Evolving viscous anisotropy in the upper mantle and its geodynamic implications

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Abstract

Asthenospheric shear causes some minerals, particularly olivine, to develop anisotropic textures that can be detected seismically. In laboratory experiments, these textures are also associated with anisotropic viscous behavior, which should be important for geodynamic processes. To examine the role of anisotropic viscosity for asthenospheric deformation, we developed a numerical model of coupled anisotropic texture development and anisotropic viscosity, both calibrated with laboratory measurements of olivine aggregates. This model characterizes the time-dependent coupling between large-scale formation of lattice-preferred orientation (i.e., texture) and changes in asthenospheric viscosity for a series of simple deformation paths that represent upper-mantle geodynamic processes. We find that texture development beneath a moving surface plate tends to align the a-axes of olivine into the plate-motion direction, which weakens the effective viscosity in this direction and increases plate velocity for a given driving force. Our models indicate that the effective viscosity increases for shear in the horizontal direction perpendicular to the a-axes. This increase should slow plate motions and new texture development in this perpendicular direction, and could impede changes to the plate motion direction for 10s of Myrs. However, the same well-developed asthenospheric texture may foster subduction initiation perpendicular to the plate motion and 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-deformation in the presence of a well-formed asthenospheric texture illustrate the importance of the mean olivine orientation, and its associated viscous anisotropy, for a variety of geodynamic processes.

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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

Key words

Olivine, Anisotropic viscosity, LPO, Texture development, Plate motions, Asthenospheric deformation

Abstract

Asthenospheric shear causes some minerals, particularly olivine, to develop anisotropic textures that can be detected seismically. In laboratory experiments, these textures are also associated with anisotropic viscous behavior, which should be important for geodynamic processes. To examine the role of anisotropic viscosity for asthenospheric deformation, we developed a numerical model of coupled anisotropic texture development and anisotropic viscosity, both calibrated with laboratory measurements of olivine aggregates. This model characterizes the time-dependent coupling between large-scale formation of lattice-preferred orientation (i.e., texture) and changes in asthenospheric viscosity for a series of simple deformation paths that represent upper-mantle geodynamic processes. We find that texture development beneath a moving surface plate tends to align the a-axes of olivine into the plate-motion direction, which weakens the effective viscosity in this direction and increases plate velocity for a given driving force. Our models indicate that the effective viscosity increases for shear in the horizontal direction perpendicular to the a-axes. This increase should slow plate motions and new texture development in this perpendicular direction, and could impede changes to the plate motion direction for 10s of Myrs. However, the same well-developed asthenospheric texture may foster subduction initiation perpendicular to the plate motion and 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-deformation in the presence of a well-formed asthenospheric texture illustrate the importance of the mean olivine orientation, and its associated viscous anisotropy, for a variety of geodynamic processes.

Plain language summary

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-forming mineral in the asthenosphere, rotate into a preferred direction parallel to the deformation, developing a texture that can affect the response of the asthenosphere to tectonic stresses. Laboratory measurements show that the deformation rate depends on the orientation of the shear stress relative to the olivine texture. We use numerical models to apply the 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 response to shear stress, which are highly coupled. Our results suggest that anisotropic viscosity in the asthenosphere can significantly affect the motions of tectonic plates, as plate motion in a continuous direction should become faster while abrupt changes in the direction of plate motion should meet high resistance in the underlying asthenosphere. We suggest that olivine textures in the asthenosphere play a critical role in upper mantle dynamics.

1. Introduction

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

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

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

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

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

2. Methods

2.1 Mathematical formulation

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

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

$$\sigma_{kl} = \eta_{ijkl}\dot{\varepsilon}_{ij} \, , \tag{1}$$

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, σ_{kl} is the deviatoric-stress tensor, and η_{ijkl} is the viscosity tensor (Christensen, 1987; Pouilloux et al., 2007). Due to their symmetry, the deviatoric-stress and the strain-rate tensors can both be reduced to vectors using Kelvin notation, which preserves the norm of each of the tensors in (1) (Dellinger et al., 1998),

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

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

It follows that the viscosity can be reduced to a 6x6 tensor (e.g., Pouilloux et al., 2007). Because of the non-linear rheological behavior of olivine, the viscosity tensor is also a function of stress. The rheology can thus be expressed by a stress-independent material constant ($\underline{A}$), which relates to the viscosity as

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

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

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

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

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

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

$$
\underline{\underline{E}} = \underline{\underline{A}} \cdot \underline{\underline{S}}, \qquad (7)
$$

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

$$
\begin{bmatrix}
{II_{\sigma_1}}^{(n-1)/2}\sigma_{1_1} & {II_{\sigma_1}}^{(n-1)/2}\sigma_{2_1} & {II_{\sigma_1}}^{(n-1)/2}\sigma_{3_1} & {II_{\sigma_1}}^{(n-1)/2}\sigma_{4_1} & {II_{\sigma_1}}^{(n-1)/2}\sigma_{5_1} & {II_{\sigma_1}}^{(n-1)/2}\sigma_{6_1} \\
{II_{\sigma_2}}^{(n-1)/2}\sigma_{1_2} & {II_{\sigma_2}}^{(n-1)/2}\sigma_{2_2} & {II_{\sigma_2}}^{(n-1)/2}\sigma_{3_2} & {II_{\sigma_2}}^{(n-1)/2}\sigma_{4_3} & {II_{\sigma_2}}^{(n-1)/2}\sigma_{5_2} & {II_{\sigma_2}}^{(n-1)/2}\sigma_{2_2} \\
{II_{\sigma_3}}^{(n-1)/2}\sigma_{1_3} & {II_{\sigma_3}}^{(n-1)/2}\sigma_{2_3} & {II_{\sigma_3}}^{(n-1)/2}\sigma_{3_3} & {II_{\sigma_3}}^{(n-1)/2}\sigma_{4_3} & {II_{\sigma_3}}^{(n-1)/2}\sigma_{5_3} & {II_{\sigma_3}}^{(n-1)/2}\sigma_{6_3} \\
{II_{\sigma_4}}^{(n-1)/2}\sigma_{1_4} & {II_{\sigma_4}}^{(n-1)/2}\sigma_{2_4} & {II_{\sigma_4}}^{(n-1)/2}\sigma_{3_4} & {II_{\sigma_4}}^{(n-1)/2}\sigma_{4_4} & {II_{\sigma_4}}^{(n-1)/2}\sigma_{5_4} & {II_{\sigma_4}}^{(n-1)/2}\sigma_{6_4} \\
{II_{\sigma_5}}^{(n-1)/2}\sigma_{1_5} & {II_{\sigma_5}}^{(n-1)/2}\sigma_{2_5} & {II_{\sigma_5}}^{(n-1)/2}\sigma_{3_5} & {II_{\sigma_5}}^{(n-1)/2}\sigma_{4_5} & {II_{\sigma_5}}^{(n-1)/2}\sigma_{5_5} & {II_{\sigma_5}}^{(n-1)/2}\sigma_{6_5} \\
{II_{\sigma_6}}^{(n-1)/2}\sigma_{1_6} & {II_{\sigma_6}}^{(n-1)/2}\sigma_{2_6} & {II_{\sigma_6}}^{(n-1)/2}\sigma_{3_6} & {II_{\sigma_6}}^{(n-1)/2}\sigma_{4_6} & {II_{\sigma_6}}^{(n-1)/2}\sigma_{5_6} & {II_{\sigma_6}}^{(n-1)/2}\sigma_{6_6}
\end{bmatrix}
$$

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

$$\underline{\underline{A}}' = \underline{\underline{E}}' \cdot \underline{\underline{S}}'^{-1} \qquad (8)$$

can be solved.

