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

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Developing an appropriate characterization of upper mantle viscosity structure presents one of the biggest challenges for understanding geodynamic processes in the upper mantle. This is because different creep mechanisms become activated depending on depth, accumulated strain, and applied stress, and other factors such grain size and anisotropic fabric can change as the deformation develops, changing the effective viscosity. Here we focus on the relationship between anisotropic fabric development and viscous anisotropy.

Under applied shear, olivine crystals, which form a large proportion of the asthenosphere, rotate towards the shear direction and accumulate a lattice preferred orientation (LPO) parallel to the macroscopic deformation. On a large scale, LPO can be observed through the propagation of seismic waves because of the anisotropic elastic properties of olivine. As olivine is anisotropic in its viscous properties, this developing texture within the asthenosphere can affect the macro-scale viscosity of the asthenosphere. This behavior has been detected in rock mechanics measurements on pure olivine aggregates, showing more than an order magnitude of viscosity change between shear parallel to the olivine aggregate’s LPO versus shear across this fabric (Hansen et al., EPSL 2016a, JGR 2016b).

Here, we use numerical models developed first in MATLAB and then implemented into the mantle convection code ASPECT. These models incorporate both anisotropic fabric development and anisotropic viscosity, both calibrated according to laboratory measurements on slip system activities of olivine aggregates (Hansen et al., JGR 2016b), to better understand the coupling between the large-scale formation of LPO textures and changes in asthenospheric viscosity.

The modeling results allows us to discuss the role of anisotropic viscosity on the processes of plate tectonics. An asthenosphere with a well-developed LPO becomes weak parallel to its texture, allowing for increasing plate velocity at the surface, for a given applied driving force. On the other hand, this fabric resists abrupt changes in the direction of plate motion because the effective viscosity is elevated for shear perpendicular to the developed LPO. This increased resistance to fabric-perpendicular shear also decreases strain rates, which slows texture development. This means that asthenospheric fabric can impede changes in plate motion direction for periods of over 10 Myrs. However, the same well-developed texture in the asthenosphere could enhance the
initiation of subduction or lithospheric gravitational instabilities as vertical deformation is favored across a sub-lithospheric olivine fabric, and the sheared fabric can quickly rotate into a vertical LPO. These end-member cases examining shear-deformation across a formed asthenospheric fabric illustrate the importance of olivine fabrics, and their associated viscous anisotropy, for a variety of geodynamic processes.