Mantle convection, plasticity and plate kinematics

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Convection models combined with a simple picture of material plasticity have proven to be very useful in describing some aspects of the coupled system of plate motions and mantle flow. In this talk I will review recent developments in this area and then address ways in which we might use our knowledge of the kinematics of plate boundary evolution to improve plasticity models.

In the context of viscous deformation, we normally formulate plastic deformation as the sum of a viscous (or viscoelastic) strain rate, $\varepsilon^{\mathrm{ve}}$ and a plastic strain rate, ε^{p} which becomes active at high stresses

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{\mathrm{ve}} + \dot{\varepsilon}_{ij}^{\mathrm{p}} \tag{1}$$

The plastic strain rate is a general function of the applied stress which ensures that the yield conditions (on the stress tensor) are satisfied.

$$\dot{\varepsilon}_{ij}^{\mathrm{p}} = \lambda \Lambda_{ijkl} \tau_{kl} \tag{2}$$

where Λ captures the form / symmetry of the plastic deformation and λ determines its magnitude; τ is the deviatoric stress.

If the deviatoric stress is expressed in terms of the strain rate we obtain

$$\tau_{ij} = 2\eta \dot{\varepsilon}_{ij} - \beta \Pi_{ijkl} \dot{\varepsilon}_{kl} \tag{3}$$

in which $2\eta\dot{\varepsilon}_{ij}$ is a hypothetical stress predicted from the viscous (or viscoelastic) constitutive law and $\beta\Pi_{ijkl}\dot{\varepsilon}_{kl}$ is a correction. As before, Π represents the form / symmetry of the stress correction relative to the deformation rate, β is the magnitude of the correction.

Commonly, the plastic deformation is determined mathematically from the yield condition on the stress together with some simplifying assumptions which ensure consistent deformation at the yield stress. The symmetry of plastic deformation is therefore implicit in the yield criterion and consistency assumptions.

However, for plate tectonics, we have a very successful kinematic description of plate boundary evolution and a relatively poor understanding of the stress field and yield strength. For this reason it may be worthwhile to instead constrain the symmetry of deformation at yield (Λ) directly to satisfy the observed behaviour. I will show how to develop simple kinematic flow rules for each of the principal plate boundary types, and how to construct a corresponding visco-plastic constitutive model (Π) and yield criterion. I will also discuss the limitations of this approach.