Knowing the fluidity parameter tensor, $\underline{\underline{A}}'$, 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

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

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

2.2 Geodynamic model

To investigate the influence of anisotropic viscous behavior in geodynamic scenarios with changing orientations of stress, we model the deformation of a set of olivine grains 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 km that is necessary to balance an edge force of 4.1·10^12 N/m (a lower bound estimate for the value of slab pull force transferred to the plate from the negative buoyancy of a subducting oceanic lithosphere; Schellart, 2004) above a 200-km-thick asthenosphere (*Fig. 1A*). We track the deformation of the asthenosphere using the micromechanical model of texture-development and viscous anisotropy described above. Based on the anisotropic properties of a representative olivine aggregate, we compute the strain rate within the asthenosphere, and associated parameters such as plate speed and movement direction, all as a function of time, accumulated strain, and olivine texture development. To calculate the plate 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

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

To investigate different deformation paths that are analogs for a variety of upper mantle processes, we change the orientation of the applied shear stress, and consequently the deformation applied to the asthenosphere, at a chosen instant after an olivine texture has formed (*Fig. 1B*). Such a change could be induced by a change in the external driving forces applied to the asthenosphere. An intuitively simple approach would be to rotate the imposed driving stress relative to the texture that initially formed. However, for numerical and analytical simplicity, we instead rotate the olivine texture with respect to the imposed stress (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 9) unchanged. Later, we will discuss the geodynamic scenarios represented by the various rotations of the olive texture with respect to the applied shear stress.

We define the angles α and β 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, α 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 β 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 (*β*), as follows:

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

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 (6000x6000 km^2) plate using the average of 5 model runs of 1000 grains each.

3.1. Monotonic simple shear

First, we present the evolution of asthenospheric strain rates and olivine texture development from a uniformly distributed texture (i.e., an isotropic mantle) to a well-developed texture (anisotropic, weak mantle). As the mantle accumulates strain, the a-axes of olivine rotate towards the shear direction *(Fig. 1B)*, developing a texture that decreases the effective viscosity of the asthenosphere and, therefore, increases the velocity of the plate. We examined two sets of models differing only in the randomly created uniformly distributed orientations at the start of the models (*Fig. 2*, black and grey curves). The similarity of these two model averages implies that the average of model runs with 5x1000 grains gives a reasonably stable result. However, subtle differences in the initial textures of the two models can still cause 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 strain rate hereafter) exhibits characteristic variations throughout this deformation (*Fig. 2*), 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, the strain rate in the asthenosphere is 1.5-1.7·10^{-14} s^{-1}, which corresponds to a plate velocity of ~9.5-10.5 cm/yr velocity. As accumulated strain increases, the olivine texture develops, the effective viscosity of the asthenosphere decreases, and the plate velocity increases, reaching a maximum of 14.8 cm/yr (2.4·10^{-14} s^{-1}) around a strain of 8, i.e. after ~14 Myr of shearing. With further shearing, the plate velocity decreases and subsequently stabilizes at 12.3 cm/yr (1.9·10^{-14} 1/s). The effective viscosity is inversely proportional to the strain rate, reaching a minimum at ~14.5 Myr (strain of 8) and slightly increasing during the later history. The 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.

Both the shear components of the fluidity tensor (A_{44}, A_{55}, A_{66} in *Fig. 2B*) and the off-diagonal components (A_{45} and A_{65} in *Fig. 2C*) exhibit variations with time as the olivine texture develops. The non-zero component of the stress tensor is σ_{13}, (σ_5 in Kelvin notation), which means that A_{55} represents the fluidity in the shear direction (shearing on the (3) plane in the (1) direction, creating $\partial v_1/\partial x_3$). Note that since $\sigma_{31}= \sigma_{13}$ (symmetry of the stress tensor), then A_{55} also represents the fluidity for the reciprocal deformation (i.e., shearing on the (1) plane in the (3) direction, creating $\partial v_3/\partial x_1$). A_{44} and A_{66} represent the values of the fluidity 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 σ_{23} ($=\sigma_{32}$) or σ_{12} ($=\sigma_{21}$), respectively.

Initially, there is no preferred orientation of the olivine grains, and the three shear fluidity components are the same. As the asthenosphere deforms and the texture develops in association with shearing on the (3) plane in the (1) direction, A_{55} increases, which is associated with a decrease in viscosity and an increase in the plate velocity. In contrast, the fluidity component A_{44} (A_{2323}) decreases, which indicates that it would become harder and harder to shear the asthenosphere with a stress σ_{23}, which would induce shearing on the (3) plane in the (2) direction (i.e., plate motion in a perpendicular direction), or reciprocally on the (2) plane in the (3) direction. Surprisingly, A_{66} increases with progressive deformation, and most of the time is even larger than A_{55}. Thus, as the texture develops, it also becomes easier to shear the asthenosphere along the vertical (*2*) plane in the (3) direction (or, 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 σ_{13} to $\dot{\varepsilon}_{23}$ and $\dot{\varepsilon}_{12}$, respectively (eq. 5). These components are initially zero, but do take on finite values with 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 directions other than the primary shear direction. However, because these components are two orders of magnitude lower than A_{55}, the strain rate in this simple case is dominated by the effects of A_{55}. Consequently, values of A_{55} (*Fig 2B*), strain rate (*Fig. 2D&E*), and plate velocity (*Fig. 2D*) all exhibit the same trend as a function of time and strain.

3.1.1. Rheology and texture parameters

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

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

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).

First, we describe the results of an instantaneous change in the direction of the asthenospheric 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 deformation behavior of (1) the rate of rotation of the shear force direction (from 1 Myr/90° to 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 implement a change in the driving force (or shear stress) by rotating the textured olivine aggregate (formed by applying the shear of model 1 for a chosen amount of accumulated strain) while keeping the shear stress constant (*Fig. 1C*).

