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A fundamental discussion of what triggers localized deformation in geological materials

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Discontinuous or localized structures are often marked by the transition from a homogeneously deforming into a highly localized mode. This transition has extensively been described in ductile shear zones, folding and pinch-and-swell boudinage, in natural examples, rock deformation experiments and numerical simulations, at various scales. It is conventionally assumed that ductile instabilities, which act as triggers for localized deformation, exclusively arise from structural heterogeneities, i.e. geometric interactions or material imperfections. However, Hansen et al. (2012) concluded from recent laboratory experiments that localized deformation might arise out of steady-state conditions, where the size of initial perturbations was either insufficiently large to trigger localization, or these heterogeneities were simply negligible at the scale of observation. We therefore propose the existence of a principal localization phenomenon, which is based on the material-specific rate-dependency of deformation at elevated temperatures.

The concept of strain localization out of a mechanical steady state in a homogeneous material at a critical material parameter and/or deformation rate has previously been discussed for engineering materials (Gruntfest, 1963) and frictional faults (Veveakis et al., 2010). We expand this theory to visco-plastic carbonate rocks, considering deformation conditions and mechanisms encountered in naturally deformed rocks. In the numerical simulation, we implement a grain-size evolution based on the Paleowattmeter scaling relationship of Austin & Evans (2007), which takes both grain size sensitive (diffusion) and insensitive (dislocation) creep combined with grain growth into account (Herwegh et al., 2014). Based on constant strain rate simulations carried out under isothermal boundary conditions, we explore the parameter space in order to obtain the criteria for localization. We determine the criteria for the onset of localization, i.e. the critical amount of dissipative work translated into heat over the diffusive capacity of the system by an instability study designed for such materials (Gruntfest, 1963). With respect to our numerical experiments, this critical parameter determines the timing when the entire amount of deformation energy translated into heat cannot be diffusively transported out of the system anymore. The resulting local temperature rise then induces strain localization. In contrast to classical shear heating scenarios with (catastrophic) thermal runaways, temperature variations of less than 1 K are sufficient for this localization mode to occur due to the balance between heat producing (e.g. dislocation creep) and consuming (grain growth) processes in the present setup. We demonstrate that this rise in latent heat is sufficient to provoke grain growth, operating as an endothermic reaction, stabilizing the simulated localized structure in turn.

Various localized ductile structures, such as folded or boudinaged layers, can therefore be placed at the same material failure mode due to fundamental energy bifurcations triggered by dissipative work out of homogeneous state. Finally, we will discuss situations, in which structural heterogeneities are considered negligible and where the energy theory described here plays an underlying role by means of a comparison between numerical experiments and natural examples.

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