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Linking natural microstructures with numerical modeling of pinch-and-swell structures

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For a variety of geological problems, the change from homogeneous to localized deformation and the establishment of steady-state conditions are equally important. Here, we show that pinch-and-swell structures are ideal candidates for the study of the switch in deformation style and mechanism during ductile creep.
We present an interdisciplinary approach to the onset of pinch-and-swell structures and to the flow conditions during pre- to post-localization stages in ductile rocks. For this reason, naturally boudinaged calcite veins, embedded in a calc-mylonite, and their microfabrics were investigated quantitatively. Remnants of slightly deformed calcite hosts build up the swells, showing twinning and minor dislocation glide as crystal plastic deformation mechanisms which are accompanied by subgrain rotation recrystallization (SGR). Towards the pinches, we find a gradient of severe grain size reduction through progressive SGR, developing a characteristic dislocation creep crystallographic preferred orientation (CPO). Along this gradient, the finest recrystallized calcite grains appear randomly oriented, expressed by a “smearing-out” of the CPO and missing systematics of misorientation angles in the most extended areas. We interpret this microstructure as a switch from dislocation dominated creep to grain boundary sliding processes. Further, we show that the onset of boudinage is independent on both the original orientation and grain size of calcite hosts.
We implemented these microstructural observations into a layered elasto-visco-plastic finite element framework, tracing variations in grain size (Peters et al., 2015). We base the microstructural evolution on thermo-mechanical-chemical principles and end-member flow laws (Herwegh et al., 2014). The simulated pinch-and-swell structures indicate that low strain rates in the swells favor dislocation creep, whereas accelerated rates provoke continuous grain size reduction allowing strain accommodation by diffusion creep dominated deformation at relatively high extensional strains in the pinches. The numerical simulations indicate that viscosity weakening due to dissipated heat from grain size reduction marks the onset of localization, resulting in continuous necking of the layer. Interestingly, there exist multiple steady states, i.e. a first homogeneous state out of which localization arises, steady states of the stable end-member structure, expressed by homogeneous conditions in both pinches and swells, and in the surrounding matrix, the latter obeying a linear rheology.
Based on our microstructural and numerical results, we suggest that the onset of localization represents a fundamental material bifurcation. This implies that the studied structures can be described as ductile instabilities. Finally, we discuss the profound role of the energy theory of localization described here, which allows deriving the paleo-deformation conditions, as well as fundamental material properties in a self-consistent manner.

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