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 σ_{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.: $D_{F_3} = \begin{bmatrix} 0 & 0 & 0 \\ 2\dot{\varepsilon}_{12} & 0 & 0 \\ 2\dot{\varepsilon}_{13} & 2\dot{\varepsilon}_{23} & 0 \end{bmatrix} = {D_{F_1}}^T$. F_2 and F_5 are consistent with a stress tensor in which only σ_{23} and σ_{32} are non-zero and deformation is given by $D_{F_2} = \begin{bmatrix} 0 & 0 & 2\dot{\varepsilon}_{13} \\ 2\dot{\varepsilon}_{12} & 0 & 2\dot{\varepsilon}_{23} \\ 0 & 0 & 0 \end{bmatrix} \wedge D_{F_5} = {D_{F_2}}^T$. F_4 and

F_6 are both consistent with a stress tensor where only σ_{12} and σ_{21} are non-zero and induce deformation given by $D_{F_4} = \begin{bmatrix} 0 & 2\dot{\varepsilon}_{12} & 2\dot{\varepsilon}_{13} \\ 0 & 0 & 0 \\ 0 & 2\dot{\varepsilon}_{23} & 0 \end{bmatrix} \wedge D_{F_6} = {D_{F_4}}^T$. As mentioned before, these deformations are equivalent to those achieved by rotating the mantle (i.e. the olivine 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 the *x*-axis represents a change from F_1 to F_4, around the *y*-axis reproduces F_3, and around the *z*-axis reproduces F_2. F_5 is modeled by rotating the aggregate around the *x*- and then *z*-axes, and F_6 is modeled by rotation around the *x*- then *y*-axes. Referring to *Fig. 4*, rotating the aggregate around its *x* or its *x* then *y* axes represents shearing produced by a transform fault (F_4 or F_6), rotation around the *y* or the *x* then *z* axes represents shearing associated with dripping or subduction (F_3 or F_5), while rotation around the *z* axis represents a change in the 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^{-1} (*Fig. 5B,* orange and green curves). Translating to plate velocity, this change implies a decrease from 14.8 cm/yr to 3 cm/yr.

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

3.2.1.1 Representing change in plate motion direction

Rotating the olivine aggregate around its *z*-axis represents a relative change in the direction of the plate driving force. The result of a model with 90° instantaneous rotation (green curve in *Fig. 5B*) exhibits a dramatic reduction in strain rate and a slow recovery of the olivine texture 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^{-1}, which is still less than the strain rate for the initially isotropic aggregate. Because of the slow deformation associated with the diminished strain rate, this partial recovery took almost 50 Myr. Examination of the change in olivine texture directly after the rotation (at strain of 8.5, *Fig. 5*) illustrates that the orientations are well organized but that the preferred orientation is perpendicular to the direction of shearing (*Fig. 5*). When the strain rate finally starts to increase, the a-axis distribution is more random or girdle-like rather than point-like, even at a total strain of 21. Regarding the fluidity tensor, when the texture is rotated, the A_{55} component (which relates σ_{13} to $\dot{\varepsilon}_{13}$) decreases while both A_{45} and A_{65} exhibit a minor increase, leading to similar values for all three components.

3.2.1.2 Shear forces associated with transform faults

There are two possibilities for creating shear stress in a horizontal direction along a vertical plane, which roughly approximates the stress state associated with a transform fault. The possible shear forces are F_4 or F_6 (*Fig. 4*), which produce very different paths in the strain-rate evolution (*Fig. 5C*) if there is already a well-developed texture associated with deformation 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^{-1}) compared to the earlier deformation (driven by F_1). The pink curve, representing the switch from F_1 to F_4, after the initial peak strain rate, slowly decreases to ~$1.5 \cdot 10^{-14}$ s^{-1}. Switching from F_1 to F_6 is relatively easy, as the model exhibits increasing strain rate (up to ~$6.7 \cdot 10^{-14}$ s^{-1}) associated with the texture evolution after the rotation for an additional shear strain of ~4 (*Fig. 5C*, dark blue curve). This peak is followed by a quickly decreasing strain rate that stabilizes around ~$2 \cdot 10^{-14}$ s^{-1}, which is comparable to the strain rate 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 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*-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 distribution and leading to slower strain rates than prior to the change in shear direction.

3.2.1.3 Shear forces associated with dripping/subduction

There are two possibilities for creating shear stress in a vertical direction as a rough approximation of the stress state associated with subduction or dripping instabilities. 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 deformations, as described above) followed by a decrease in strain rate (i.e. small increase in the effective viscosity) as the texture evolves (*Fig. 5A*, cyan curve). Subsequent texture 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^{-1}. The model results exhibit a decreasing trend in strain rate immediately after this peak, reaching a final strain rate of $2 \cdot 10^{-14}$ s^{-1} (after a total strain of 21). In contrast, changing from F_1 to F_5 (orange curve in *Fig. 5B*) induces a dramatically diminished strain rate ($5 \cdot 10^{-15}$ s^{-1}, equivalent to that produced by F_2 as described above) that slowly recovers over the next 20-25 Myr (by a total strain of 14) and stabilizes around 2.2-$2.3 \cdot 10^{-14}$ s^{-1}, which is slightly higher than the strain rate at high stresses in model 1. Similar to the "transform fault" models, the strain-rate curves for "subduction/dripping" can be linked to the texture development. The higher strain rate at the end of the model that applies F_5 (*x*- then *y*- rotation) compared to the model end after applying F_3 results from a more point-like distribution of the olivine a-axes (*Fig. 5A&B*).

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).

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

3.2.3. Role of texture evolution prior to the rotation

In an additional series of calculations, we varied the amount of accumulated strain between 2 and 14 prior to a 90° rotation, which was implemented using two different rotation rates (90° 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 magnitude, while the other models reach strain of 21 with only 5.4-8.4 cm/yr plate velocity (*Fig. 7B*).

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

3.2.4. Role of the amount of rotation

In more realistic geodynamic scenarios, the driving forces on plates are unlikely to rotate as much as 90°, so we additionally tested a range of rotations from 22° to 90° degrees with slow (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 rotation, the lower the average strain rate, and therefore the lower the average plate velocity (*Fig. 8B&D*). Furthermore, the models with faster rotation rates exhibit a greater variability of plate motion directions and velocities than the models with slower rotation rates (*Fig. 8*). With only 22° rotation, β differs from α by only 15° during the rotation in both models, and this difference linearly decreases as the model progresses until, at the end of the model, the plate motion becomes parallel to the shear direction. The plate velocity decreases to 7.5-7.8 cm/yr, which then climbs back to the isotropic rate (~10 cm/yr) by the end of the models. If the total change in shear direction is 45° or more, all models result in ~20° difference between α and β during the rotation, independent of the rate of rotation. Later, the models with slower rotation rate result in even larger differences between α and β. The plate motion direction can change more quickly if the plate velocity is high, such as in the model with 45° rotation at 90°/Myr during the period between 25 and 35 Myr (*Fig. 8B*). On the other hand, in the model with 67° rotation at 9°/Myr, the plate velocity remains between 3.5-5 cm/yr, and α-β remains ~20° (15-25°).

4. *Discussion*

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

0.27, respectively) versus parallel to the c-axes (where the strength of the (010)[001] slip system is 1.29). Thus, deformations that dominantly activate the (010)[100] slip system (e.g., 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 8, *Fig. 5C*) exhibit much faster strain rates compared to those that dominantly activate the (010)[001] slip system (e.g., F_2 and F_5 at a strain of 8, *Fig. 5B*).

