The formation of viscous anisotropy in the asthenosphere and its effect on plate tectonics

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Introduction:

→ Olivine has three independent slip systems on which deformation can occur
Each slip system has a different strength, that is they activate in the response of different amount of critical stress

→ Olivine texture develops with asthenosphere deformation, yielding directional variations in viscosity of more than an order of magnitude

→ Shearing olivine with a well-developed texture is easy parallel to the a-axes and the b-axes but difficult parallel to the c-axes

→ Texture development and anisotropic viscosity are codependent

→ Anisotropic viscosity promotes faster plate motions, subduction initiation and dripping, but impedes directional changes in plate motions

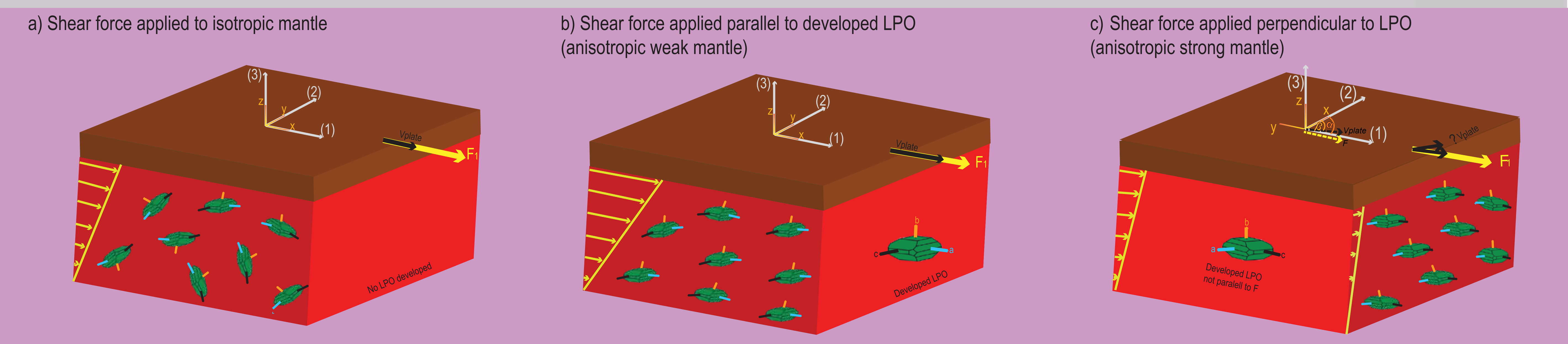


Figure 1: Relation between anisotropic viscosity and olivine texture formation. a): A force (F1) applied to an initially isotropic asthenosphere (random texture) yields a moderate plate speed. b): The same force applied parallel to the a-axis of a well-developed texture drives a much larger plate speed. c): Applying this force across the texture (parallel to the c-axis) causes the plate to move much more slowly. The configuration of the anisotropically strong asthenosphere (c) can be realized from the weak one (b) in two ways: either the force can be rotated relative to the fabric (as for many geodynamic scenarios) or the "mantle" can be rotated respect to the force (as shown in (c) and implemented in our modeling effort).

