheric viscosity for a series of simple 29 deformation paths that represent upper-mantle geodynamic processes. We find that texture 30 development beneath a moving surface plate tends to align the a-axes of olivine into the plate-31 motion direction, which weakens the effective viscosity in this direction and increases plate 32 velocity for a given driving force. Our models indicate that the effective viscosity increases 33 for shear in the horizontal direction perpendicular to the a-axes. This increase should slow 34 plate motions and new texture development in this perpendicular direction, and could impede 35 changes to the plate motion direction for 10s of Myrs. However, the same well-developed 36 asthenospheric texture may foster subduction initiation perpendicular to the plate motion and 37 deformations related to transform faults, as shearing on vertical planes seems to be favored across a sub-lithospheric olivine texture. These end-member cases examining shear-38 39 deformation in the presence of a well-formed asthenospheric texture illustrate the importance 40 of the mean olivine orientation, and its associated viscous anisotropy, for a variety of 41 geodynamic processes.

#### 43 Plain language summary

44 The uppermost layer of Earth's mantle, the asthenosphere, experiences large deformations due to a variety of tectonic processes. During deformation, grains of olivine, the main rock-45 46 forming mineral in the asthenosphere, rotate into a preferred direction parallel to the 47 deformation, developing a texture that can affect the response of the asthenosphere to tectonic 48 stresses. Laboratory measurements show that the deformation rate depends on the orientation 49 of the shear stress relative to the olivine texture. We use numerical models to apply the 50 findings of the laboratory measurements to geodynamic situations that are difficult to simulate in a laboratory. These models track the development of olivine texture and its directional 51 52 response to shear stress, which are highly coupled. Our results suggest that anisotropic 53 viscosity in the asthenosphere can significantly affect the motions of tectonic plates, as plate 54 motion in a continuous direction should become faster while abrupt changes in the direction 55 of plate motion should meet high resistance in the underlying asthenosphere. We suggest that 56 olivine textures in the asthenosphere play a critical role in upper mantle dynamics. 57

#### 58 **1. Introduction**

59 The physical characteristics of the upper mantle, e.g. its density and rheology, control a variety of surface features, such as general tectonic regime, faulting characteristics, dynamic 60 61 topography, and plate velocity. Many of these features are thus related to the properties of 62 olivine, which comprises ~60% of the upper mantle (Stixrude and Lithgow-Bertelloni, 2005). 63 It has long been known that olivine is anisotropic in its elastic properties, and this directional 64 dependence has been observed in the upper mantle using seismic waves (e.g., Tanimoto and 65 Anderson, 1984). This observed seismic anisotropy is mainly the result of the lattice preferred 66 orientation (LPO, or texture) of the olivine crystals, which causes the speed of seismic waves 67 to depend on propagation direction and additionally causes shear waves to split into two perpendicularly polarized waves (faster and slower) (Bamford and Crampin, 1977; 68 69 Christensen, 1984; Mainprice et al., 2015). The texture (or LPO) itself is thought to result 70 from shear strain in the upper mantle, which causes olivine crystals to rotate into a preferred 71 direction, generally with the seismically fast axis parallel to the direction of shearing (e.g., 72 Ribe, 1989; Karato and Wu, 1993). Seismic observations of this anisotropy have been used to 73 infer patterns of upper-mantle deformation (Long and Becker, 2010), for example related to 74 tectonic plate motions (e.g., Becker, 2008; Becker et al., 2014, 2008, 2003; Behn et al., 2004; 75 Conrad and Behn, 2010; Gaboret et al., 2003), subduction (e.g., Long, 2013), continental 76 collision (e.g., Silver, 1996), and motion on transform faults (e.g., Eakin et al., 2018).

77 Early laboratory experiments found that olivine is not limited to anisotropy in its elastic 78 properties, but also exhibits anisotropy in its viscosity. Durham and Goetze (1977) 79 demonstrated that the deformation rate of a single olivine crystal is orientation dependent and 80 can vary by a factor of 50. To assess the role of single-crystal anisotropy in controlling the 81 anisotropy of an aggregate of crystals, Hansen et al. (2012) first deformed aggregates of 82 olivine in torsion and subsequently deformed them in extension. In torsion, the samples 83 gradually weaken as the texture forms, but subsequent extensional deformation normal to the 84 initial shear plane is characterized by a factor of 14 increase in viscosity. Similarly, but in a 85 reverse order, Hansen et al., (2016b) first deformed aggregates of olivine in extension and 86 subsequently deformed them in torsion. In extension, the samples gradually weaken as the 87 texture forms, but subsequent torsional deformation is again characterized by much higher 88 viscosities. Taken together, these experiments demonstrate that prolonged deformation in a 89 consistent orientation leads to texture formation that reduces the viscosity, and a subsequent 90 change in the orientation of deformation results in a dramatic increase in the viscosity.

91 However, Hansen et al.'s (2016b) laboratory experiments were only able to test a small 92 number of deformation paths (i.e., first extension, then torsion, and vice versa), making it 93 difficult to directly apply their results to deformation in the mantle. To apply their results 94 more generally to mantle deformation, Hansen et al., (2016a) used the existing experiments to 95 define and calibrate a mechanical model of slip-system activities and texture development 96 within olivine aggregates. This model can predict both the evolution of olivine textures and 97 the associated anisotropic viscous behavior for olivine aggregates undergoing arbitrary 98 deformation paths. This coupled micromechanical and textural development model enables us 99 to investigate the role of viscous anisotropy for a range of geodynamic processes.

100 Decades ago, researchers used early numerical modeling techniques to test the relevance of 101 viscous anisotropy on geodynamical processes, such as mantle convection or post-glacial 102 rebound (Christensen, 1987). These studies relied on the laboratory measurements of Durham 103 and Goetze (1977), which constrained the anisotropic behavior of single olivine crystals, and 104 the work of Karato (1987), who studied the mechanisms of olivine texture formation. Due to 105 the absence of more detailed laboratory data, previous modelers assumed transverse isotropy 106 in a two-dimensional mantle (i.e., isotropic viscosity for shearing in the horizontal plane, and 107 anisotropy expressed as differences between shearing in the horizontal and vertical 108 directions). More recently, the effect of anisotropic viscosity on mantle convection has been 109 revisited (Mühlhaus et al., 2003), with additional investigations into Raleigh-Taylor 110 instabilities and subduction-zone processes within an anisotropically viscous mantle and/or 111 lithosphere (Lev and Hager, 2011, 2008). These studies are based on the director method 112 (Mühlhaus et al., 2002), which models olivine orientations as a set of directors, that is, 2D 113 unit vectors pointing normal to the easy shear plane. Anisotropic viscosity is expressed by a 114 combination of normal and shear viscosities, and the effective shear viscosity is a function of 115 the distribution of the directors. Furthermore, because the directors are advected and rotated 116 by the flow, this method effectively couples texture development to the anisotropic viscosity 117 of the mantle. The 2D nature of the director method, however, limits its ability to capture the 118 complete anisotropy associated with olivine, which has three independent slip systems that 119 accommodate deformation at different rates (Hansen et al., 2016a).

Here we have modified the director method to accommodate three-dimensional deformations of olivine aggregates using the micromechanical approach of Hansen et al. (2016a). This model is calibrated by laboratory constraints on slip system activities and parameters of texture development (i.e., the relative rotation rates of the different olivine slip systems, see

124 Table 1 in Hansen et al, 2016a). The resulting model allows us to explore both the texture 125 development of an olivine aggregate in a wide range of deformation paths and the mechanical 126 response of these textured aggregates to applied stresses associated with these deformation 127 paths. Our goal is to create first-order models of tectonic plate movement subject to a 128 continuous driving force (e.g., slab pull) in one direction. As the olivine texture develops in 129 the asthenosphere, we expect the mechanical response of the system to change as a function 130 of time and accumulated strain, resulting in a changing plate velocity. Next, by changing the 131 direction of the driving force, we can examine the response of the system to the application of 132 stress in a new direction. The resulting deformation paths are analogs for geodynamic 133 applications such as changes in the direction of plate movement, lithospheric dripping, 134 initiation of subduction, and transform faulting. These simple exercises lead us to a better 135 understanding of the interplay among olivine-texture development, anisotropic mantle 136 rheology, and large-scale geodynamic processes.

#### 137 **2. Methods**

#### 138 **2.1 Mathematical formulation**

139 Our method is based on the micromechanical model described and characterized by Hansen et 140 al. (2016a). This approach uses a pseudo-Taylor approximation (after Taylor, 1938) to 141 calculate the stress needed to create an equivalent strain rate on each olivine crystal, allowing 142 for slip along three linearly independent slip systems. Each slip system is characterized by a 143 critical shear stress that describes its strength relative to the isotropic strength of the 144 aggregate. The best-fit model parameters obtained by Hansen et al. (2016a) for the pseudo-145 Taylor model are the following: 0.30 for the (010)[100] slip system, 0.27 for the (001)[100] slip system, and 1.29 for the (010)[001] slip system. The micromechanical model is coupled 146 147 to a texture development model, in which the deformation of the olivine aggregate results in 148 grain rotations. The rotation rate depends on the orientation of each grain with respect to the 149 deformation, and a set of texture parameters that define the relative rotation rates along the 150 four olivine slip systems (see Table 1 in Hansen et al., 2016a). These combined models 151 provide the basis for a method to calculate the anisotropic viscosity (or conversely, the 152 fluidity) for any given olivine texture. The resulting three-dimensional tensor can then be used 153 to predict the deformation behavior for several geodynamic applications. In the following, we 154 present details of this method and the results of first-order models in which the olivine-rich 155 upper mantle undergoes different deformation paths induced by temporal variations in an 156 applied shear stress.

157 To calculate the strain rate induced by the imposed stress, some further steps are necessary 158 beyond those described by the mechanical model of Hansen et al. (2016a). The macroscopic 159 constitutive relationship between stress and strain rate for an anisotropic viscous medium is

160 
$$\sigma_{kl} = \eta_{ijkl} \dot{\varepsilon}_{ij} , \qquad (1)$$

161 where  $\dot{\varepsilon}_{ij} = \frac{1}{2} \left( \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right)$  is the strain-rate tensor,  $\sigma_{kl}$  is the deviatoric-stress tensor, and  $\eta_{ijkl}$ 162 is the viscosity tensor (Christensen, 1987; Pouilloux et al., 2007). Due to their symmetry, the 163 deviatoric-stress and the strain-rate tensors can both be reduced to vectors using Kelvin 164 notation, which preserves the norm of each of the tensors in (1) (Dellinger et al., 1998),

$$165 \qquad \dot{\varepsilon}_{ij} = \begin{bmatrix} \dot{\varepsilon}_{11} & \dot{\varepsilon}_{12} & \dot{\varepsilon}_{13} \\ \dot{\varepsilon}_{12} & \dot{\varepsilon}_{22} & \dot{\varepsilon}_{23} \\ \dot{\varepsilon}_{13} & \dot{\varepsilon}_{23} & \dot{\varepsilon}_{33} \end{bmatrix} \equiv \begin{bmatrix} \dot{\varepsilon}_{11} \\ \dot{\varepsilon}_{22} \\ \dot{\varepsilon}_{33} \\ \sqrt{2}\dot{\varepsilon}_{23} \\ \sqrt{2}\dot{\varepsilon}_{13} \\ \sqrt{2}\dot{\varepsilon}_{13} \\ \sqrt{2}\dot{\varepsilon}_{12} \end{bmatrix} \equiv \begin{bmatrix} \dot{\varepsilon}_{1} \\ \dot{\varepsilon}_{2} \\ \dot{\varepsilon}_{3} \\ \dot{\varepsilon}_{4} \\ \dot{\varepsilon}_{5} \\ \dot{\varepsilon}_{6} \end{bmatrix}$$
(2)