The evolution of the plate velocity and plate-motion direction (or the entire matrix of $\dot{\varepsilon}$) is a function of the olivine texture, which evolves due to the deformation. Hence the asthenospheric rheology depends on the kinematics and vice-versa. Indeed, the models with an instantaneous change in the force direction demonstrate that applying the same stress but with different velocity boundary conditions (i.e. enforcing deformations consistent with individual forces on the asthenosphere, as shown on *Fig. 4*) can produce very different strain rate histories (e.g. *Fig. 5,* right column). For example, after creating a texture by force F_1, switching to F_2 or F_5 both involve the same new stress state and both initially activate the same (010)[001] slip system. Thus, both deformations initially produce the same (although much reduced) strain rate (Fig. 5B). However, enforcing shear deformation in the vertical direction (i.e. by F_5) allows for faster rotations of the olivine grains into the new shear direction, allowing for higher strain rates as the texture develops.

Without changes in the shear force direction, the plate-velocity evolution follows a similar trend to the values of *P-a* (point-like distribution value for the olivine a-axes) (*Fig. 3*). However, if the direction of the shear force changes, this correlation is less clear. We 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 the z-axis with respect to the shear stress (in 1 Myr), then the changes in the values of *P*-a are no longer correlated to the changes in the plate velocity, especially around the time of the 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.

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-*

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

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

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

5. *Relevance to natural phenomena*

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

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

5.1 Change in the direction of plate motion

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

Thus, we expect that anisotropic viscosity may significantly modify the relationship between plate motions and the forces that drive them (e.g., Becker et al., 2006; Conrad and Lithgow-Bertelloni, 2004). Although Becker and Kawakatsu (2011) found that mantle flow models that included viscosity anisotropy behaved similarly to isotropic models, their study did not examine time-dependent behavior. Instead, our results suggest that time-dependent changes to the driving forces on plates, or to the amplitude or orientation of the anisotropic texture beneath them, should result in potentially large differences between the orientation of the net driving force on a plate and the direction of the resulting asthenospheric flow and plate motion. Note that the effective viscosity of the asthenosphere may also vary spatially beneath the plate depending on the orientation and maturity of the olivine texture locally. These 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*).

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

5.2 Transform faults

Asthenospheric mantle, sheared by plate motions, should experience shear stresses in a horizontal direction on vertical planes near transform faults. Strain that results from these stresses will be enhanced by viscous anisotropy. If the shearing direction is parallel to the 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 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 weakens the asthenosphere. Interestingly, the results of this simple analysis are consistent with the large number of transform faults in the oceanic lithosphere. Although transform faults usually form close to the ridge where the asthenosphere has not been sheared for long, and where texture development involves a more complicated history associated with corner flow (Blackman et al., 2017), it is possible that the low asthenospheric resistance aids the formation of lithospheric scale transform faults.

5.3 Initiation of subduction or dripping

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

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

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 mechanically anisotropic nature of the textured asthenosphere. Our results indicate that differences in the effective viscosity associated with shearing asthenosphere primarily result from the relative activation of olivine’s weak and strong slip systems. The resulting differences in effective viscosity can be over an order of magnitude, and should hinder some tectonic processes and foster others, depending on their sense of deformation relative to asthenospheric textures (*Fig. 10*). If the new shear direction is such that the strongest slip system, (010)[001], has to be activated to produce deformation, then the effective viscosity will increase. This increase is generally the case for a change in the direction of plate motion or vertical shearing on a plane parallel to plate motions. In contrast, the mantle should remain weak, or even become weaker, for shear forces that primarily induce deformation on the other two, weaker slip systems, (010)[100] and (001)[100], which is the case for transform motions, subduction initiation, or ongoing plate motion in the same direction. Thus, based on our simple models, we expect asthenospheric textures to significantly slow changes to the direction of plate motions and hinder the formation of ridge-perpendicular subduction zones. Conversely, these textures should assist in the initiation of new subduction zones parallel to mid-ocean ridges (perpendicular to plate motion) and promote the development of lithospheric scale transform faults. To fully understand the impact of anisotropic viscosity on plate tectonics and asthenospheric dynamics, olivine texture development, and the anisotropic viscosity that is associated with it, needs to be integrated into 3D dynamic models of the relevant processes.