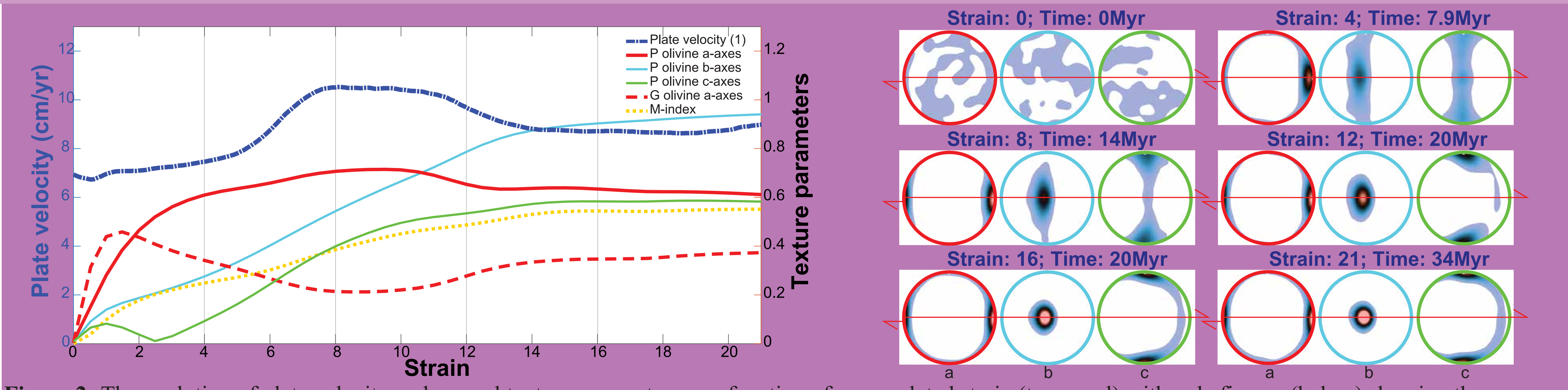
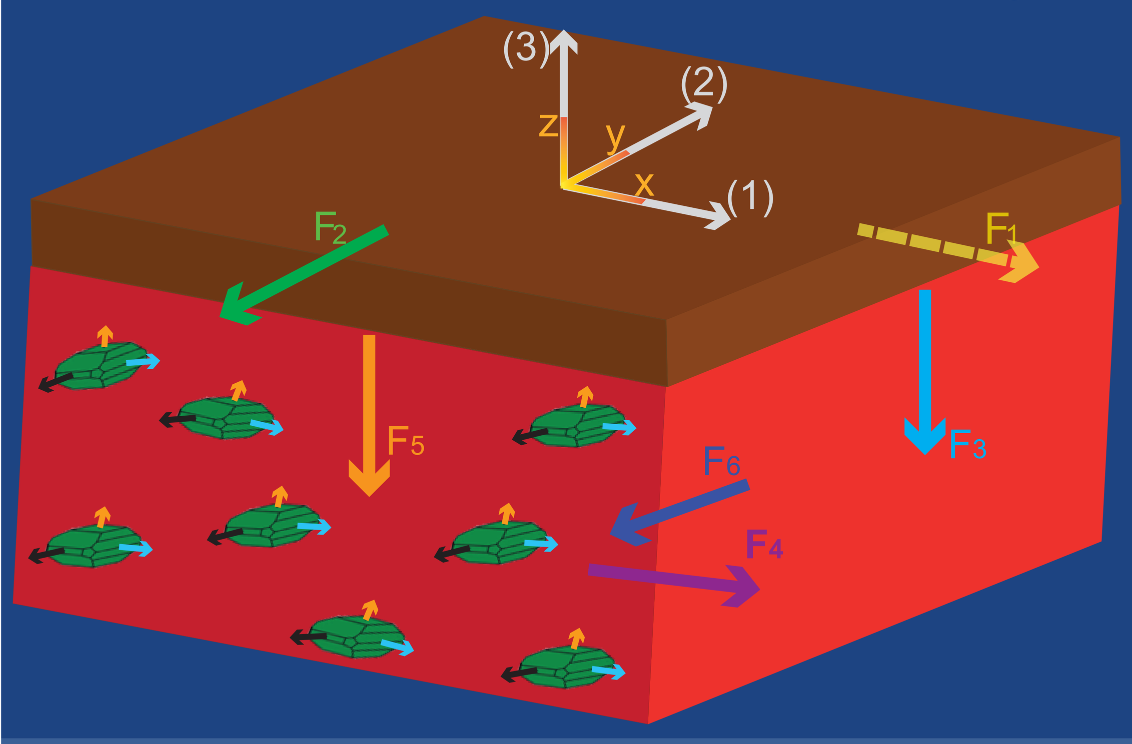


Figure 2: The evolution of plate velocity and several texture parameters as a function of accumulated strain (top panel) with pole figures (below) showing the orientation density of olivine aggregates for different total strains. The shear direction (marked by red arrows) is towards the right and the shear plane is the same as the figure's plane.

Testing different Geodynamic scenarios



To study 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 rotate the olivine texture with respect to the imposed stress (as shown in Fig. 1C), which is held steady.