166

$$167 \quad \sigma_{ij} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & \sigma_{22} & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} \end{bmatrix} \equiv \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sqrt{2}\sigma_{23} \\ \sqrt{2}\sigma_{23} \\ \sqrt{2}\sigma_{13} \\ \sqrt{2}\sigma_{12} \end{bmatrix} \equiv \begin{bmatrix} \sigma_{1} \\ \sigma_{2} \\ \sigma_{3} \\ \sigma_{4} \\ \sigma_{5} \\ \sigma_{6} \end{bmatrix}.$$

$$(3)$$

168 It follows that the viscosity can be reduced to a 6x6 tensor (e.g., Pouilloux et al., 2007). 169 Because of the non-linear rheological behavior of olivine, the viscosity tensor is also a 170 function of stress. The rheology can thus be expressed by a stress-independent material 171 constant (<u>A</u>), which relates to the viscosity as

172 
$$inv(\eta_{ij}) = A_{ij} \cdot II_{\sigma}^{(n-1)/2}$$
. (4)

173 Equation 4 describes the fluidity of the material at a given stress, where  $II_{\sigma}$  denotes the 174 second invariant of the deviatoric stress and *n* is the power-law factor. Using eq. (4), the strain 175 rate can be expressed as a function of the stress and the fluidity according to

$$176 \quad \begin{bmatrix} \dot{\varepsilon}_1 \\ \dot{\varepsilon}_2 \\ \dot{\varepsilon}_3 \\ \dot{\varepsilon}_4 \\ \dot{\varepsilon}_5 \\ \dot{\varepsilon}_6 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} & A_{15} & A_{16} \\ A_{21} & A_{22} & A_{23} & A_{24} & A_{25} & A_{26} \\ A_{31} & A_{32} & A_{33} & A_{34} & A_{35} & A_{36} \\ A_{41} & A_{42} & A_{43} & A_{44} & A_{45} & A_{46} \\ A_{51} & A_{52} & A_{53} & A_{54} & A_{55} & A_{56} \\ A_{61} & A_{62} & A_{63} & A_{64} & A_{65} & A_{66} \end{bmatrix} \cdot \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} \cdot II_{\sigma}^{(n-1)/2}. \tag{5}$$

To solve eq. (5) for the strain rate, the material constant  $\underline{A}$ , which we will refer to as the 177 178 fluidity parameter tensor, must be known.  $\underline{A}$  is a function of temperature and grain size, but 179 also depends on the crystal orientations of the aggregate. The micromechanical model of 180 Hansen et al. (2016a) allows us to find the stress needed to produce any strain rate for a given 181 olivine texture. Therefore, to find the components of  $\underline{A}$  with the pseudo-Taylor mechanical 182 model, we need to apply 6 different strain rates to the aggregate and calculate the 6 stress 183 vectors that are required to produce these strain rates. The six strain rates define the columns 184 of the tensor  $\underline{E}$ ,

185 
$$E = \begin{bmatrix} \dot{\varepsilon}_0 & -\dot{\varepsilon}_0/2 & -\dot{\varepsilon}_0/2 & 0 & 0 & 0\\ -\dot{\varepsilon}_0/2 & \dot{\varepsilon}_0 & -\dot{\varepsilon}_0/2 & 0 & 0 & 0\\ -\dot{\varepsilon}_0/2 & -\dot{\varepsilon}_0/2 & \dot{\varepsilon}_0 & 0 & 0 & 0\\ 0 & 0 & 0 & \dot{\varepsilon}_0/\sqrt{2} & 0 & 0\\ 0 & 0 & 0 & 0 & \dot{\varepsilon}_0/\sqrt{2} & 0\\ 0 & 0 & 0 & 0 & 0 & \dot{\varepsilon}_0/\sqrt{2} \end{bmatrix},$$
(6)

186 where  $\dot{\varepsilon}_0$  is the applied strain rate amplitude. By applying the micromechanical model of 187 Hansen et al. (2016a) separately to each column of  $\underline{E}$ , we can compute the set of stress tensors 188 associated with each of these six strain rates. We use these stress tensors to construct the 189 tensor  $\underline{S}$ , for which each row represents the stress vector associated with the strain-rate vector 190 in each column of  $\underline{E}$ , multiplied by  $II_{\sigma}^{(n-1)/2}$ . These two tensors are related according to the 191 equation

$$192 \quad \underline{\mathbf{E}} = \underline{\mathbf{A}} \cdot \underline{\mathbf{S}}, \tag{7}$$

193 where 
$$\underline{S} =$$

In <u>S</u>,  $\sigma_{i_i}$  denotes the i<sup>th</sup> component of the deviatoric stress in Kelvin notation corresponding to 194 the j<sup>th</sup> column of  $\underline{E}$ , calculated with the pseudo-Taylor method described by (Hansen et al., 195 2016a), and  $II_{\sigma_j}$  is the second invariant of each stress tensor (corresponding to the j<sup>th</sup> column 196 of  $\underline{E}$ ). Equation (7) needs to be inverted to determine  $\underline{\underline{A}}$ . However, due to the 197 incompressibility criteria and because  $\underline{S}$  builds up by deviatoric stresses,  $\sum_{i=1}^{3} E_{ii} = 0 \wedge$ 198  $\sum_{i=1}^{3} S_{ij} = 0$  for each j. This means that  $\underline{S}$  is not invertible in its full form. However, we do 199 not lose information by reducing both  $\underline{E}$  and  $\underline{S}$  by one column and one row (the first column 200 and row) because the first component of both the strain rate and the deviatoric stress can be 201 202 reconstructed from their second and third components. This reduction yields  $\underline{\mathbf{E}}' = \underline{\mathbf{A}}' \cdot \underline{\mathbf{S}}'$ , where 203 each matrix has 5 rows and columns and a rank of 5. Hence,  $\underline{S}'$  is invertible, so

$$\underline{A} = \underline{\underline{B}} \cdot \underline{\underline{S}}^{-1} \tag{8}$$

can be solved.

Knowing the fluidity parameter tensor,  $\underline{A'}_{\pm}$  for a given olivine texture allows us to compute the full strain-rate tensor for any given applied stress tensor. The actual deformation that is produced depends on model assumptions about how this deformation is geodynamically expressed in the rock. In this study, we examine geodynamic processes associated with simple shear of the asthenosphere, e.g., as produced by the motion of a surface plate over an asthenospheric layer (Figure 1). To implement this deformation, we impose a deformation gradient consistent with simple shear, for which the deformation tensor ( $D_{ij} = \partial u_i / \partial x_j$ ) is

213 
$$D_{F_1} = \begin{bmatrix} 0 & 2\dot{\varepsilon}_{12} & 2\dot{\varepsilon}_{13} \\ 0 & 0 & 2\dot{\varepsilon}_{23} \\ 0 & 0 & 0 \end{bmatrix}$$
(9)

214 for the case in which the asthenosphere is sheared with force  $F_1$  (Fig. 1) and thus driven by a stress  $\sigma_{13}$ . The deformation that results is described in (9) by  $D_{12}$ ,  $D_{23}$ , and  $D_{13}$ , where  $D_{12}$  and 215 216  $D_{23}$  are only excited because of the anisotropic nature of the rheology. Note that we neglect 217 the normal strain rate components  $(D_{11}=D_{22}=D_{33}=0)$  assuming that the geometric constraints 218 on the system do not permit net elongation or contraction in any direction. From the imposed 219 deformation, we can calculate the associated texture evolution as a function of time for a 220 given applied stress history. The time-step in the calculation is set based on the strain rate to 221 have 0.1 strain increment for each time-step, which we have found to produce stable results.

#### 222 **2.2 Geodynamic model**

223 To investigate the influence of anisotropic viscous behavior in geodynamic scenarios with 224 changing orientations of stress, we model the deformation of a set of olivine grains 225 representing the behavior of the asthenosphere. We apply a shear stress (=force/area) of 0.68 MPa, which roughly corresponds to the shear stress acting on a plate of area 6000 km by 6000 226 227 km that is necessary to balance an edge force of 4.1.10^12 N/m (a lower bound estimate for 228 the value of slab pull force transferred to the plate from the negative buoyancy of a 229 subducting oceanic lithosphere; Schellart, 2004) above a 200-km-thick asthenosphere (Fig. 230 1A). We track the deformation of the asthenosphere using the micromechanical model of 231 texture-development and viscous anisotropy described above. Based on the anisotropic properties of a representative olivine aggregate, we compute the strain rate within the 232 233 asthenosphere, and associated parameters such as plate speed and movement direction, all as a 234 function of time, accumulated strain, and olivine texture development. To calculate the plate 235 velocity, we assume that the velocity is 0 at the base of the  $H_a = 200$  km thick asthenosphere and that the horizontal velocity at the top of the asthenosphere is the plate velocity, hence 236

237 
$$V_{plate} = 2 \cdot \sqrt{\dot{\varepsilon}_{13}^2 + \dot{\varepsilon}_{23}^2} \cdot H_a$$
 (10)

238 To investigate different deformation paths that are analogs for a variety of upper mantle 239 processes, we change the orientation of the applied shear stress, and consequently the 240 deformation applied to the asthenosphere, at a chosen instant after an olivine texture has 241 formed (Fig. 1B). Such a change could be induced by a change in the external driving forces 242 applied to the asthenosphere. An intuitively simple approach would be to rotate the imposed 243 driving stress relative to the texture that initially formed. However, for numerical and 244 analytical simplicity, we instead rotate the olivine texture with respect to the imposed stress 245 (as shown in Fig. 1C), which is held steady. This approach produces an equivalent result and allows us to keep the definition of both the shear stress and the deformation tensors (equation 246 247 9) unchanged. Later, we will discuss the geodynamic scenarios represented by the various 248 rotations of the olive texture with respect to the applied shear stress.

We define the angles  $\alpha$  and  $\beta$  as the orientations of the imposed shear stress and the resulting plate motion with respect to a coordinate system fixed in the asthenosphere (x-axis, *Fig. 1C*). Thus,  $\alpha$  is the angle between the (1)-axis (which is the same as the direction of the shear stress) and the x-axis (which is the angle of rotation of the texture) in *Fig. 1*, and  $\beta$  is the angle between the plate motion direction and the (x)-axis. The horizontal shear components of the strain rate ( $\dot{\varepsilon}_{23} \wedge \dot{\varepsilon}_{13}$ ) are used to calculate the direction of the plate movement ( $\beta$ ), as follows:

255 
$$\beta = atan\left(\frac{\dot{\varepsilon}_{23}}{\dot{\varepsilon}_{13}}\right) + \alpha$$
 (9)

#### **3. Results**

We present the results of 27 models with different deformation paths. Each model result is an average of 5 individual runs, each initiated with 1000 olivine grains with initial orientations randomly drawn from a uniform distribution. Therefore, we effectively represent the asthenosphere under a large ( $6000 \times 6000 \text{ km}^2$ ) plate using the average of 5 model runs of 1000 grains each.