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Figures

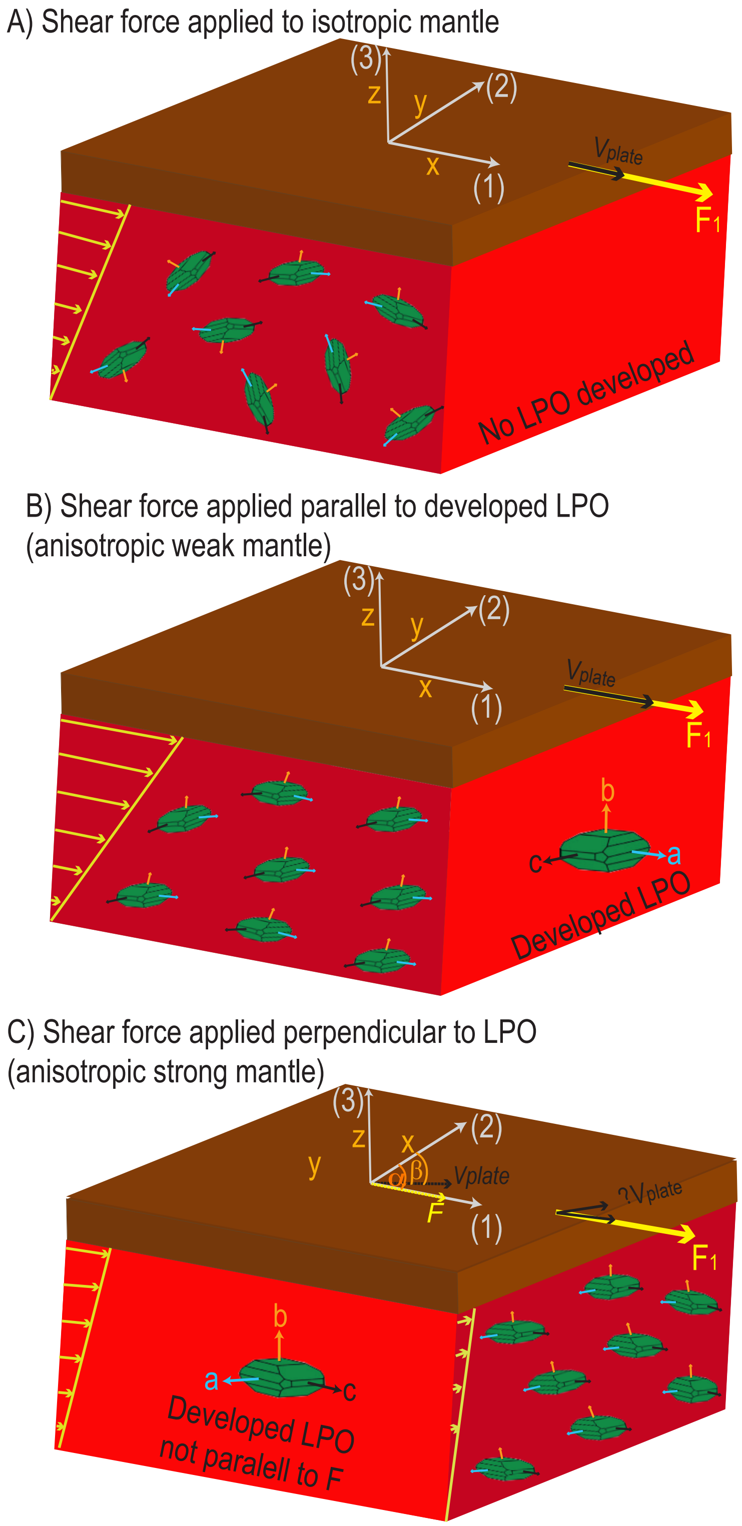

Figure 1: Relationship between anisotropic viscosity and olivine texture formation. A) A force (F_1) applied to an initially isotropic asthenosphere (i.e., without a pre-existing texture) yields a moderate plate speed, and the associated asthenospheric deformation fosters olivine texture development. B) The same force applied parallel to the a-axis of a well-developed texture results in a much larger plate speed. C) Applying this force parallel to the c-axis causes the

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 texture (as for many geodynamic scenarios) or the texture can be rotated with respect to the force (as illustrated in (C) and implemented in our modeling effort).

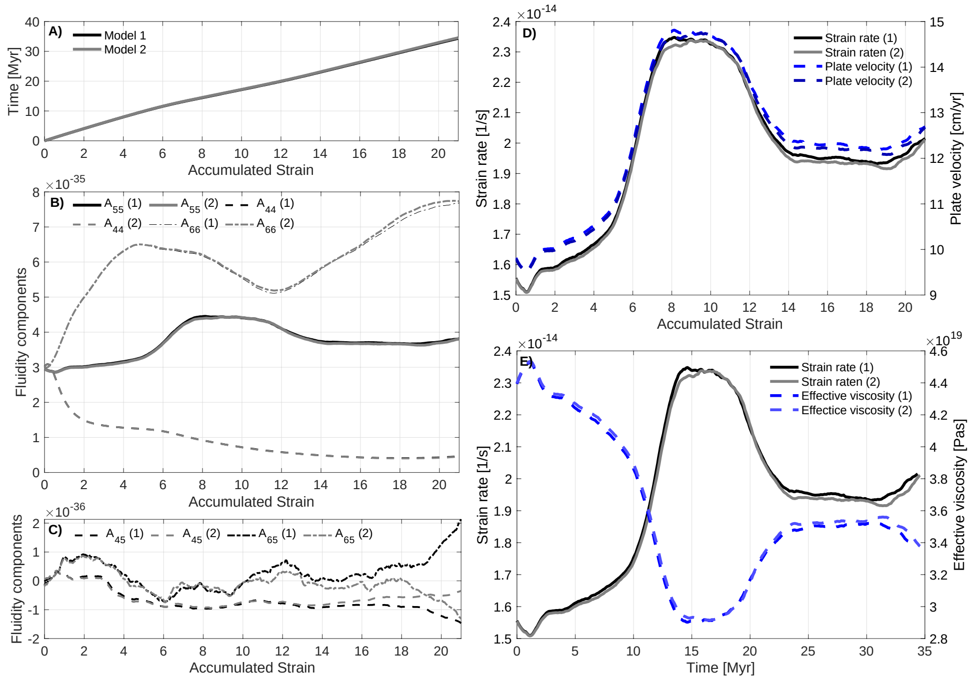

Figure 2: Results of two sets of models with constant shear stress (σ_{13}= 0.68 MPa), both computed as average results from 5 model runs each starting from 1000 uniformly distributed grain orientations. A) Accumulated strain as a function of time. B) Shear components of the fluidity parameter tensor.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

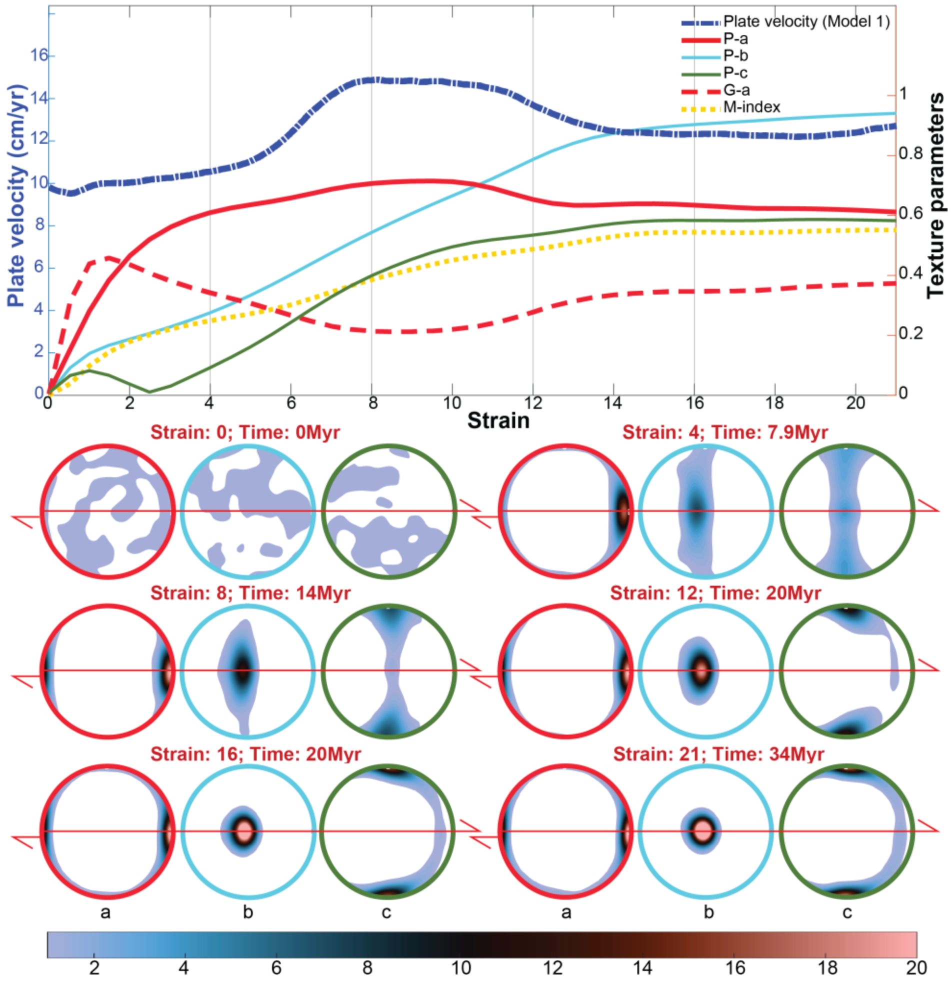

Figure 3: The evolution of plate velocity and several texture parameters as a function of accumulated strain (top panel) with pole figures (below) indicating the orientation density of a-, b-, and c- axes for olivine aggregates with different total strains. The color scale indicates multiples of a uniform density. The shear direction (marked by red arrows) is towards the right and the shear plane is the same as the figure's plane.

