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Can we approximate non-Newtonian rheology to model mantle convection?

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One of the most important parameters in mantle convection studies is the rheology since it is directly responsible for the convective vigor, heat transport and shape of up- and downwellings. Deformation in terrestrial mantles is accommodated by two main deformation mechanisms: diffusion and dislocation creep. While the former probably plays a dominant role at high pressures, the latter is thought to be important at relatively low pressures, as inferred by seismic anisotropy of the Earth's upper mantle [1].

Dislocation creep is more challenging to handle than diffusion creep as the viscosity becomes strain-rate dependent [2], introducing a strong non-linearity that requires much longer computational times. In order to avoid this additional complexity, a Newtonian rheology (i.e. diffusion creep) with reduced activation parameters is often used to mimic non-Newtonian behaviour as described in [3], although this approximation has never been carefully tested for a stagnant-lid regime. Mobile-lid steady-state simulations presented in [3] show that the reduction of the activation parameters should be applied with care and in dependence of the problem considered (e.g., amount of internal heating, pressure- or temperature-dominated viscosity). Nevertheless, this simplification is widely employed in convection studies assuming its presumed general validity (e.g. [4,5]).

We perform numerical simulations in 2D Cartesian, cylindrical and 3D spherical geometry using the mantle convection codes YACC [6] and Gaia [7] to investigate the consequences of this simplification for various scenarios. To verify our methods, we rerun some of the cases from [3] finding a good agreement. Using rheological parameters from [2] and the approximation from [3], our results show that some global properties such as mean temperature, root mean square velocity and nusselt number are indeed similar (within $\sim$10%) to those obtained when employing a fully non-linear rheology. However, the mantle convective planform and stress distribution differ substantially. In addition, for thermal evolution scenarios with decreasing internal heat sources, the reduction of activation parameter is not well constrained.

We conclude that approximating dislocation creep with diffusion creep and a reduced activation enthalpy may strongly affect local temperature and stress distribution and thus influences partial melting and plastic yielding.

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