#### 262

#### 3.1. Monotonic simple shear

263 First, we present the evolution of asthenospheric strain rates and olivine texture development 264 from a uniformly distributed texture (i.e., an isotropic mantle) to a well-developed texture 265 (anisotropic, weak mantle). As the mantle accumulates strain, the a-axes of olivine rotate 266 towards the shear direction (Fig. 1B), developing a texture that decreases the effective 267 viscosity of the asthenosphere and, therefore, increases the velocity of the plate. We examined 268 two sets of models differing only in the randomly created uniformly distributed orientations at 269 the start of the models (Fig. 2, black and grey curves). The similarity of these two model 270 averages implies that the average of model runs with 5x1000 grains gives a reasonably stable 271 result. However, subtle differences in the initial textures of the two models can still cause 272 minor differences in the amplitudes of the fluidity parameters (Fig. 2B).

The amplitude of the shear strain rate  $(|\dot{\varepsilon}| = 2 \cdot \sqrt{\dot{\varepsilon}_{12}^2 + \dot{\varepsilon}_{13}^2 + \dot{\varepsilon}_{23}^2})$ , simply referred to as 273 274 strain rate hereafter) exhibits characteristic variations throughout this deformation (Fig. 2), 275 which result from the texture evolution of the olivine aggregates and the associated changes in the fluidity parameter tensor (Fig. 2B and 2C). With an initially uniform olivine distribution, 276 the strain rate in the asthenosphere is  $1.5 - 1.7 \cdot 10^{-14}$  s<sup>-1</sup>, which corresponds to a plate velocity of 277 ~9.5-10.5 cm/yr velocity. As accumulated strain increases, the olivine texture develops, the 278 279 effective viscosity of the asthenosphere decreases, and the plate velocity increases, reaching a maximum of 14.8 cm/yr  $(2.4 \cdot 10^{-14} \text{ s}^{-1})$  around a strain of 8, i.e. after ~14 Myr of shearing. 280 With further shearing, the plate velocity decreases and subsequently stabilizes at 12.3 cm/yr 281  $(1.9 \cdot 10^{-14} \text{ 1/s})$ . The effective viscosity is inversely proportional to the strain rate, reaching a 282 minimum at ~14.5 Myr (strain of 8) and slightly increasing during the later history. The 283

magnitude of the viscosity varies from 2.9-4.5  $\times 10^{19}$  Pa·s. Hence, with continuous shearing, any further evolution of the olivine texture decreases the asthenosphere's effective viscosity by less than a factor of 2.

287 Both the shear components of the fluidity tensor ( $A_{44}$ ,  $A_{55}$ ,  $A_{66}$  in Fig. 2B) and the off-diagonal 288 components ( $A_{45}$  and  $A_{65}$  in Fig. 2C) exhibit variations with time as the olivine texture 289 develops. The non-zero component of the stress tensor is  $\sigma_{13}$ , ( $\sigma_5$  in Kelvin notation), which 290 means that  $A_{55}$  represents the fluidity in the shear direction (shearing on the (3) plane in the 291 (1) direction, creating  $\partial v_1 / \partial x_3$ ). Note that since  $\sigma_{31} = \sigma_{13}$  (symmetry of the stress tensor), 292 then  $A_{55}$  also represents the fluidity for the reciprocal deformation (i.e., shearing on the (1) 293 plane in the (3) direction, creating  $\partial v_3 / \partial x_1$ ).  $A_{44}$  and  $A_{66}$  represent the values of the fluidity 294 that would control the deformation (shearing given by  $\partial v_3 / \partial x_2$  or  $\partial v_2 / \partial x_3$  for  $A_{44}$  and by  $\partial v_1 / \partial x_2$  or  $\partial v_2 / \partial x_1$  for  $A_{66}$ ) if we were to change the shear stress to  $\sigma_{23}$  (= $\sigma_{32}$ ) or  $\sigma_{12}$ 295 296  $(=\sigma_{21})$ , respectively.

- 297 Initially, there is no preferred orientation of the olivine grains, and the three shear fluidity 298 components are the same. As the asthenosphere deforms and the texture develops in 299 association with shearing on the (3) plane in the (1) direction, A<sub>55</sub> increases, which is 300 associated with a decrease in viscosity and an increase in the plate velocity. In contrast, the 301 fluidity component  $A_{44}$  ( $A_{2323}$ ) decreases, which indicates that it would become harder and 302 harder to shear the asthenosphere with a stress  $\sigma_{23}$ , which would induce shearing on the (3) plane in the (2) direction (i.e., plate motion in a perpendicular direction), or reciprocally on 303 304 the (2) plane in the (3) direction. Surprisingly,  $A_{66}$  increases with progressive deformation, 305 and most of the time is even larger than  $A_{55}$ . Thus, as the texture develops, it also becomes 306 easier to shear the asthenosphere along the vertical (2) plane in the (3) direction (or, 307 reciprocally, along the (3) plane in the (2) direction). The  $A_{45}$  and  $A_{65}$  off-diagonal components (Fig. 2C) are noteworthy because these components couple  $\sigma_{I3}$  to  $\dot{\varepsilon}_{23}$  and  $\dot{\varepsilon}_{12}$ , 308 309 respectively (eq. 5). These components are initially zero, but do take on finite values with 310 progressive deformation. In other words, as the anisotropy of the system develops, the applied shear stress begins to induce shear strains on planes other than the primary shear plane, and in 311 312 directions other than the primary shear direction. However, because these components are two 313 orders of magnitude lower than  $A_{55}$ , the strain rate in this simple case is dominated by the 314 effects of  $A_{55}$ . Consequently, values of  $A_{55}$  (Fig 2B), strain rate (Fig. 2D&E), and plate 315 velocity (Fig. 2D) all exhibit the same trend as a function of time and strain.
- 316

#### 317 3.1.1. Rheology and texture parameters

As demonstrated above, the plate velocity (calculated from the horizontal strain rate) and the 318 319 shear-parallel  $(A_{55})$  component of the fluidity tensor are linearly dependent, and those terms 320 are inversely proportional to the effective viscosity. To further understand the initially 321 increasing and subsequently decreasing evolution of the strain rate, the relationship between 322 the texture and the rheological behavior of the asthenosphere (olivine aggregate) needs to be 323 examined. In the literature, a number of texture parameters have been proposed to quantify 324 the orientation distribution of a group of crystals. For example, the J-index (also referred to as 325 the texture strength) provides a metric for the degree of alignment of crystal orientations 326 (Bunge, 1982), varying between 1 (uniform distribution) and infinity (single-crystal texture). 327 The M-index (Skemer et al., 2005) also assesses the degree of alignment and results from the 328 difference between the uncorrelated and the uniform misorientation-angle distributions, with a 329 value between 0 (uniform distribution) and 1 (single-crystal texture). We calculated both the 330 J- and the M- indices with MTEX (Mainprice et al., 2015) and plotted the latter along with the 331 plate velocity against the accumulated strain (Fig. 3A). Comparing the two curves (blue and 332 yellow, for the plate velocity and the M-index, respectively), no direct relationship is 333 observable.

334 We examine the subtleties of the textural development with pole-figures that indicate the 335 orientation distributions of the three main axes of the olivine grains (Fig.3). These plots 336 illustrate that better correlation may be found between the plate velocity and the distributions 337 of individual axes instead of the M-index, which describes the orientation distribution of all 338 three axes. For example, as the plate velocity decreases between the strains of 8 and 16, the 339 distributions of the a- and c-axes become more girdled, while the distribution of the b-axes 340 becomes more clustered, resulting in an increasing M-index. Thus, the qualitative comparison 341 of the pole figures with the plate velocity suggests that the distribution of a-axes, which 342 represents the easiest slip direction, exerts a primary influence on the rheological behavior of 343 the aggregate.

Therefore, we calculate three additional parameters that describe the degree to which the orientation distribution is random (R), girdle-like (G) or point-like (P), for each crystallographic axis (a-axes: P-a, G-a, R-a; b-axes: P-b, G-b, R-b; c-axes P-c, G-c, R-c) (Vollmer, 1990). All three parameters vary between 0 and 1, and the sum of all three parameters is 1 for each axis distribution. We plot these texture parameters against the accumulated strain and the plate velocity (Fig. 3A), revealing some correlation between the P- a values and the plate velocity and some anticorrelation between the *G-a* values and the plate velocity.

352

#### **353 3.2.** Change in the direction of the shear force

The aim of this section is to test several deformation paths that, to first order, represent those expected for different geodynamic processes. For example, changing the force acting on the plate from the (1) direction to the (2) direction (i.e., from force  $F_1$  to force  $F_2$  in *Fig. 4*) represents a change in the direction of the pull force acting on a tectonic plate, and should change the direction of plate movement (*Fig. 4*). Other changes to the force that we explore are illustrated in Fig. 4. These force directions can mimic shearing induced by subduction initiation and/or dripping ( $F_3$  and  $F_5$ ) or the start of transform faulting ( $F_4$  and  $F_6$ ).

361 First, we describe the results of an instantaneous change in the direction of the asthenospheric 362 shear force (from  $F_1$  to  $F_2$ ,  $F_3$ ,  $F_4$ ,  $F_5$ , or  $F_6$  in Fig. 4). We then examine the influence on the 363 deformation behavior of (1) the rate of rotation of the shear force direction (from 1 Myr/90° to 364 12 Myr/90°), (2) the amount of texture development prior to the change, and (3) the total rotation angle of the driving stress when switching from  $F_1$  to  $F_2$ . As noted above, we 365 366 implement a change in the driving force (or shear stress) by rotating the textured olivine 367 aggregate (formed by applying the shear of model 1 for a chosen amount of accumulated 368 strain) while keeping the shear stress constant (Fig. 1C).

369 3

#### 3.2.1 Instantaneous change in shear direction

At a strain of 8 (i.e., after shearing the olivine aggregate for 14.5 Myr), the a-axes distribution reaches the maximum value of *P* (*Fig. 3*). Hence, to maximize the effect of anisotropy in our tests, we first reach a shear strain of 8 by applying  $\sigma_{13}$  with deformation consistent with applying the force  $F_1$  (using the same initial texture as in model 1), then switching to a new force direction (defined in *Fig. 4*). Due to the symmetric nature of the stress tensor,  $F_3$  is achieved using the same applied stress as  $F_1$ , but by employing different applied boundary conditions that enforce deformation consistent with vertical shearing, i.e.:  $D_{F_3} =$ 

377  $\begin{bmatrix} 0 & 0 & 0 \\ 2\dot{\varepsilon}_{12} & 0 & 0 \\ 2\dot{\varepsilon}_{13} & 2\dot{\varepsilon}_{23} & 0 \end{bmatrix} = D_{F_1}^{T} \cdot F_2 \text{ and } F_5 \text{ are consistent with a stress tensor in which only } \sigma_{23} \text{ and}$ 

378  $\sigma_{32}$  are non-zero and deformation is given by  $D_{F_2} = \begin{bmatrix} 0 & 0 & 2\dot{\varepsilon}_{13} \\ 2\dot{\varepsilon}_{12} & 0 & 2\dot{\varepsilon}_{23} \\ 0 & 0 & 0 \end{bmatrix} \land D_{F_5} = D_{F_2}^{T}. F_4$  and

379  $F_6$  are both consistent with a stress tensor where only  $\sigma_{12}$  and  $\sigma_{21}$  are non-zero and induce

380 deformation given by 
$$D_{F_4} = \begin{bmatrix} 0 & 2\dot{\epsilon}_{12} & 2\dot{\epsilon}_{13} \\ 0 & 0 & 0 \\ 0 & 2\dot{\epsilon}_{23} & 0 \end{bmatrix} \wedge D_{F_6} = D_{F_4}^{T}$$
. As mentioned before, these

381 deformations are equivalent to those achieved by rotating the mantle (i.e. the olivine 382 aggregate) with respect to the force  $F_1$  and keeping the imposed boundary conditions expressed by the deformation tensor  $D_{F_1}$  (equation 9). A 90° rotation of the aggregate around 383 384 the x-axis represents a change from  $F_1$  to  $F_4$ , around the y-axis reproduces  $F_3$ , and around the 385 z-axis reproduces  $F_2$ .  $F_5$  is modeled by rotating the aggregate around the x- and then z-axes, 386 and  $F_6$  is modeled by rotation around the x- then y-axes. Referring to Fig. 4, rotating the 387 aggregate around its x or its x then y axes represents shearing produced by a transform fault 388  $(F_4 \text{ or } F_6)$ , rotation around the y or the x then z axes represents shearing associated with 389 dripping or subduction ( $F_3$  or  $F_5$ ), while rotation around the z axis represents a change in the 390 direction of the horizontal shear  $(F_2)$  (e.g., due to a change in the direction of slab pull force).