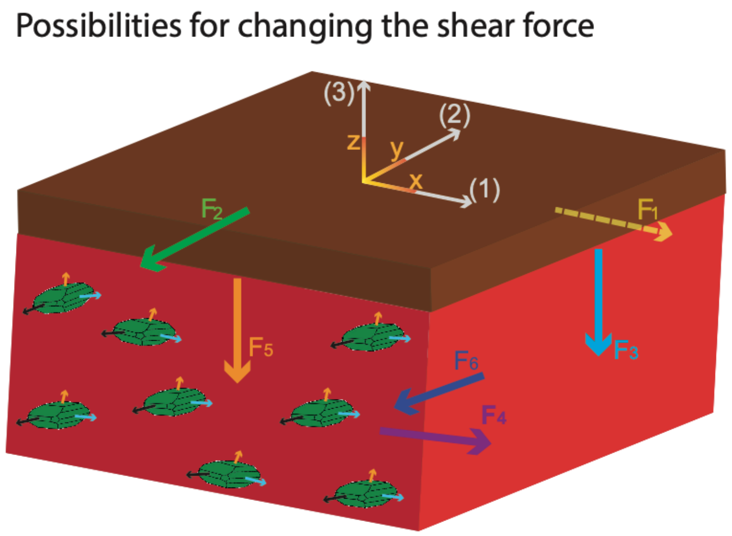

Figure 4: Possible orientations for the shear force, with F_1 representing the orientation associated with initial plate motion (e.g., as in Fig. 1b). F_2 represents a shear force acting on a horizonal plane at 90° to the initial plate motion direction, analogous to a change in the direction of the plate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

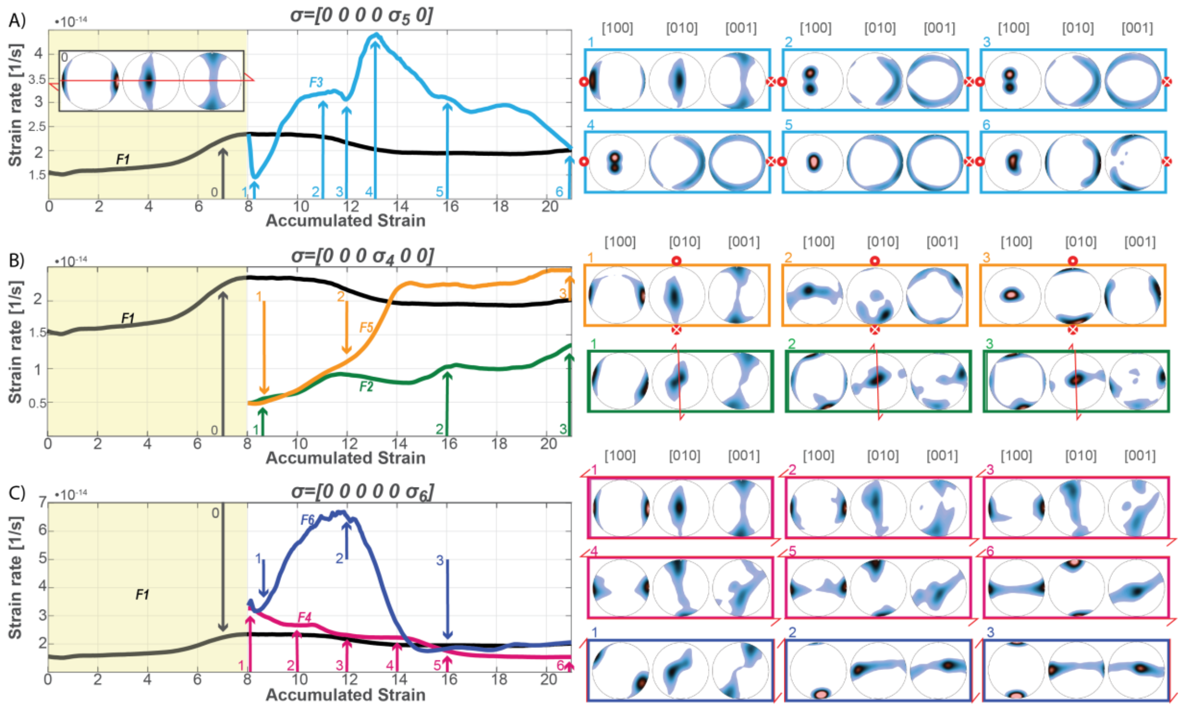

Figure 5: Strain rate as a function of accumulated strain for the five different changes to the imposed shear force (Fig. 4). On the left side, an initially isotropic aggregate is deformed

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).

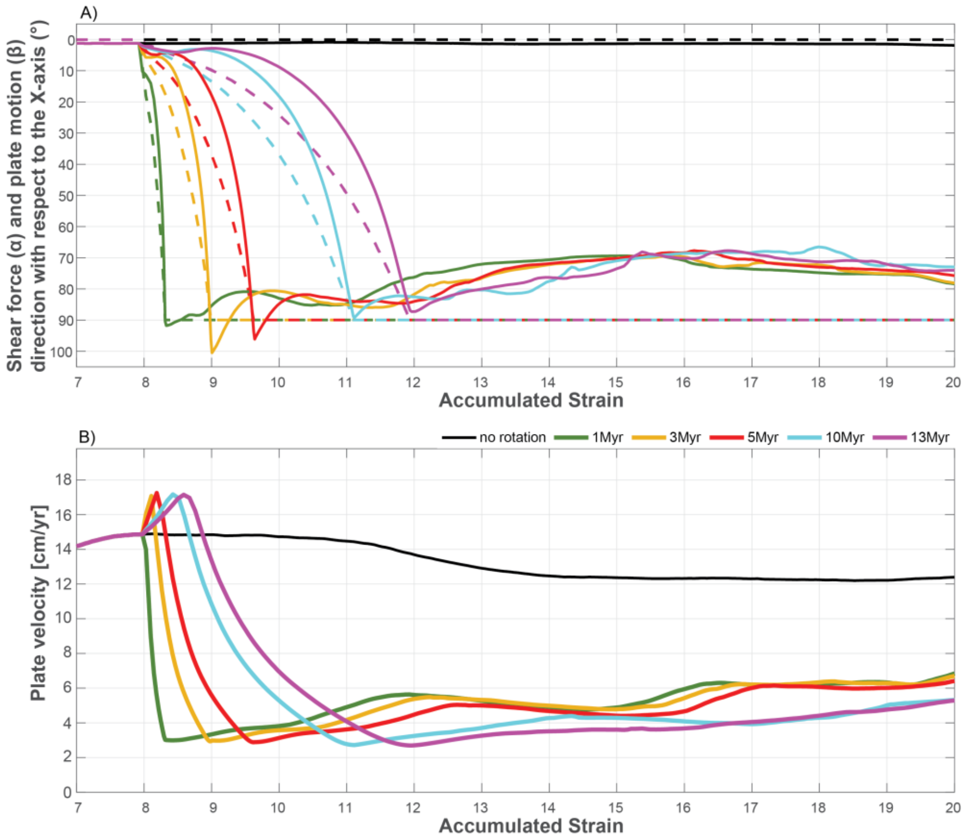

Figure 6: Results from models with different rates of imposed rotation of the shear stress. An initial texture (associated with an accumulated strain of 8, using model 1 of Fig. 2) is rotated 90° around the z-axis (representing a change from F_1 to F_2) within a period between 1 and 13 Myr. a) Change in the direction of the shear force (α, dashed lines) and plate motion (β, solid lines) with respect to the x-axis (fixed to the mantle), as a function of accumulated strain. b) Amplitude of the plate velocity as a function of accumulated strain.

