Thermal Convection and Mantle Plume Dynamics with Grain-Size Dependent Viscosity

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Using a numerical model, the effect of grain-size dependent (GSD)-rheology is tested on thermal convection in a two-dimensional box. The mantle viscosity is determined by a combination of diffusion creep, which is enhanced at small grain size, and dislocation creep. In order to examine in detail the effects of grain size and dynamic recrystallization, other effects on viscosity such as temperature- and pressure-dependence are neglected. It is well-known that the equilibrium grain size is dependent on the applied shear stress. Combined with the GSD-rheology, the viscosity of diffusion creep effectively becomes stress-dependent with a stress-exponent of about 5. Diffusion creep is thus potentially more strongly non-linear than dislocation creep. However, the GSD-viscosity probably has an equilibration timescale similar to the timescale inherent in mantle convection, resulting in an interesting non-linear feedback as the relative importance of dislocation to diffusion creep changes.

One of the more puzzling results is that, when (using common notation) A_{diff} is increased relative to A_{disloc}, which should result in a strenghening of diffusion creep relative to dislocation creep, the exact opposite is what is observed. The explanation of this surprising finding is probably that grain-size diminution is caused only by dislocation creep; hence, when dislocation creep is reduced, the timescale of grain-size equilibration increases such that the non-linearity of the GSD-rheology is never fully activated. The result seems to turn upside-down the expectation of where in the mantle the flow is dominated by diffusion creep and where it is governed by dislocation creep.

Other observations of convection with GSD-rheology include: stronger time-dependence with periods of fast mantle overturning interspersed between quiescent periods characterized by large grain size; regions of the mantle with large grain size which over relatively long timescales do not participate in active convection and which may thus alter the mixing behavior of mantle convection; pulsating mantle plumes; plumes that stagnate mid-way in the mantle; and plumes that are anchored quite stably directly on a dividing line within the thermal boundary layer with large grains on one side and smaller grains on the other. It is clear that the present model has only limited applicability to mantle convection because of the simplifying assumptions. While especially the pressure-dependence of the two competing viscosities is not well known, the results indicate that convection and plumes may display an even richer dynamical behavior due to the GSD-rheology (not that we really needed yet more types of mantle plumes...).