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Towards the determination of deformation rates – pinch-and-swell structures as a natural and simulated paleo-strain rate gage

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Layered rocks deformed under viscous deformation conditions frequently show boudinage, a phenomenon that results from differences in effective viscosity between the involved layers. In the case of continuous necking of a mechanically stiffer layer embedded in a weaker matrix, symmetric boudins are interpreted as the result of dominant visco-plastic deformation (Goscombe et al., 2004). However, information on the physical conditions, material properties and deformation processes are yet unknown.

Natural samples deformed under low-grade (T<350°C) metamorphic conditions were studied in detail in the Dent de Morcles and Doldenhorn nappes of the Helvetic Alps in order to accurately simulate their deformation styles by numerical models.
In these samples, monomineralic calcite (Cc) veins were repeatedly boudinaged on cm- to μm-scale. Remnants of incompletely recrystallized original vein Cc grains in the swells indicate a sequence of deformation twinning, followed by progressive dynamic recrystallization along former twin planes up to complete recrystallization in the pinches (Schmalholz and Maeder, 2012). This sequence suggests dislocation creep to be active as important deformation mechanism. In contrast to the pinch-and-swell structures, the grain size of the Cc in the surrounding matrix is much finer-grained due to pinning by secondary particles, forcing the matrix to deform under viscous granular creep, i.e. by diffusion accommodated grain boundary sliding.

The deformation processes observed in the natural samples were incorporated into a numerical model in order to evaluate the rheology of both layer and matrix, using an extension to a user material subroutine (Karrech et al., 2011a) for the finite element solver ABAQUS. We implemented thermo-mechanical coupling allowing elastic, viscous and plastic deformation of Cc (Herwegh et al., in press). We simulate a pure-shear box using finite elements, each representing a grain size distribution, which undergo layer-parallel extension. The box is built up by 3 layers, consisting of a central layer of coarse-grained populations, surrounded by finer-grained populations on bottom and top. The rheology evolves from transient stages (elasticity and strain hardening) to composite viscous flow (GSI & GSS) with increasing shear strain. The small grain sizes in top and bottom layers are strain-invariant and limited in their growth (comparable to Zener pinning) forcing the matrix to deform by exclusively by GSS creep. In contrast, the initially coarse grain sizes of the central layer are allowed to adapt to the physical deformation conditions by either grain growth or grain size reduction following the Paleowattmeter of Austin and Evans (2007) combined with the thermodynamic approach of Regenauer-Lieb and Yuen (2004). Depending on the dissipated energy, grain sizes in these domains vary substantially in space and time. While low strain rates (low stresses) in the swells favor grain growth and GSI dominated deformation, high strain rates in the pinches provoke dramatic grain size reduction with an increasing contribution of GSS as a function of decreasing grain size. The development of symmetric necks observed in nature thus seems to coincide
with the transition from dislocation to diffusion creep dominated flow with continuous grain size reduction and growth from swell to neck at relatively high extensional strains.

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