Figure 3: Possible ways to change the shearing orientation away from F_1. F_2 represents a change in the direction of the plate driving force. F_4 and F_6 represent a force that creates shearing deformation along a transform shear zone. F_3 and F_5 represent subduction initiation or a dripping instability. All forces have the same amplitude as F_1

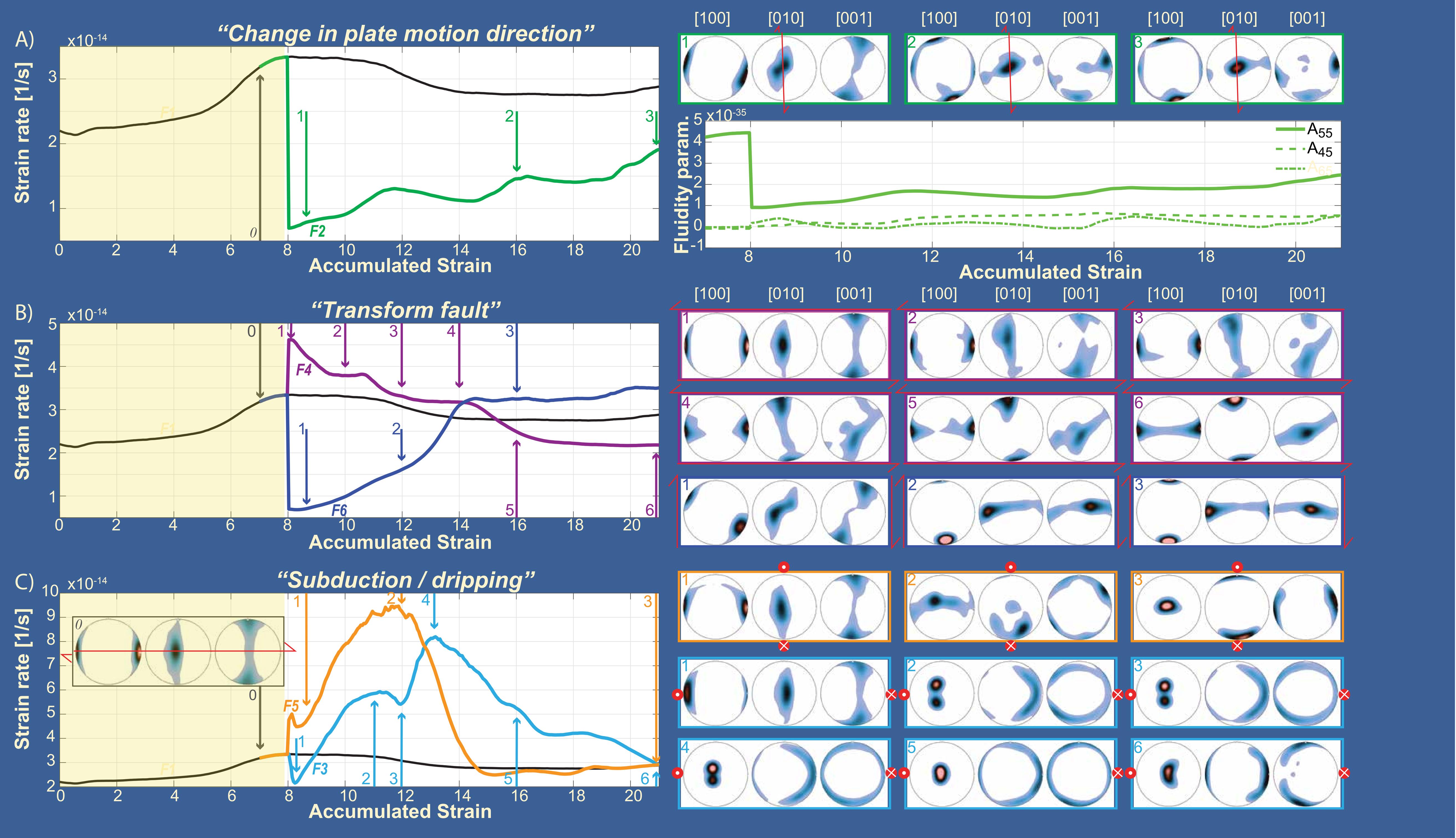


Figure 4: Strain rate vs accumulated strain for the five different changes to the imposed shear force (Fig. 3). On the left side, an initially isotropic aggregate is deformed with shear force F_1 until a strain of 8. At a strain of 8, the direction of the shear force is instantaneously changed into the directions F_2 - F_6 (Fig. 3). On the right side, pole figures show the rock texture for several moments denoted by arrows in the left diagrams. Note that all of the texture orientations are shown relative to mantle reference frame, and the shear acting on the mantle is marked by red arrows (and arrow points and tails). In panel A) we show the fluidity components related to the actual shear stress for the case of a change in the direction of the plate driving force (F_1 to F_2).

