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Localization criterion for ductile shear zone formation by thermal softening

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Strain localization in ductile rock and the associated formation of shear zones is fundamental for many geodynamic processes such as the initiation of subduction, the evolution of strike slip zones or the formation of tectonic nappes. The conversion of dissipative work into heat, the related temperature increase and the associated decrease of temperature-dependent rock viscosities have frequently been suggested as important mechanism for strain localization and shear zone formation. Many analytical studies suggest particular dimensionless numbers, such as the Brinkmann or Gruntfest number, which are frequently used to evaluate whether thermal softening is important for strain localization. However, these dimensionless numbers usually require a priori knowledge of certain parameters related to the already developed shear zone, such as the shear zone thickness, the shear stress applied to the shear zone or the strain rate inside the shear zone. Such dimensionless numbers are not suitable to predict whether a shear zone will develop during the nearly-homogeneous, non-localized deformation of a rock unit which is considerably thicker than a potentially developing shear zone.

We use a thermo-mechanical numerical model of ductile rock deformation based on the conservation equations of continuum mechanics and apply constitutive equations for ductile creep, that is, stress is related to strain rate via a temperature dependent effective viscosity. We also perform a dimensional scaling analysis and data collapse based on a numerical model of a one-dimensional (1D) shear zone for which simple shearing is controlled by a far-field shear velocity and strain localization can be triggered by a temperature, hence viscosity, perturbation in the model center.

We present a localization criterion that predicts the temperature in a ductile shear zone, caused by thermal softening, without a priori knowledge of the shear zone. Only the far field velocity, the time of deformation, the thermal diffusivity and the flow law parameters are required for the temperature prediction. We show that the analytical prediction based on the 1D simple shear model is also applicable to shear zones forming in 2D and 3D numerical models, which are based on far-field pure shear deformation. For any initial temperature, the analytical prediction of the shear zone temperature can be used as localization criterion because our results show that a temperature difference between shear zone temperature and initial temperature of ca. 50 K is sufficient for considerable strain localization.