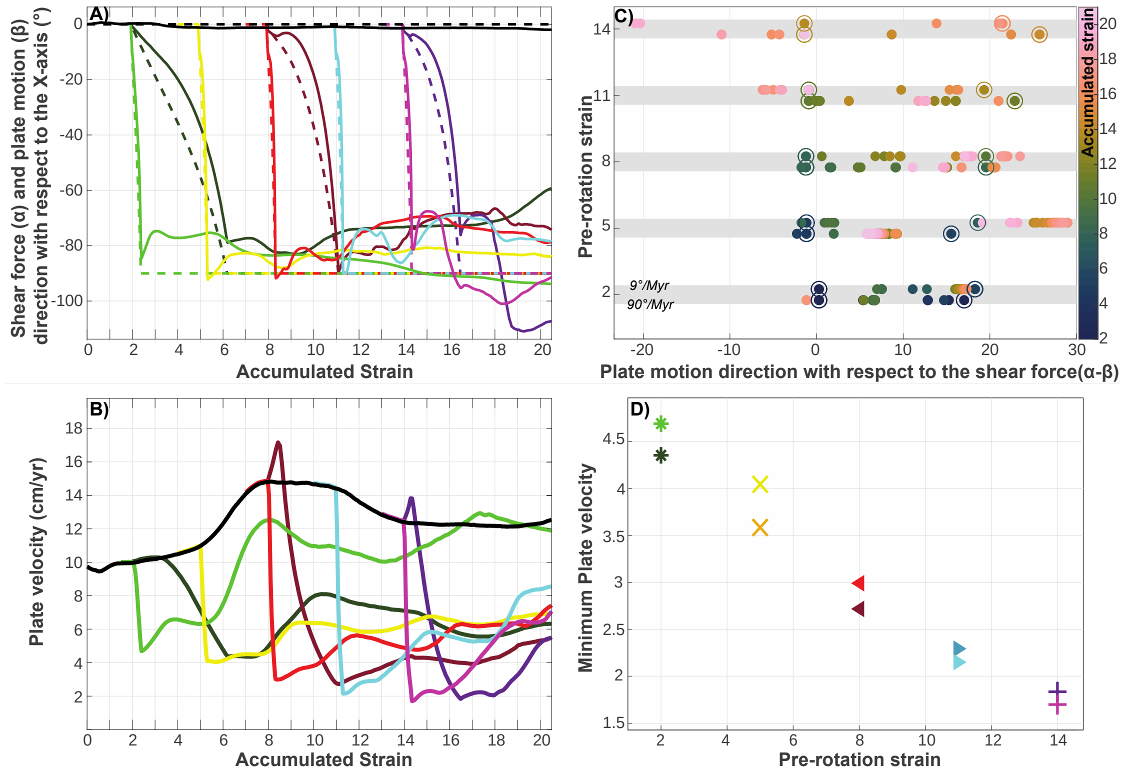

Figure 7: Results from models with varying amounts of accumulated strain (and therefore texture strength) at the time of the rotation (Pre-rotation strain). A) Direction of the shear force (α, dashed lines) and the plate motion (β, solid lines) for models that rotate the texture 90° in either 1 Myr (lighter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

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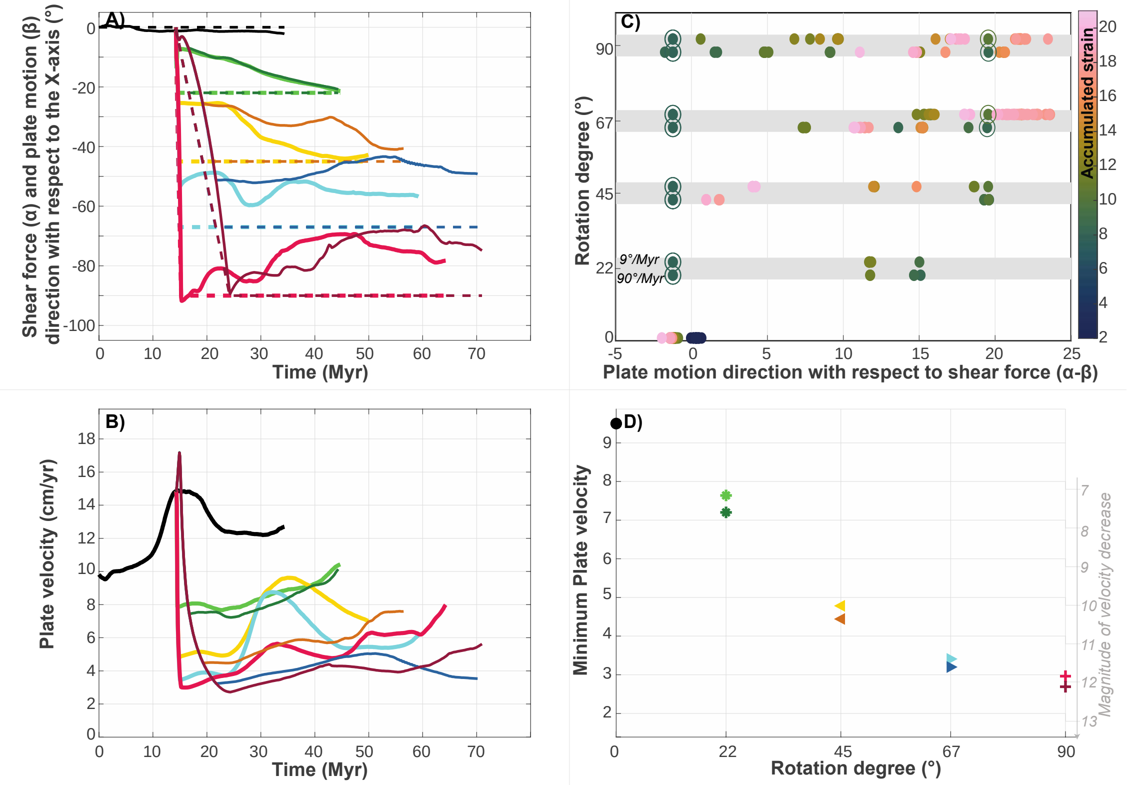