The effect of changing the shear direction largely depends on the direction of the new shear stress with respect to the textured mantle (*Fig. 5*). For example, when the rotation results in a new shear stress that primarily induces deformation on the hardest (010)[001] slip system ( $F_2$ or  $F_5$ ), the strain rate decreases dramatically, from 2.3  $\cdot 10^{-14}$  to 4.9  $\cdot 10^{-15}$  s<sup>-1</sup> (*Fig. 5B*, orange and green curves). Translating to plate velocity, this change implies a decrease from 14.8 cm/yr to 3 cm/yr.

397 Note that reciprocal pairs of shear deformations (that is,  $F_1$ - $F_3$ ,  $F_2$ - $F_5$ , and  $F_4$ - $F_6$ ) are 398 associated with the same stress state (shear stress given by  $\sigma_{13}$ ,  $\sigma_{23}$ ,  $\sigma_{12}$ , respectively) and 399 initially activate the same slip systems because they are deforming the same initial texture. 400 Thus, the effective viscosity, and the associated deformation rates, for each of these pairs is 401 initially the same (as shown at a strain of 8 in Figs. 5A, 5B, and 5C, respectively). However, 402 because the rotation associated with these deformation pairs is different (because we employ 403 different boundary conditions D), the textures for these pairs evolve differently (Fig. 5, right 404 column), and their strain-rates diverge (*Fig. 5*, left column).

405

#### 3.2.1.1 Representing change in plate motion direction

406 Rotating the olivine aggregate around its *z*-axis represents a relative change in the direction of 407 the plate driving force. The result of a model with 90° instantaneous rotation (green curve in 408 *Fig. 5B*) exhibits a dramatic reduction in strain rate and a slow recovery of the olivine texture 409 after the rotation. By the end of the model run (total shear strain of 21) the strain rate has

increased to  $1.3 \cdot 10^{-14}$  s<sup>-1</sup>, which is still less than the strain rate for the initially isotropic 410 411 aggregate. Because of the slow deformation associated with the diminished strain rate, this 412 partial recovery took almost 50 Myr. Examination of the change in olivine texture directly 413 after the rotation (at strain of 8.5, Fig. 5) illustrates that the orientations are well organized but 414 that the preferred orientation is perpendicular to the direction of shearing (Fig. 5). When the 415 strain rate finally starts to increase, the a-axis distribution is more random or girdle-like rather 416 than point-like, even at a total strain of 21. Regarding the fluidity tensor, when the texture is 417 rotated, the  $A_{55}$  component (which relates  $\sigma_{13}$  to  $\dot{\varepsilon}_{13}$ ) decreases while both  $A_{45}$  and  $A_{65}$  exhibit 418 a minor increase, leading to similar values for all three components.

419

#### 3.2.1.2 Shear forces associated with transform faults

420 There are two possibilities for creating shear stress in a horizontal direction along a vertical 421 plane, which roughly approximates the stress state associated with a transform fault. The 422 possible shear forces are  $F_4$  or  $F_6$  (Fig. 4), which produce very different paths in the strain-rate 423 evolution (Fig. 5C) if there is already a well-developed texture associated with deformation 424 due to  $F_1$ . At the time of rotation (at a strain of 8), both models exhibit an elevated strain rate (to  $3.3 \cdot 10^{-14}$  s<sup>-1</sup>) compared to the earlier deformation (driven by  $F_1$ ). The pink curve, 425 426 representing the switch from  $F_1$  to  $F_4$ , after the initial peak strain rate, slowly decreases to ~1.5·10<sup>-14</sup> s<sup>-1</sup>. Switching from  $F_1$  to  $F_6$  is relatively easy, as the model exhibits increasing 427 strain rate (up to  $\sim 6.7 \cdot 10^{-14} \text{ s}^{-1}$ ) associated with the texture evolution after the rotation for an 428 additional shear strain of ~4 (*Fig. 5C*, dark blue curve). This peak is followed by a quickly 429 decreasing strain rate that stabilizes around  $\sim 2 \cdot 10^{-14}$  s<sup>-1</sup>, which is comparable to the strain rate 430 431 for larger strains in reference model 1 (black curve). The high strain rate produced by the model representing  $F_6$  is associated with a quick texture evolution and a point-like 432 433 distribution in the new shear direction that is more strongly aligned than the distribution prior to the change in shear direction. In contrast, changing from  $F_1$  to  $F_4$  (rotation around the x-434 435 axes) keeps the a-axis distribution basically aligned with the shear direction, but with subsequent strain, the a-axis distribution forms a girdle, decreasing the initial point-like 436 437 distribution and leading to slower strain rates than prior to the change in shear direction.

438

#### 3.2.1.3 Shear forces associated with dripping/subduction

439 There are two possibilities for creating shear stress in a vertical direction as a rough 440 approximation of the stress state associated with subduction or dripping instabilities. 441 Changing from  $F_1$  to  $F_3$  (texture rotation around the y-axis; *Fig. 4*), results in initial

deformation occurring at the same rate as for  $F_1$  (because  $F_1$  and  $F_3$  are reciprocal 442 deformations, as described above) followed by a decrease in strain rate (i.e. small increase in 443 444 the effective viscosity) as the texture evolves (Fig. 5A, cyan curve). Subsequent texture 445 evolution produces a period with increasing strain rate, between strains of 8.5 (0.5 after the switch) to 13, peaking at  $4.4 \cdot 10^{-14}$  s<sup>-1</sup>. The model results exhibit a decreasing trend in strain 446 rate immediately after this peak, reaching a final strain rate of  $2 \cdot 10^{-14}$  s<sup>-1</sup> (after a total strain of 447 448 21). In contrast, changing from  $F_1$  to  $F_5$  (orange curve in Fig. 5B) induces a dramatically diminished strain rate  $(5 \cdot 10^{-15} \text{ s}^{-1})$ , equivalent to that produced by  $F_2$  as described above) that 449 slowly recovers over the next 20-25 Myr (by a total strain of 14) and stabilizes around 2.2-450  $2.3 \cdot 10^{-14}$  s<sup>-1</sup>, which is slightly higher than the strain rate at high stresses in model 1. Similar to 451 the "transform fault" models, the strain-rate curves for "subduction/dripping" can be linked to 452 453 the texture development. The higher strain rate at the end of the model that applies  $F_5$  (x- then 454 y- rotation) compared to the model end after applying  $F_3$  results from a more point-like 455 distribution of the olivine a-axes (Fig. 5A&B).

456

#### 3.2.2. Rate of rotation of the stress orientation

In the preceding section, the change in texture orientation relative to the applied forces was instantaneous. In the following sections, the rate, timing, and amount of rotation of the olivine aggregate are examined. Here we focus on the simplest case, a change in the plate-motion direction ( $F_1$  changing to  $F_2$ ). Here, we impose a 90° rotation over a time interval ranging from 1 to 13 Myr, after ~14 Myr of initial shearing (an accumulated strain of 8).

462 As described above, we use  $\alpha$  and  $\beta$  (eq. 9) to indicate the angle between the x-axis (in the 463 aggregate reference frame) and the shear force and plate motion directions, respectively. 464 During rotation of the aggregate,  $\alpha$  linearly changes with time from 0° to -90°. In contrast, the 465 angle  $\beta$  does not change linearly with time and can differ from  $\alpha$  significantly because the 466 olivine texture excites plate motion differently in varied directions. During the rotation period, 467 and independently of its duration, the plate movement differs from the shear direction by up 468 to  $20^{\circ}$  (*Fig. 6A*). Minor differences can be observed depending on the rotation rate. Once  $90^{\circ}$ 469 rotation is achieved, the plate movement is either parallel to the shear direction (1 and 10 Myr 470 rotation period), overturned (3 and 5 Myr rotation period) or rotated less than the shear 471 direction (13 Myr rotation period). After rotation, all models evolve in a similar manner, 472 resulting in velocity vectors 15-20° away from the shear direction. The plate speed drastically 473 decreases, reaching 3 cm/yr by the end of the rotation period (Fig. 6B). As in the 474 instantaneous rotation model, the plate movement cannot recover its original rate after the 475 rotation (Fig. 6B). The models with shorter rotation time (1-5 Myr) reach a maximum of 7 476 cm/yr while the models with longer texture rotation time (10-13 Myr) reach a maximum of 5 cm/yr by the end of the model (at strain ~ 20-21). Interestingly, during the first ~ $4^{\circ}$  of 477 478 rotation, the plate velocity increases, except for the model with 1 Myr rotation time, where the 479 rotation step is 9°/timestep (as the timestep is fixed to 100 kyr during the rotation). This 480 increase can be explained by the mean orientation of the olivine texture (see pole figures for a 481 strain of 8 on Fig. 3) and the plate movement (Fig. 6A) before the onset of rotation, which are 482 both a few degrees (~  $4^{\circ}$  and -1.2°, resp.) offset from the shear direction. Hence, at the onset 483 of rotation, the texture initially becomes more aligned with the shearing, resulting in up to 2 484 cm/yr increase in the plate velocity (see texture evolution animations, which are available in 485 the supplementary materials for each model).

486 3.2.3. Role of texture evolution prior to the rotation

487 In an additional series of calculations, we varied the amount of accumulated strain between 2 488 and 14 prior to a 90° rotation, which was implemented using two different rotation rates (90° 489 and 9°/Myr).

The magnitude of the velocity decrease associated with rotation appears to be proportional to the textural maturity of the aggregate before rotation (*Fig. 7B*). However, the rate of rotation has only a small effect, as described previously (*Fig. 6*). Note that for the models in which the rotation is imposed after a strain of 11 or 14, faster rotation results in a slightly lower minimum plate velocity (*Fig. 7D*). Only the model with fast and early rotation (rotation at a strain of 2) exhibits velocities that return to the original plate velocity (*Fig. 7B*).

