Dynamic weakening mechanism in Earth’s mantle - A comparison between damage-dependent weakening and grain-size sensitive rheologies

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The creation and maintenance of narrow plate boundaries and their role in the thermo-chemical evolution of Earth remain one of the major problems in geodynamics. In particular, the cause and consequences of strain localization and weakening within the upper mantle remain debated, even though strain memory and tectonic inheritance, i.e. the ability to preserve and reactivate inherited weak zones over geological time, and strain localization appear to be critical features in plate tectonics.

Frictional-plastic faults in nature and brittle shear zones in the lithosphere may be weakened by high transient, or static, fluid pressures, or mechanically by gouge, or mineral transformations. Weakening in ductile shear zones in the viscous domain may be governed by a change from dislocation to diffusion creep caused by grain-size reduction. In mechanical models, strain weakening and localization in the shallow parts of the lithosphere has mainly been modeled by an approximation of brittle behavior using a pseudo visco plastic rheology. This has often been implemented by a linear decrease of the yield strength of the lithosphere with increasing deformation. Strain weakening in viscous shear zones, on the other hand, may be described by a linear dependence of the effective viscosity on the accumulated deformation.

Here, we analyze how a parameterized, apparent-strain, or “damage”, dependent weakening (SDW) rheology governs strain localization and weakening as well as healing in the lithosphere. The weakening and localization due to the SDW rheology has been related to a grain-size sensitive (GSS) composite rheology (diffusion and dislocation creep). While we focus on GSS rheology to constrain the parameters of SDW, the analysis is not limited to grain-size evolution as the only possible microphysical mechanism. We explore different types of strain weakening (plastic- (PSS) and viscous-strain (VSS) softening) and compare them to the predictions from different models of grain-size evolution for a range of temperatures and a step-like variation of total strain rate with time. PSS leads to a weakening and strengthening of the effective viscosity of about the same order of magnitude as due to a GSS rheology, while the rate depends on the strain-weakening parameter combination. In addition, the SDW weakening rheology allows for memory of
deformation, which weakens the fault zone for a longer period. Once activated, the memory effect and weakening of the fault zone allows for a more frequent reactivation of the fault for smaller strain rates, depending on the strain-weakening parameter combination.