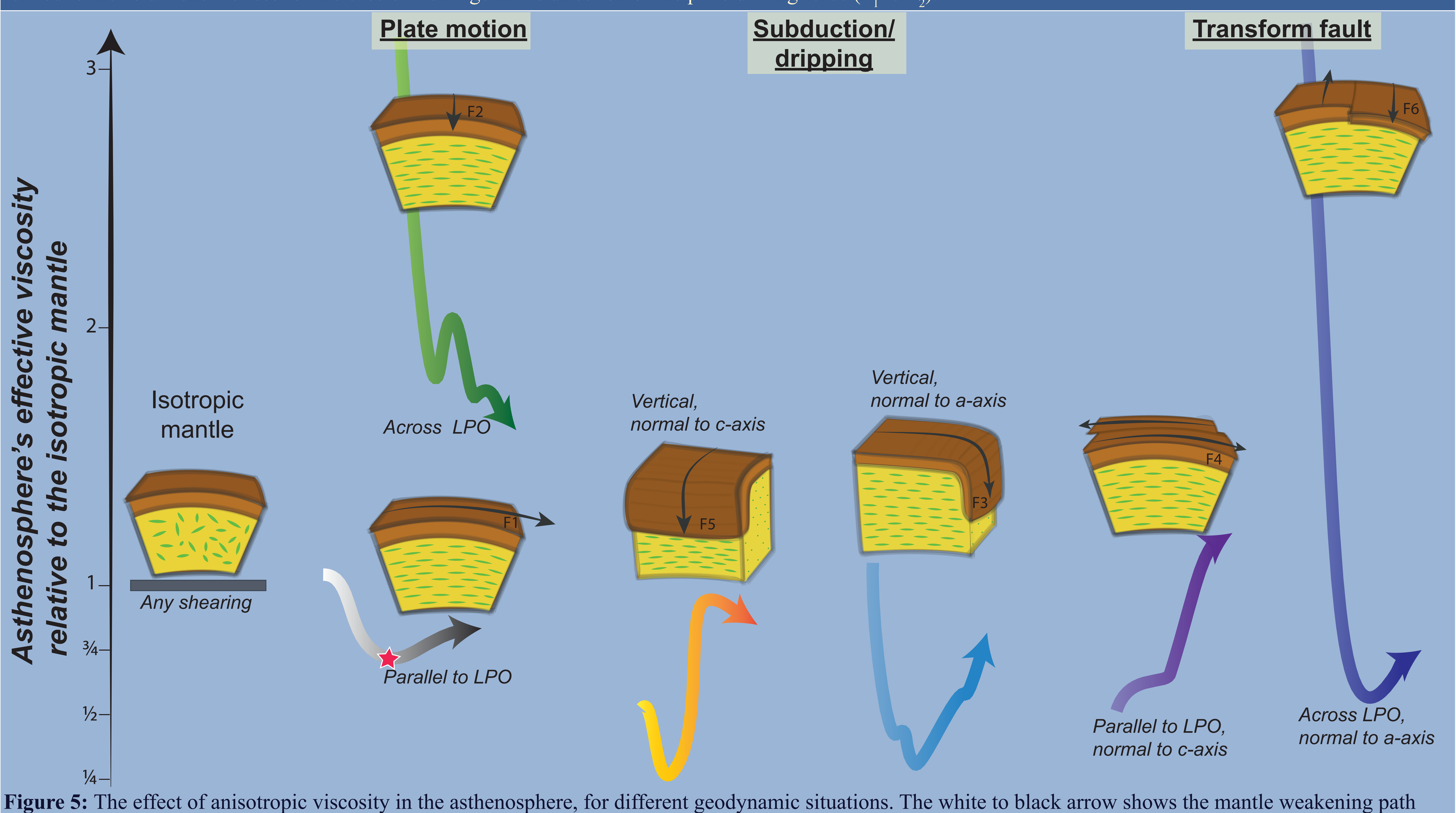


Figure 5: The effect of anisotropic viscosity in the asthenosphere, for different geodynamic situations. The white to black arrow shows the mantle weakening path associated with development of LPO texture as the asthenosphere accumulates strain due to simple shear (e.g. in model 1). The colored arrows show the time evolution of the effective viscosity from the moment of switching the shear direction (strain of 8, marked with a star on the white-to-black arrow) until a strain of 21 (based on results shown in Fig. 4). Geodynamic processes for which the effective viscosity elevates (F_2 plate motion and F_6 transform fault) will be initially impeded by anisotropic viscosity, while those for which the effective viscosity decreases (F_3 and F_5, subduction and dripping, and F_4 transform fault) will 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.