497 A large range of variation in the plate motion direction can be observed depending on the 498 amount of initial strain, rotation rate, and time/total accumulated strain (Fig. 7A & C). In most of the models, the difference  $\alpha$ - $\beta$  grows from ~-1° to ~15-20° during rotation (see the two 499 500 outlined circles in each line on Fig.7C), which is also the maximum difference between  $\alpha$  and 501  $\beta$ . There are three slight outlier models, in which extreme magnitudes of  $\alpha$ - $\beta$  occur during the 502 model evolution. With an initial strain of 5 and a slow-rotation rate, the plate motion direction 503 can differ from the shear direction by up to 29°, while in the models in which an initial strain 504 of 14 is imposed, the plate-motion direction rotates more than the shear direction, reaching extremes of  $-6^{\circ}$  and  $-21^{\circ}$  (with 1 and 10 Myr rotation time, respectively). 505

#### 506 3.2.4. Role of the amount of rotation

507 In more realistic geodynamic scenarios, the driving forces on plates are unlikely to rotate as 508 much as 90°, so we additionally tested a range of rotations from  $22^{\circ}$  to  $90^{\circ}$  degrees with slow 509 (9°/Myr) and fast (90°/Myr) rotation rates. In all of these models, the aggregate was sheared with force  $F_1$  until a strain of 8 prior to the rotation. We found (Fig. 8) that the larger the 510 511 rotation, the lower the average strain rate, and therefore the lower the average plate velocity 512 (Fig. 8B&D). Furthermore, the models with faster rotation rates exhibit a greater variability of 513 plate motion directions and velocities than the models with slower rotation rates (Fig. 8). 514 With only 22° rotation,  $\beta$  differs from  $\alpha$  by only 15° during the rotation in both models, and 515 this difference linearly decreases as the model progresses until, at the end of the model, the 516 plate motion becomes parallel to the shear direction. The plate velocity decreases to 7.5-7.8 517 cm/yr, which then climbs back to the isotropic rate (~10 cm/yr) by the end of the models. If 518 the total change in shear direction is  $45^{\circ}$  or more, all models result in ~20° difference between 519  $\alpha$  and  $\beta$  during the rotation, independent of the rate of rotation. Later, the models with slower 520 rotation rate result in even larger differences between  $\alpha$  and  $\beta$ . The plate motion direction can 521 change more quickly if the plate velocity is high, such as in the model with 45° rotation at 522 90°/Myr during the period between 25 and 35 Myr (Fig. 8B). On the other hand, in the model 523 with 67° rotation at 9°/Myr, the plate velocity remains between 3.5-5 cm/yr, and  $\alpha$ - $\beta$  remains ~20° (15-25°). 524

#### 525 **4.** *Discussion*

526 The results described above suggest that the effective viscosity and strain rate of the 527 asthenosphere, and the associated plate velocity at the surface, are extremely sensitive to the 528 olivine texture. The asthenosphere weakens as the olivine texture develops with the a-axes 529 parallel to the shear direction ('anisotropic weak' on Fig. 1B), allowing for a 40% increase in 530 plate velocity (or equally, decrease in effective viscosity). The asthenosphere acts 'strong' 531 (Fig. 1C) if the mean a-axes direction is perpendicular to, and the mean c-axes direction is 532 parallel to, the shear direction. In this case, the effective viscosity is up to ~5 times higher 533 than if the a-axes are parallel to the shear force, resulting in a slower plate velocity that is only 534 a third of the velocity over the isotropic asthenosphere and a fifth of that in the 'anisotropic 535 weak' case (Fig. 10). This difference in viscosity is in accordance with the differences in the 536 strengths of the slip systems (Table 1 in Hansen et al., 2016a), favoring deformation parallel 537 to the a-axes (i.e. on the (010)[100] and (001)[100] slip systems, with strengths of 0.3 and

- 538 0.27, respectively) versus parallel to the c-axes (where the strength of the (010)[001] slip
- 539 system is 1.29). Thus, deformations that dominantly activate the (010)[100] slip system (e.g.,
- 540  $F_1$  and  $F_3$  at a strain of 8, Fig. 5A) and the (001)[100] slip system (e.g.,  $F_4$  and  $F_6$  at a strain of
- 541 8, Fig. 5C) exhibit much faster strain rates compared to those that dominantly activate the
- 542 (010)[001] slip system (e.g.,  $F_2$  and  $F_5$  at a strain of 8, *Fig.* 5B).
- 543 The evolution of the plate velocity and plate-motion direction (or the entire matrix of  $\dot{\varepsilon}$ ) is a 544 function of the olivine texture, which evolves due to the deformation. Hence the 545 asthenospheric rheology depends on the kinematics and vice-versa. Indeed, the models with 546 an instantaneous change in the force direction demonstrate that applying the same stress but 547 with different velocity boundary conditions (i.e. enforcing deformations consistent with 548 individual forces on the asthenosphere, as shown on Fig. 4) can produce very different strain 549 rate histories (e.g. Fig. 5, right column). For example, after creating a texture by force  $F_{l}$ , switching to  $F_2$  or  $F_5$  both involve the same new stress state and both initially activate the 550 551 same (010)[001] slip system. Thus, both deformations initially produce the same (although 552 much reduced) strain rate (Fig. 5B). However, enforcing shear deformation in the vertical 553 direction (i.e. by  $F_5$ ) allows for faster rotations of the olivine grains into the new shear 554 direction, allowing for higher strain rates as the texture develops.
- 555 Without changes in the shear force direction, the plate-velocity evolution follows a similar 556 trend to the values of P-a (point-like distribution value for the olivine a-axes) (Fig. 3). 557 However, if the direction of the shear force changes, this correlation is less clear. We 558 calculated the texture parameters described in section 3.1.1 for each model for a 0.5 strain increment, for which an example is presented in Figure 9. If the texture is rotated 90° around 559 560 the z-axis with respect to the shear stress (in 1 Myr), then the changes in the values of P-a are 561 no longer correlated to the changes in the plate velocity, especially around the time of the 562 rotation (between a strain of 8 and 11), at which point the values of P for the a-, b-, and c-axes (P-a, P-b, P-c) and the M-index are the largest (Fig. 9), while the plate velocity is the lowest. 563
- To analyze the overall relationship between texture parameters and kinematic parameters (e.g. plate velocity), we performed a Pearce correlation for all the models representing shearing by plate pull. The correlation values between the plate velocity and texture parameters (*Fig. 9*) demonstrate that the mean orientation of the olivine a-axes (*ori-a* on *Fig. 9*) as well as the mean orientation of the c-axes (*ori-c*) are highly anticorrelated with the plate velocity. In contrast, *P-a* has the highest correlation with the plate velocity of 0.64, which is similar to the strength of the anticorrelation between the G-value (girdle-like distribution) of the a-axes (*G*-

571 a) and the plate velocity  $(v_{plate})$ . It is important to note that these parameters are not 572 independent from each other, as G-a and P-a are anticorrelated with a coefficient of -0.94 573 (similarly, -0.83 between *G*-*b* and *P*-*b*) and a 0.85 correlation between *ori-a* and *ori-c* (*Suppl.* 574 Fig. S1). Based on the correlation between the texture parameters and the plate velocity, as 575 well as between each pair of texture parameters, we find that the plate velocity can be linked 576 essentially to two parameters, the mean orientation and the value of P for the distribution of 577 the a-axes of the olivine grains, and therefore we see the strongest correlation between the 578 plate velocity and the product of those two parameters (*P-a*  $\cdot cos(ori-a)$  in Figure 9).

579 The need to consider both mean orientation and value of P for the a-axes provides important 580 context for comparison to previous investigations of texture evolution in olivine. Boneh et al. 581 (2015) used DRex, a different model of texture evolution (Kaminski and Ribe, 2002), to 582 investigate the influence of changing the deformation kinematics on texture. By examining 583 scenarios similar to our cases  $F_2$  and  $F_3$ , Boneh et al. (2015) concluded that olivine texture 584 evolves to a new steady state by a shear strain of ~4. This conclusion was based on tracking 585 the dominant a-axis orientation, and is consistent with our observations (Fig. 5). However, 586 our investigation of the mechanical response of an olivine aggregate suggests that the 587 evolution of the viscosity can be considerably more protracted (especially for F<sub>2</sub>), and our 588 correlation analysis demonstrates that additional features of the texture, most notably P-a, are 589 likely responsible for that difference.

590 The orientation of the olivine grains also exerts an important control on the direction of the 591 plate motion (or asthenospheric flow) with respect to the driving force. As noted above, in the 592 case of continuous shearing in one direction, the shear stress induces very little non-parallel 593 shear strain, but as soon as the shear direction is changed toward the mean orientation of the 594 olivine c-axes (i.e. the strongest slip system), we observe an increase in strain rates in 595 directions that are non-parallel to the shear stress. While the relationship between these 596 factors is not straightforward, it is clear that as *ori-a* starts to differ from the shear direction, 597 there is a corresponding change in the plate-motion direction (Fig. 7 & 8). The highest values 598 of  $\beta$  (plate-motion direction) occur at times in which *ori-a* differs 30-60° from the shear 599 direction. When this angle is higher,  $\beta$  decreases to ~0°, and the plate velocity slows 600 considerably. This behavior occurs because it is not possible to create strain perpendicular to 601 the forcing. Thus, when a grain is oriented such that the a-axis is perpendicular to the shear 602 direction, the easiest slip system cannot be activated (Suppl. Fig. S2).

#### **5.** *Relevance to natural phenomena*

604 Although our models are simplistic by nature, we can use them to gain some intuition about 605 how viscous anisotropy may affect different geodynamic processes. However, before we 606 proceed, it is important to note the limitations of our models. In particular, we have assumed 607 that the asthenosphere under a large (6000x6000 km<sup>2</sup>) plate deforms uniformly, and therefore the olivine texture, and its associated rheology, changes uniformly under the entire plate. 608 609 Certainly, we may expect some textural heterogeneity for most realistic geodynamic 610 scenarios, and this complexity may localize or otherwise change deformation patterns, 611 affecting the results. Furthermore, our assumption that deformation occurs in a 200-km thick 612 homogeneous layer of asthenosphere does not account for the possibility that deformation 613 may be shifted to deeper layers if asthenospheric textures act to increase the asthenosphere's 614 effective viscosity. Indeed, such a scenario is consistent with layered anisotropic textures 615 under continents (e.g., Yuan and Romanowicz, 2010) and oceans (e.g., Beghein et al., 2014). 616 Furthermore, other factors not included in our model, such as the presence of melt or strain 617 localization, may affect deformation and/or textural development. As an example, our model 618 also does not explicitly account for dynamic recrystallization, which Signorelli and Tommasi, 619 (2015) showed can slightly increase the rate of fabric realignment relative to models with no 620 recrystallization. However, our model parameters are calibrated based on laboratory 621 experiments that inherently include such recrystallization (Hansen et al., 2016a, 2016b), and 622 therefore, any application of this model assumes that rates of dynamic recrystallization are 623 similar to those in laboratory experiments.

624 Despite these caveats, our simple experiments suggest that the textural anisotropy of the 625 mantle should be associated with directional differences in effective viscosity that can be 626 large (up to order of magnitude) and can change with time as textures develop. Anisotropic 627 viscosity should thus influence a range of different geodynamic processes, and we can use our 628 simple models to identify these influences (Fig. 10). In particular, depending on the 629 orientation of the tectonic force with respect to the mean orientation of the olivine grains, and 630 with respect to the three slip systems that can accommodate deformation, the anisotropic 631 texture may either assist or resist continued deformation for a given process. This means that 632 anisotropic viscosity may facilitate certain types of tectonic processes and impede others. We 633 can thus use our simple models to generally characterize the expected trends relating viscous 634 anisotropy to geodynamic processes. More quantitative characterization of the impact of 635 viscous anisotropy will require more sophisticated modeling efforts.

