Using thermo-mechanical models to bridge scales between experimental rheology and large-scale observational constraints on mantle and plate dynamics

Fanny Garel[1], Catherine Thoraval[1], Andrea Tommasi[1], Sylvie Demouchy[1], and D. Rhodri Davies[2]
[1]Géosciences Montpellier, CNRS & Université de Montpellier, France (fanny.garel@gm.univ-montp2.fr)
[2]Research School of Earth and Ocean Sciences, Australian National University, Canberra, Australia

Mantle convection and plate dynamics transfer and deform solid material on scales of hundreds to thousands of km. However, viscoplastic deformation of rocks arises from motions of defects at sub-crystal scale, such as vacancies or dislocations. In this study, results from numerical experiments of dislocation dynamics in olivine for temperatures and stresses relevant for both lithospheric and asthenospheric mantle (800–1700 K and 50–500 MPa;) are used to derive three sigmoid parameterizations ($erf, tanh, algebraic$), which express stress evolution as a function of temperature and strain rate. The three parameterizations fit well the results of dislocation dynamics models and may be easily incorporated into geodynamical models. Here, they are used in an upper mantle thermo-mechanical model of subduction, in association with diffusion creep and pseudo-brittle flow laws. Simulations using different dislocation creep parameterizations exhibit distinct dynamics, from unrealistically fast-sinking slabs in the erf case to very slowly-sinking slabs in the $algebraic$ case. These differences could not have been predicted a priori from comparison with experimentally determined mechanical data, since they principally arise from feedbacks between slab sinking velocity, temperature, drag, and buoyancy, which are controlled by the strain rate dependence of the effective asthenosphere viscosity. Comparison of model predictions to geophysical observations and to upper-mantle viscosity inferred from glacial isostatic adjustment shows that the $tanh$ parameterization best fits both crystal-scale and Earth-scale constraints. However, the parameterization of diffusion creep is also important for subduction bulk dynamics since it sets the viscosity of slowly deforming domains in the convecting mantle. Within the range of uncertainties of experimental data and, most importantly, of the actual rheological parameters prevailing in the upper mantle (e.g. grain size, chemistry), viscosity enabling realistic mantle properties and plate dynamics may be reproduced by several combinations of parameterizations for different deformation mechanisms. Deriving mantle rheology cannot therefore rely solely on the extrapolation of semi-empirical flow laws. The present study shows that thermo-mechanical models of plate and mantle dynamics can be used to constrain the effective rheology of Earth's mantle in the presence of multiple deformation mechanisms.