991 *Figure 8: Results from models with varying amounts of rotation around the z-axis. Panels are*
992 *the same as in Fig. 7, except using rotation angle instead of pre-rotation strain in (C) and*
993 *(D).*

994

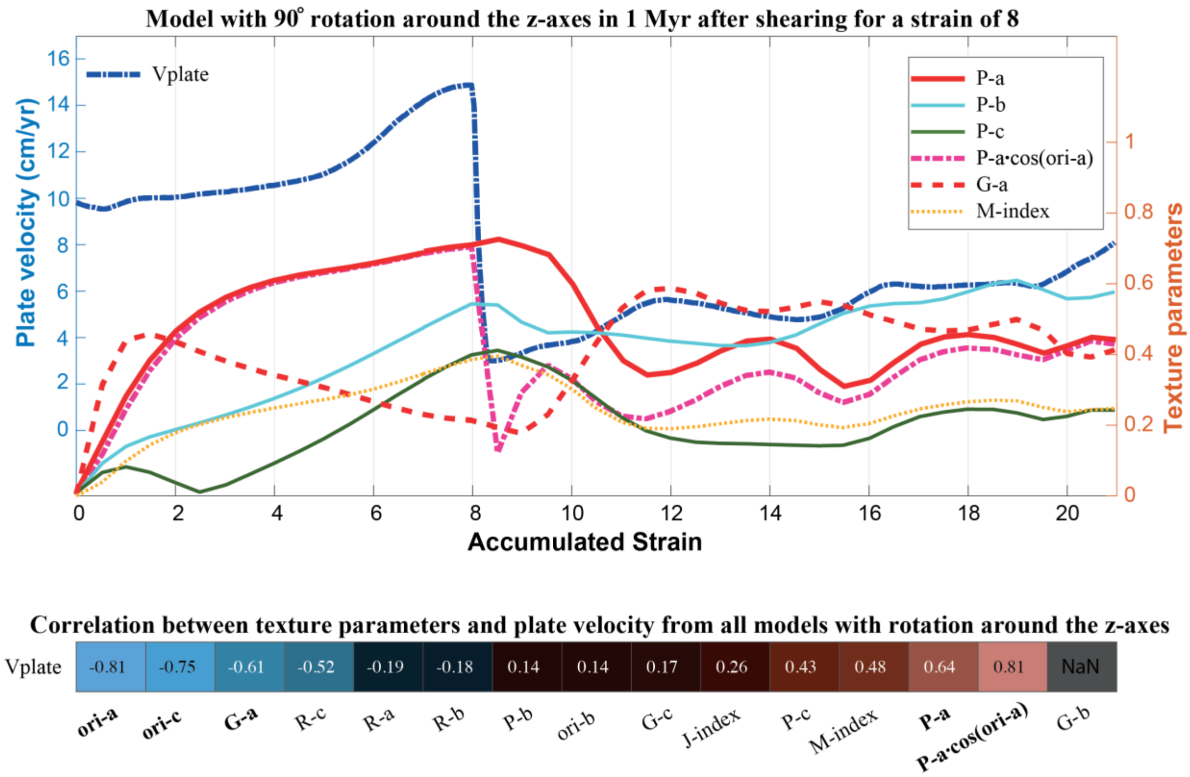

Figure 9: Top) plate velocity and texture parameters, as a function of accumulated strain, for a model in which a 90° rotation (representing a change from F_1 to F_2) is imposed over 1 Myr after a strain of 8 (the fastest rotation presented in Fig. 6). Bottom) correlation between texture parameters and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

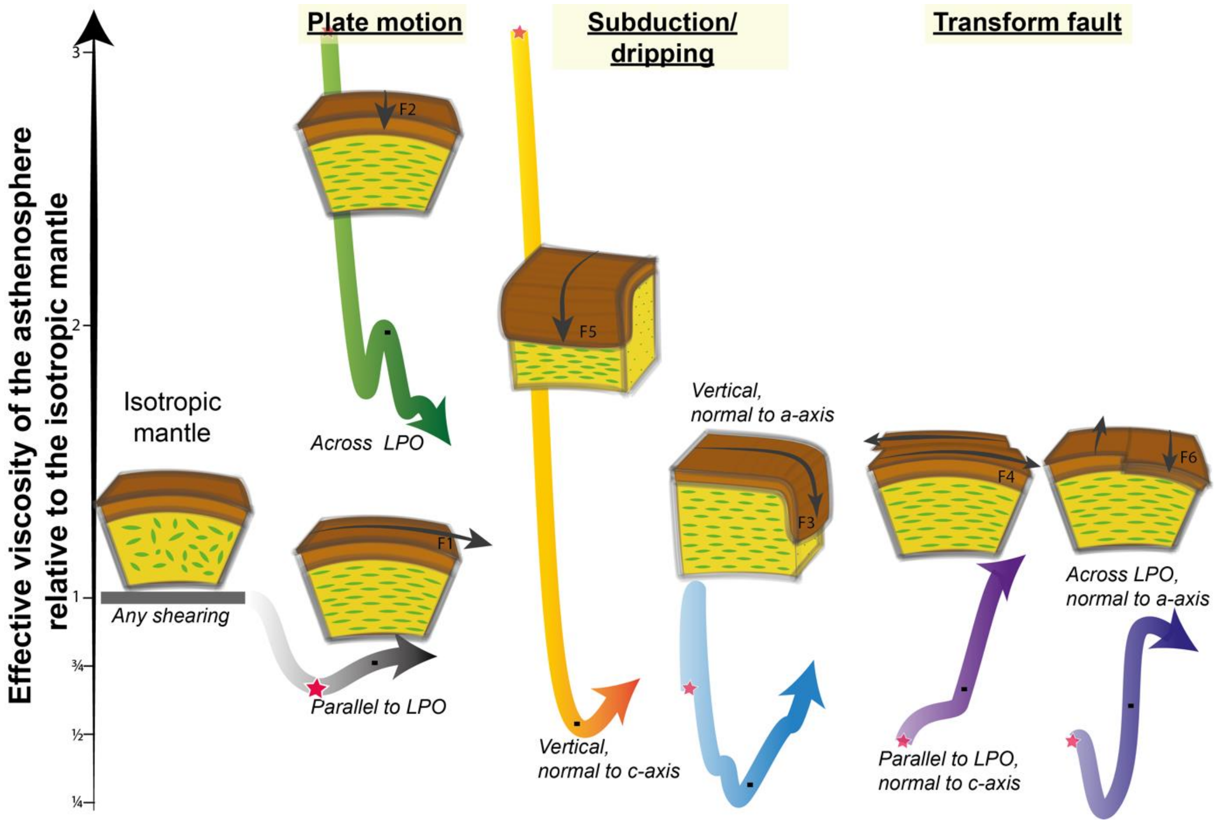

Figure 10: Trends for the manner in which anisotropic viscosity in the asthenosphere should influence different geodynamic situations. The white to black arrow indicates the mantle weakening path associated with development of an LPO as the asthenosphere accumulates strain due to simple shear (e.g. in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