#### 636 **5.1 Change in the direction of plate motion**

637 By changing the orientation of the shear force in the horizontal direction (e.g. Fig. 5A), we 638 demonstrate that the asthenospheric texture should significantly influence the motion of a 639 tectonic plate. Indeed, for horizontally-oriented shear, the effective viscosity of an olivine 640 aggregate may be a factor of  $\sim 5$  times smaller when the shear force is parallel to the mean 641 orientation of the a-axis of olivine grains (ori-a) compared to perpendicular to ori-a (Fig. 10). 642 Thus, if the texture beneath the plate is characterized by strong alignment of the a-axes, then a 643 large change in the orientation of forces on the plate may result in a significant slowing of the 644 plate velocity (up to a factor of 5 in the case of a uniformly-deforming asthenosphere), even if 645 the change in the orientation of forces occurs over a period of more than 10 million years 646 (Fig. 6). The stronger the initial texture (e.g., formed as a result of strains greater than 2, Fig. 647 7), and the larger the change in the orientation of the plate driving force (e.g., more than  $45^{\circ}$ , 648 Fig. 8), the larger and more lasting the asthenospheric resistance will be to changes in the 649 orientation of the driving forces. This asthenospheric resistance, induced by shear forces 650 misaligned with the preferred orientation of the texture, can also result in plate motion that is 651 not parallel to the plate driving force (Figs. 6A, 7A, 8A). This misalignment can last for 10s of 652 millions of years because the asthenospheric texture may be slow to redevelop.

653 Thus, we expect that anisotropic viscosity may significantly modify the relationship between 654 plate motions and the forces that drive them (e.g., Becker et al., 2006; Conrad and Lithgow-655 Bertelloni, 2004). Although Becker and Kawakatsu (2011) found that mantle flow models that 656 included viscosity anisotropy behaved similarly to isotropic models, their study did not 657 examine time-dependent behavior. Instead, our results suggest that time-dependent changes to 658 the driving forces on plates, or to the amplitude or orientation of the anisotropic texture 659 beneath them, should result in potentially large differences between the orientation of the net 660 driving force on a plate and the direction of the resulting asthenospheric flow and plate 661 motion. Note that the effective viscosity of the asthenosphere may also vary spatially beneath 662 the plate depending on the orientation and maturity of the olivine texture locally. These 663 spatial, temporal, and directional differences in the resistance that the asthenosphere exerts on plate motions may persist for durations of 10s of Myr (e.g., Fig. 8). 664

665 Our results suggest that anisotropic viscosity may cause a plate to respond only sluggishly to 666 changes in the direction of its driving forces. Indeed, plate motions in global plate 667 reconstruction models are observed to remain relatively stable for long periods (10s of Myr), 668 except for a few brief periods of global reorganization (Bercovici et al., 2000). This overall 669 stability has been attributed to slow evolution of the plate driving forces (e.g., Richards and 670 Lithgow-Bertelloni, 1996), despite the possibility that slab breakoff (Andrews and Billen, 671 2009) or even a change in the direction and magnitude of subduction-related stresses (e.g., 672 Capitanio et al., 2011; Jahren et al., 2005) may change the driving forces on plates quickly. 673 The sluggishness with which anisotropic textures adjust to changes in the orientation of the 674 applied driving force may represent an alternative mechanism to explain the gradual changes 675 in the direction of plate motions observed in reconstructions. This mechanism predicts that driving forces, asthenospheric resistance, and hence plate motions may be misaligned for 676 677 significant periods of time. Indeed such misalignment might be relevant for the Pacific plate 678 over the past 20 Myr (Faccenna et al., 2012).

#### 679 **5.2 Transform faults**

680 Asthenospheric mantle, sheared by plate motions, should experience shear stresses in a 681 horizontal direction on vertical planes near transform faults. Strain that results from these 682 stresses will be enhanced by viscous anisotropy. If the shearing direction is parallel to the 683 plate motions that generated the asthenospheric texture ( $F_4$  in Fig. 4; Fig. 5C; Fig. 10) the initially weakened asthenosphere will likely become stronger due to the evolving texture that 684 685 results in a strengthening, girdle-like distribution. For transform motion perpendicular to this texture ( $F_6$  in Fig. 4; Fig. 5C; Fig. 10), the initial rotation of the olivine grains significantly 686 weakens the asthenosphere. Interestingly, the results of this simple analysis are consistent 687 688 with the large number of transform faults in the oceanic lithosphere. Although transform 689 faults usually form close to the ridge where the asthenosphere has not been sheared for long, 690 and where texture development involves a more complicated history associated with corner 691 flow (Blackman et al., 2017), it is possible that the low asthenospheric resistance aids the 692 formation of lithospheric scale transform faults.

693

#### 5.3 Initiation of subduction or dripping

694 Changing the direction of the shear force from horizontal to vertical can be roughly associated 695 with the initiation of slab subduction or dripping of lithospheric mantle. Our results ( $F_3$  and  $F_5$ 696 in *Fig. 5A&B, Fig. 10*) suggest that asthenosphere with well-oriented olivine grains imposes 697 small resistance for such processes if they are oriented perpendicular to the initial plate-698 motion direction, but large resistance if they are oriented on the plane that is parallel to the 699 plate motion. This finding is consistent with the observed orientation of subduction trenches, 697 which are usually close to perpendicular to the long-term plate motion direction. Motion in 701 response to a vertically-oriented shear force on a plane perpendicular to the initial plate-702 motion direction (e.g, trench-perpendicular subduction,  $F_3$  in Figure 4) exhibits a short period 703 of increased resistance to deformation that must be overcome before the texture weakens 704 (Figure 5C, blue curve). Thus, asthenospheric textures may initially pose a slight impediment 705 to subduction initiation, but after a few Myrs, the olivine texture evolution may hasten the 706 evolution of subduction. In contrast, vertical motion in response to a vertical shear force on a plane parallel to plate motions (e.g., very oblique subduction or Richter-rolls,  $F_1$  to  $F_5$  in Fig. 707 708 4) is highly resisted by the anisotropic fabric, but in the long term, olivine texture 709 development induces asthenospheric weakening, which may allow for accelerated growth of 710 lithospheric instabilities (Fig. 5B, orange curve).

711 However, both subduction initiation and small-scale convection involve more complex 712 deformation than the simple instantaneous change in shear direction that is modeled here. For 713 example, subduction zones often start along transform faults or in the vicinity of active 714 subductions (Crameri et al., 2020), both of which can fundamentally change the 715 asthenospheric texture and hence its resistance to the formation of new slabs or lithospheric 716 instabilities. The rheology of the lithosphere also plays a potentially large role in subduction 717 initiation, and it is possible that olivine texture can become frozen into the oceanic lithosphere 718 as it cools (Tommasi, 1998), which would likely affect the rheology of the plate, and hence, 719 its resistance to bending. Although analysis of this deformation is beyond the scope of this 720 study, the combined effect of asthenospheric and lithospheric weakening due to anisotropy 721 could allow for subduction zone initiation in response to lower tectonic stresses than usually 722 expected (e.g., Gurnis et al., 2004). To explore the role of asthenospheric and lithospheric 723 viscous anisotropy in such complex processes, more sophisticated 3D geodynamic modeling 724 is required.

725

#### 726 **6.** *Conclusions*

Olivine texture development in the asthenosphere and its response to shearing are highly coupled and can exert considerable influences on geodynamic processes. In response to unidirectional shearing of the asthenosphere, the formation of an olivine texture causes a significant decrease in effective mantle viscosity after accumulating a shear strain of ~5. After this texture has formed, changes to the direction of the forces on the system, as induced by a change in the tectonic setting, result in a different effective viscosity because of the 733 mechanically anisotropic nature of the textured asthenosphere. Our results indicate that 734 differences in the effective viscosity associated with shearing asthenosphere primarily result 735 from the relative activation of olivine's weak and strong slip systems. The resulting 736 differences in effective viscosity can be over an order of magnitude, and should hinder some 737 tectonic processes and foster others, depending on their sense of deformation relative to 738 asthenospheric textures (Fig. 10). If the new shear direction is such that the strongest slip 739 system, (010)[001], has to be activated to produce deformation, then the effective viscosity 740 will increase. This increase is generally the case for a change in the direction of plate motion 741 or vertical shearing on a plane parallel to plate motions. In contrast, the mantle should remain 742 weak, or even become weaker, for shear forces that primarily induce deformation on the other 743 two, weaker slip systems, (010)[100] and (001)[100], which is the case for transform motions, 744 subduction initiation, or ongoing plate motion in the same direction. Thus, based on our 745 simple models, we expect asthenospheric textures to significantly slow changes to the 746 direction of plate motions and hinder the formation of ridge-perpendicular subduction zones. 747 Conversely, these textures should assist in the initiation of new subduction zones parallel to 748 mid-ocean ridges (perpendicular to plate motion) and promote the development of 749 lithospheric scale transform faults. To fully understand the impact of anisotropic viscosity on 750 plate tectonics and asthenospheric dynamics, olivine texture development, and the anisotropic 751 viscosity that is associated with it, needs to be integrated into 3D dynamic models of the 752 relevant processes.

#### 753 Acknowledgement

This manuscript was significantly improved by constructive feedback from two anonymous
reviewers. This work was supported by the Research Council of Norway Centres of
Excellence project 223272. Data and code availability: <u>https://doi.org/10.11582/2020.00039</u>
(Please also refer to the supplementary material for more information about the model data
and code).

759

#### 760 **References**

Andrews, E.R., Billen, M.I., 2009. Rheologic controls on the dynamics of slab detachment.
 Tectonophysics, Interpreting the tectonic evolution of Pacific Rim margins using plate

- 763 kinematics slab window and volcanism 464. 60-69. 764 https://doi.org/10.1016/j.tecto.2007.09.004
- Bamford, D., Crampin, S., 1977. Seismic anisotropy the state of the art. Geophysical Journal 765 766 Of The Royal Astronomical Society 49, 1–8. https://doi.org/10.1111/j.1365-767 246X.1977.tb03697.x
- 768 Becker, T.W., 2008. Azimuthal seismic anisotropy constrains net rotation of the lithosphere. 769 Geophys. Res. Lett. 35, L05303. https://doi.org/10.1029/2007GL032928
- 770 Becker, T.W., Chevrot, S., Schulte-Pelkum, V., Blackman, D.K., 2006. Statistical properties

of seismic anisotropy predicted by upper mantle geodynamic models. Journal of 772 Geophysical Research: Solid Earth 111. https://doi.org/10.1029/2005JB004095

