Geodynamic consequences of anisotropic mantle viscosity

Ágnes Király[1], Clinton P. Conrad[1], Lars N. Hansen[2]

[1] Centre for Earth Evolution and Dynamics, University of Oslo
[2] Department of Earth Sciences, University of Oxford

Olivine, the primary mineral in the upper mantle, is anisotropic in its mechanical properties. As a result, significant shearing of the upper mantle causes olivine crystals to form a preferred orientation, which we can observe, for example, using seismic wave propagation. The crystallographic alignment of olivine grains also results in anisotropic viscous behavior that may result in significant changes in effective viscosity as the direction of flow changes. Recent laboratory measurements have provided crucial constraints on viscosity during complicated deformation paths. However, the employed laboratory experiments are only able to test a small number of deformation paths, making direct application to mantle deformation difficult. Thus, in our previous work, we used the existing experiments to define and calibrate a mechanical model of slip system activity and texture development within olivine aggregates that can predict the viscous response for arbitrary deformation paths.

Here we use this previously calibrated model to explore the mechanical response of an olivine aggregate for a wide range of deformation paths that are relevant to shearing the upper mantle. We find that texture development due to simple shear in a single direction causes effective viscosity to decrease by a factor of ~2 (from 10^{20} to $5 \cdot 10^{19}$). Once the texture is well developed, we change the direction of shear by gradually rotating the texture with respect to the shear direction (this is equivalent to changing the shear direction). Our results highlight that the pace and orientation of this rotation are the most important factors that determine the path and time towards recovery of the fully-deformed texture. We find the largest resistance to shear occurs for texture that is rotated 90° on the original shear plane (i.e. with horizontal shear, the texture is rotated along the vertical axes). In this case, shear-parallel viscosity can increase by a factor of 7 and the modeled plate velocity drops from 12-14 cm/yr to 2 cm/yr. After the rotation of the texture, it takes at least 15 Myr for the modeled plate to start to recover its initial velocity, however, this timescale can be much longer if the rotation is accomplished in short time. On the other hand, rotating the texture around the shear plane (i.e. about one of the horizontal axes), with a fast rotation causes the shear-parallel viscosity to significantly decrease, while a slow rotation leads to a viscosity increase. We can relate these behaviors to the texture development.

The initial stage of simple shear in our numerical experiments is analogous to the texture forming flow in the upper mantle/asthenosphere as oceanic lithosphere moves away from the ridges. Our mechanical models predict that it will be difficult to then shear this textured asthenosphere in a perpendicular direction. Therefore, the anisotropic viscosity of the asthenosphere may offer significant resistance to changes in plate motion direction. In contrast, the anisotropic viscosity of the upper mantle may be especially conducive to shear on a vertical plane, which may help to promote subduction initiation or convective instability. More generally, we conclude that textured rocks in the asthenosphere, and the anisotropic viscosity that they induce, should significantly influence the geodynamics of plate motions and their interaction with the convecting mantle.