- 773 Becker, T.W., Conrad, C.P., Schaeffer, A.J., Lebedev, S., 2014. Origin of azimuthal seismic
- 774 anisotropy in oceanic plates and mantle. Earth and Planetary Science Letters 401, 236-250. 775 https://doi.org/10.1016/j.epsl.2014.06.014
- 776 Becker, T.W., Kawakatsu, H., 2011. On the role of anisotropic viscosity for plate-scale flow. 777 Geophysical Research Letters 38, 1-5. https://doi.org/10.1029/2011GL048584
- 778 Becker, T.W., Kellogg, J.B., Ekström, G., O'Connell, R.J., 2003. Comparison of azimuthal 779 seismic anisotropy from surface waves and finite strain from global mantle-circulation 780 models. Geophys J Int 155, 696–714. https://doi.org/10.1046/j.1365-246X.2003.02085.x
- 781 Becker, T.W., Kustowski, B., Ekström, G., 2008. Radial seismic anisotropy as a constraint for 782 upper mantle rheology. Earth and Planetary Science Letters 267, 213-227. 783 https://doi.org/10.1016/j.epsl.2007.11.038
- 784 Beghein, C., Yuan, K., Schmerr, N., Xing, Z., 2014. Changes in Seismic Anisotropy Shed 785 Light on the Nature of the Gutenberg Discontinuity. Science 343, 1237–1240. 786 https://doi.org/10.1126/science.1246724
- 787 Behn, M.D., Conrad, C.P., Silver, P.G., 2004. Detection of upper mantle flow associated with 788 the African Superplume. Earth and Planetary Science Letters 224, 259-274. 789 https://doi.org/10.1016/j.epsl.2004.05.026
- 790 Bercovici, D., Ricard, Y., Richards, M.A., 2000. The Relation between mantle dynamics and
- 791 plate tectonics: A Primer, in: Richards, M.A., Gordon, R.G., van der Hilst, R.D. (Eds.),
- 792 Geophysical Monograph Series. American Geophysical Union, Washington, D. C., pp. 5-
- 793 46. https://doi.org/10.1029/GM121p0005

- Blackman, D.K., Boyce, D.E., Castelnau, O., Dawson, P.R., Laske, G., 2017. Effects of
  crystal preferred orientation on upper-mantle flow near plate boundaries: rheologic
  feedbacks and seismic anisotropy. Geophysical Journal International 210, 1481–1493.
  https://doi.org/10.1093/gji/ggx251
- Boneh, Y., Morales, L.F.G., Kaminski, E., Skemer, P., 2015. Modeling olivine CPO evolution
  with complex deformation histories: Implications for the interpretation of seismic anisotropy
  in the mantle. Geochemistry, Geophysics, Geosystems 16, 3436–3455.
  https://doi.org/10.1002/2015GC005964
- Bunge, H., 1982. Texture Analysis in Materials Science: Mathematical Models. Butterworths,
  London.
- Capitanio, F.A., Faccenna, C., Zlotnik, S., Stegman, D.R., 2011. Subduction dynamics and
  the origin of Andean orogeny and the Bolivian orocline. Nature 480.
- Christensen, N.I., 1984. The magnitude, symmetry and origin of upper mantle anisotropy
  based on fabric analyses of ultramafic tectonites. Geophysical Journal International 76, 89–
  111. https://doi.org/10.1111/j.1365-246X.1984.tb05025.x
- Christensen, U.R., 1987. Some geodynamical effects of anisotropic viscosity. Geophysical
  Journal of the Royal Astronomical Society 91, 711–736. https://doi.org/10.1111/j.1365246X.1987.tb01666.x
- 812 Conrad, C.P., Behn, M.D., 2010. Constraints on lithosphere net rotation and asthenospheric
  813 viscosity from global mantle flow models and seismic anisotropy: ANISOTROPY AND
  814 LITHOSPHERE NET ROTATION. Geochem. Geophys. Geosyst. 11, n/a-n/a.
  815 https://doi.org/10.1029/2009GC002970
- 816 Conrad, C.P., Lithgow-Bertelloni, C., 2004. The temporal evolution of plate driving forces:
  817 Importance of "slab suction" versus "slab pull" during the Cenozoic. Journal of Geophysical
  818 Research B: Solid Earth 109, 1–14. https://doi.org/10.1029/2004JB002991
- 819 Crameri, F., Magni, V., Domeier, M., Shephard, G.E., Chotalia, K., Cooper, G., Eakin, C.M.,
- 820 Grima, A.G., Gürer, D., Király, Á., Mulyukova, E., Peters, K., Robert, B., Thielmann, M.,
- 821 2020. A transdisciplinary and community-driven database to unravel subduction zone
- 822 initiation. Nature Communications 11, 3750. https://doi.org/10.1038/s41467-020-17522-9

- Dellinger, J., Vasicek, D., Sondergeld, C., 1998. Kelvin Notation for Stabilizing ElasticConstant Inversion. Revue de l'Institut Français du Pétrole 53, 709–719.
  https://doi.org/10.2516/ogst:1998063
- Burham, W.B., Goetze, C., 1977. Plastic flow of oriented single crystals of Olivine 1.
  Mechanical Data. Journal of Geophysical Research 82, 5737–5753.
- 828 Eakin, C.M., Rychert, C.A., Harmon, N., 2018. The Role of Oceanic Transform Faults in
- 829 Seafloor Spreading: A Global Perspective From Seismic Anisotropy. Journal of Geophysical
- 830 Research: Solid Earth 123, 1736–1751. https://doi.org/10.1002/2017JB015176
- 831 Faccenna, C., Becker, T.W., Lallemand, S., Steinberger, B., 2012. On the role of slab pull in
- the Cenozoic motion of the Pacific plate. Geophysical Research Letters 39, 1–6.
  https://doi.org/10.1029/2011GL050155
- 834 Gaboret, C., Forte, A.M., Montagner, J.-P., 2003. The unique dynamics of the Pacific
- 835 Hemisphere mantle and its signature on seismic anisotropy. Earth and Planetary Science
- 836 Letters 208, 219–233. https://doi.org/10.1016/S0012-821X(03)00037-2
- Gerya, T.V., 2016. Origin, Evolution, Seismicity, and Models of Oceanic and Continental
  Transform Boundaries, in: Plate Boundaries and Natural Hazards. American Geophysical
  Union (AGU), pp. 39–76. https://doi.org/10.1002/9781119054146.ch3
- 840 Gurnis, M., Hall, C., Lavier, L., 2004. Evolving force balance during incipient subduction.
- 841 Geochemistry, Geophysics, Geosystems 5. https://doi.org/10.1029/2003GC000681
- 842 Hansen, L.N., Conrad, C.P., Boneh, Y., Skemer, P., Warren, J.M., Kohlstedt, D.L., 2016a.
- 843 Viscous anisotropy of textured olivine aggregates: 2. Micromechanical model. Journal of
- 844 Geophysical Research: Solid Earth 121, 7137–7160. https://doi.org/10.1002/2016JB013304
- Hansen, L.N., Warren, J.M., Zimmerman, M.E., Kohlstedt, D.L., 2016b. Viscous anisotropy
  of textured olivine aggregates, Part 1: Measurement of the magnitude and evolution of
  anisotropy. Earth and Planetary Science Letters 445, 92–103.
  https://doi.org/10.1016/j.epsl.2016.04.008
- Hansen, L.N., Zimmerman, M.E., Kohlstedt, D.L., 2012. Laboratory measurements of the
  viscous anisotropy of olivine aggregates. Nature 492, 415–418.
  https://doi.org/10.1038/nature11671

- Jahren, A.H., Conrad, C.P., Arens, N.C., Mora, G., Lithgow-Bertelloni, C., 2005. A plate
- tectonic mechanism for methane hydrate release along subduction zones. Earth and Planetary
- 854 Science Letters 236, 691–704. https://doi.org/10.1016/j.epsl.2005.06.009
- 855 Kaminski, É., Ribe, N.M., 2002. Timescales for the evolution of seismic anisotropy in mantle
- 856 flow. Geochemistry, Geophysics, Geosystems 3, 1–17.
  857 https://doi.org/10.1029/2001GC000222
- 858 Karato, S., 1987. Seismic anisotropy due to lattice preferred orientation of minerals: 859 Kinematic or dynamic?, in: Manghnani, M.H., Syono, Y. (Eds.), Geophysical Monograph 860 Washington, D. С., Series. American Geophysical Union, pp. 455-471. 861 https://doi.org/10.1029/GM039p0455
- Karato, S., Wu, P., 1993. Rheology of the Upper Mantle: A Synthesis. Science 260, 771–778.
- Lev, E., Hager, B.H., 2011. Anisotropic viscosity changes subduction zone thermal structure.
- 864 Geochemistry, Geophysics, Geosystems 12. https://doi.org/10.1029/2010GC003382
- Lev, E., Hager, B.H., 2008. Rayleigh-Taylor instabilities with anisotropic lithospheric
  viscosity. Geophysical Journal International 173, 806–814. https://doi.org/10.1111/j.1365246X.2008.03731.x
- Long, M.D., 2013. Constraints on Subduction Geodynamics From Seismic Anisotropy.
  Reviews of Geophysics 51, 76–112. https://doi.org/10.1002/rog.20008
- Long, M.D., Becker, T.W., 2010. Mantle dynamics and seismic anisotropy. Earth and
  Planetary Science Letters 297, 341–354. https://doi.org/10.1016/j.epsl.2010.06.036
- Mainprice, D., Bachmann, F., Hielscher, R., Schaeben, H., 2015. Descriptive tools for the
  analysis of texture projects with large datasets using MTEX: strength, symmetry and
  components. Geological Society, London, Special Publications 409, 251–271.
  https://doi.org/10.1144/SP409.8
- 876 Mühlhaus, H.-B., Čada, M., Moresi, L., 2003. Anisotropic Convection Model for the Earth's
- 877 Mantle, in: Sloot, P.M.A., Abramson, D., Bogdanov, A.V., Gorbachev, Y.E., Dongarra, J.J.,
- 878 Zomaya, A.Y. (Eds.), Computational Science ICCS 2003. Springer Berlin Heidelberg,
- 879 Berlin, Heidelberg, pp. 788–797. https://doi.org/10.1007/3-540-44863-2\_77
- 880 Mühlhaus, H.-B., Moresi, L., Hobbs, B., Dufour, F., 2002. Large Amplitude Folding in Finely
- 881 Layered Viscoelastic Rock Structures. Pure and Applied Geophysics 159, 2311–2333.
- 882 https://doi.org/10.1007/s00024-002-8737-4

- Pouilloux, L., Kaminski, E., Labrosse, S., 2007. Anisotropic rheology of a cubic medium and
  implications for geological materials. Geophysical Journal International 170, 876–885.
  https://doi.org/10.1111/j.1365-246X.2007.03461.x
- Richards, M.A., Lithgow-Bertelloni, C., 1996. Plate motion changes, the Hawaiian-Emperor
  bend, and the apparent success and failure of geodynamic models. Earth and Planetary
- 888 Science Letters 137, 19–27. https://doi.org/10.1016/0012-821X(95)00209-U
- Schellart, W.P., 2004. Kinematics of subduction and subduction-induced flow in the upper
  mantle. Journal of Geophysical Research B: Solid Earth 109, 1–19.
  https://doi.org/10.1029/2004JB002970
- 892 Signorelli, J., Tommasi, A., 2015. Modeling the effect of subgrain rotation recrystallization
- 893 on the evolution of olivine crystal preferred orientations in simple shear. Earth and Planetary
- 894 Science Letters 430, 356–366. https://doi.org/10.1016/j.epsl.2015.08.018
- Silver, P.G., 1996. SEISMIC ANISOTROPY BENEATH THE CONTINENTS: Probing the
  Depths of Geology. Annu. Rev. Earth Planet. Sci. 24, 385–432.
  https://doi.org/10.1146/annurev.earth.24.1.385
- Skemer, P., Katayama, I., Jiang, Z., Karato, S., 2005. The misorientation index: Development
  of a new method for calculating the strength of lattice-preferred orientation. Tectonophysics
  411, 157–167. https://doi.org/10.1016/j.tecto.2005.08.023
- 901 Stixrude, L., Lithgow-Bertelloni, C., 2005. Mineralogy and elasticity of the oceanic upper
- 902 mantle: Origin of the low-velocity zone. Journal of Geophysical Research: Solid Earth (1978–
- 903 2012) 110. https://doi.org/10.1029/2004JB002965
- Tanimoto, T., Anderson, D.L., 1984. Mapping convection in the mantle. Geophysical
  Research Letters 11, 287–290. https://doi.org/10.1029/GL011i004p00287
- 906 Taylor, G.I., 1938. Plastic Strain in Metals. Journal of Inst. Met. 62.
- Tommasi, A., 1998. Forward modeling of the development of seismic anisotropy in the upper
  mantle. Earth and Planetary Science Letters 160, 1–13. https://doi.org/10.1016/S0012821X(98)00081-8
- 910 Vollmer, F.W., 1990. An application of eigenvalue methods to structural domain analysis.
- 911 Bulletin of the Geological Society of America 102, 786–791. https://doi.org/10.1130/0016-
- 912 7606(1990)102<0786:AAOEMT>2.3.CO;2

- 913 Yuan, H., Romanowicz, B., 2010. Lithospheric layering in the North American craton. Nature
- 914 466, 1063–1068. https://doi.org/10.1038/nature09332

#### 916 Figures

A) Shear force applied to isotropic mantle



B) Shear force applied parallel to developed LPO (anisotropic weak mantle)



C) Shear force applied perpendicular to LPO (anisotropic strong mantle)



917

918 Figure 1: Relationship between anisotropic viscosity and olivine texture formation. A) A force

919  $(F_1)$  applied to an initially isotropic asthenosphere (i.e., without a pre-existing texture) yields

920 a moderate plate speed, and the associated asthenospheric deformation fosters olivine texture
921 development. B) The same force applied parallel to the a-axis of a well-developed texture

922 results in a much larger plate speed. C) Applying this force parallel to the c-axis causes the

923 plate to move much more slowly. The configuration depicted in panel (B) can evolve into the

configuration depicted in panel (C) in two ways. Either the force can be rotated relative to the 924

Plate velocity

[Pas]

Effective viscosity

925 texture (as for many geodynamic scenarios) or the texture can be rotated with respect to the

926 force (as illustrated in (C) and implemented in our modeling effort).

×10<sup>-14</sup> 2.4 A) D) Model 1 Model 2 Strain rate (1) Strain raten (2) الم س 20 2.3 Plate velocity (1)
 Plate velocity (2) 2.2 20 e E I I 10 rate [1/s] c 0 ° 0 10 12 nulated Strain 14 16 18 20 1.9 Strain A<sub>55</sub> (1) B)  $A_{55}(2) = -A_{44}(1)$ 1.8 A<sub>44</sub> (2) · -- · A<sub>66</sub> (1) ---- A<sub>66</sub> (2) 1.7 10 6 1.6 components 5 1.5 0 8 10 12 14 16 18 20 Accumulated Strain ×10<sup>19</sup> 4.6 ×10<sup>-14</sup> 2.4 👗 Fluidity . Strain rate (1) Strain raten (2) Effective viscos 2.3 4.4 2.2 1.2 2.1 2 1.8 1.8 1.8 0 <sup>⊾</sup> 2 3.8 18 14 16 12 20 10 Accumulated Strain 1.9 3.6 2 () components - A<sub>45</sub> (2) ---- A<sub>65</sub> (1) --(1) -- A<sub>cc</sub> (2) 1.8 1.7 3.2 Fluidity 4 1.6 -2 1.5 l 8 10 12 14 16 18 20 10 25 30 2 6 15 20 Time [Myr] Accumulated Strain



929 Figure 2: Results of two sets of models with constant shear stress ( $\sigma_{13}$  = 0.68 MPa), both 930 computed as average results from 5 model runs each starting from 1000 uniformly distributed 931 grain orientations. A) Accumulated strain as a function of time. B) Shear components of the 932 fluidity parameter tensor. A<sub>44</sub> and A<sub>66</sub> are fictive curves since the associated stresses for these 933 components,  $\sigma_{23}$  and  $\sigma_{12}$ , are zero.  $A_{55}$  represents the fluidity for the actual applied stress  $\sigma_{13}$ . 934 C) Fluidity components relating strain rates in the perpendicular direction  $(A_{45})$  or plane 935 (A<sub>65</sub>) with respect to the shear stress ( $\sigma_{13}$ ). D) Strain rate ( $|\epsilon|$ ) and plate velocity ( $V_{plate}$ ) as a 936 function of the accumulated strain. The plate velocity is calculated from the horizontal strain 937 rate component (eq. 10), while the strain-rate curve is the norm of the shear strain rate tensor 938 (for which only the non-diagonal components are non-zero). E) Strain rate and effective 939 viscosity as a function of time instead of accumulated strain.



Figure 3: The evolution of plate velocity and several texture parameters as a function of
accumulated strain (top panel) with pole figures (below) indicating the orientation density of
a-, b-, and c- axes for olivine aggregates with different total strains. The color scale indicates

944 multiples of a uniform density. The shear direction (marked by red arrows) is towards the

945 right and the shear plane is the same as the figure's plane.

#### Possibilities for changing the shear force



947

948 Figure 4: Possible orientations for the shear force, with  $F_1$  representing the orientation 949 associated with initial plate motion (e.g., as in Fig. 1b).  $F_2$  represents a shear force acting on a horizonal plane at 90° to the initial plate motion direction, analogous to a change in the 950 951 direction of the plate driving force.  $F_4$  and  $F_6$  represent forces that create shearing 952 deformation in a horizontal direction along vertical planes, analogous to transform shear 953 zones.  $F_3$  and  $F_5$  represent forces that create shearing deformation in a vertical direction on 954 vertical planes, analogous to subduction initiation or a dripping instability. In our analysis, 955 all forces have the same magnitude as  $F_1$ .

956

957





with shear force  $F_1$  until a strain of 8 (as in Fig. 2D). At a strain of 8, the direction of the shear force is instantaneously changed to the directions  $F_2$  through  $F_6$  (Fig. 4). Plots are grouped based on reciprocal pairs of deformation responding to the same imposed stress (see text). On the right side, pole figures indicate the texture for several points in the evolution denoted by arrows in the left diagrams. Note that all of the textures are presented relative to the mantle reference frame, and the shear force acting on the mantle is marked by red arrows (and arrow points and tails).

968



969

970 Figure 6: Results from models with different rates of imposed rotation of the shear stress. An

971 initial texture (associated with an accumulated strain of 8, using model 1 of Fig. 2) is rotated 972 90° around the z-axis (representing a change from  $F_1$  to  $F_2$ ) within a period between 1 and 13

973 Myr. a) Change in the direction of the shear force ( $\alpha$ , dashed lines) and plate motion ( $\beta$ , solid

974 lines) with respect to the x-axis (fixed to the mantle), as a function of accumulated strain. b)

975 Amplitude of the plate velocity as a function of accumulated strain.



977

978 Figure 7: Results from models with varying amounts of accumulated strain (and therefore 979 texture strength) at the time of the rotation (Pre-rotation strain). A) Direction of the shear 980 force ( $\alpha$ , dashed lines) and the plate motion ( $\beta$ , solid lines) for models that rotate the texture 981 90° in either 1 Myr (lighter colors) or 10 Myr (darker colors). B) Corresponding plate 982 velocity amplitudes vs. accumulated strain for the cases shown in (A). C) Local minimums 983 and maximums of the plate-motion direction marked with dots that are color-coded according 984 the accumulated strain (with respect to the shear force direction) for the five tested pre-985 rotation strains. For each switch strain, upper rows represent models using the 10 Myr 986 rotation time while the lower rows use 1 Myr rotations. D) Minimum plate velocity (i.e., 987 velocity right after the rotation) vs. the accumulated strain after which the rotation has 988 happened.



Figure 8: Results from models with varying amounts of rotation around the z-axis. Panels are
the same as in Fig. 7, except using rotation angle instead of pre-rotation strain in (C) and
(D).



996 Figure 9: Top) plate velocity and texture parameters, as a function of accumulated strain, for 997 a model in which a 90° rotation (representing a change from  $F_1$  to  $F_2$ ) is imposed over 1 Myr 998 after a strain of 8 (the fastest rotation presented in Fig. 6). Bottom) correlation between 999 texture parameters and plate velocity based on all models with rotation (0-90°) around the z-1000 axis, listed in order from negative (blue shades) to positive (red shades) correlations. 1001 Abbreviations: v<sub>plate</sub> plate velocity; ori-a (-b; -c) mean orientation of the olivine a-axes (b-1002 axes; c-axes); G, R, P (-a -b; -c) girdle, random, and point distribution parameters for each 1003 axes, respectively (Vollmer, 1990).



1005 Figure 10: Trends for the manner in which anisotropic viscosity in the asthenosphere should 1006 influence different geodynamic situations. The white to black arrow indicates the mantle 1007 weakening path associated with development of an LPO as the asthenosphere accumulates 1008 strain due to simple shear (e.g. in model 1). The colored arrows indicate the time evolution of 1009 the relative effective viscosity (vertical dimension, values based on results shown in Fig. 5) 1010 from the moment of switching the shear direction (strain of 8, marked with a star) through an 1011 accumulated strain of 14 (post-rotation strain of 6, black squares), and until a strain of 21 1012 (post-rotation strain of 13, indicated by the arrow tips). Geodynamic processes for which the 1013 effective viscosity increases ( $F_2$  plate motion and  $F_5$  subduction/dripping) could be initially 1014 impeded by anisotropic viscosity, while those for which the effective viscosity decreases ( $F_3$  -1015 subduction and dripping, and  $F_4$  and  $F_5$  - transform fault) could be initially promoted. 1016 Subsequent changes to the effective viscosity along each path indicate how continued texture 1017 development should either speed or slow each process as it develops.

Figure 1.

## A) Shear force applied to isotropic mantle

3

blate

No LPO developed

(1)

B) Shear force applied parallel to developed LPO (anisotropic weak mantle)

(3)



C) Shear force applied perpendicular to LPO (anisotropic strong mantle)



Vplate

?Vplate

Figure 2.



Figure 3.



Figure 4.

### Possibilities for changing the shear force



Figure 5.



![](_page_50_Figure_1.jpeg)

![](_page_50_Figure_2.jpeg)

Figure 6.

![](_page_52_Figure_0.jpeg)

![](_page_52_Figure_1.jpeg)

	_	
	-	
	_	
	_	
	-	
	-	
	2	U
214	(r	
3My	٢	
3My	۷r	
3My	۷r	
3My	/r	
3My	r	
3My	r	
3My	/r	
3My	r	
3My		
	r	
	r	
3My	r	

Figure 7.

![](_page_54_Figure_0.jpeg)

Figure 8.

![](_page_56_Figure_0.jpeg)

Figure 9.

![](_page_58_Figure_0.jpeg)

Vplate	-0.81	-0.75	-0.61	-0.52	-0.19	-0.18	0.14	0.14	0.17	0.26	0.43	0.48	0.64	0.81	NaN
	ori-a	oric	Gra	R-C	R-a	R.b	P.D	ori-b	G-C J-	ndex	P-C M-j	ndex	P-a P-a.cos	ori-a)	G-D

# Correlation between texture parameters and plate velocity from all models with rotation around the z-axes

![](_page_58_Picture_5.jpeg)

Figure 10.

![](_page_60_Picture_0.jpeg)