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Impact of grain size evolution on necking in calcite layers deforming by combined diffusion and dislocation creep

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ABSTRACT

Natural pinch-and-swell structure in centimetre-thick calcite layers shows a reduction of grain size from swell towards pinch. However, the impact of grain size evolution on necking and pinch-and-swell formation is incompletely understood. We perform zero-dimensional (0D) and 2D thermo-mechanical numerical simulations of calcite layer extension to quantify the impact of grain size evolution on necking for bulk extension rates between 10^{-12} s^{-1} and 10^{-14} s^{-1} and temperatures around 350 °C. For a combination of diffusion and dislocation creep we calculate grain size evolution according to the paleowattmeter (grain size is proportional to mechanical work rate) or the paleopiezometer (grain size is proportional to stress). Numerical results fit three observations: (i) significant thickness variations along the layer after extension, (ii) grain size reduction from swells towards pinches, and (ii) dislocation creep dominated deformation in swells and significant contribution of diffusion creep in pinches. Modelled grain size in pinches (10–60 μm) and swells (70–800 μm) is close to observed grain size in pinches (21 ± 6 μm) and in swells (250–1500 μm). In the models, grain size evolution has a minor impact on necking, and viscous shear heating and grain size evolution have a negligible thermal impact.

1. Introduction

Pinch-and-swell is a well-known structure in rock layers which is discussed in essentially all text books on structural geology (e.g. Ramsay, 1967; Price and Cosgrove, 1990; Pollard and Fletcher, 2005; Fossen, 2016). The characteristic feature of this structure is the significant variation of thickness along the layer (Fig. 1) which is commonly explained by necking of the layer during its extension. We use necking here as a general term to refer to local thinning due to the mechanical instability of a competent layer under extension and pinch-and-swell to refer to the regular structure that develops from repetition of necking zones, or necks, along the layer (e.g. Smith, 1977; Schmalholz and Mancktelow, 2016). Mechanical instability of necking (e.g. Ghosh, 1977; Smith, 1977; Drazin and Reid, 1981; Johnson and Fletcher, 1994; Pollard and Fletcher, 2005) means here that small geometrical perturbations on the layer interface, which always exist on natural rock surfaces and cause small lateral thickness variations, amplify with rates that are faster than the applied bulk extension rate so that the layer can locally thin faster as it would do under homogenous thinning during extension. The progressive increase of the differences in thinning rates, and hence strain rates, during layer extension represents a particular kind of strain localization, namely the transition from homogeneous to heterogeneous thinning in the extending layer.

Many studies have investigated necking in rock layers with macroscopic (here the scale of the layer) continuum mechanic models of viscous flow in which microscopic processes, such as grain size evolution, have been neglected (e.g. Smith, 1977; Neurath and Smith, 1982; Johnson and Fletcher, 1994; Schmalholz et al., 2008; Pollard and Fletcher, 2005; Duretz and Schmalholz, 2015; Adamuszek et al., 2016). We refer here to viscous flow models when in the models the applied constitutive equation is a mathematical relation between differential stress and strain rate, which applies to typical flow laws for diffusion, dislocation and exponential creep (e.g. Kohlstedt, 2007; Karato, 2008). We use here the term viscous deformation rather than plastic deformation, which is also often used for deformations described by the above mentioned creep flow laws (e.g. Kohlstedt, 2007), to avoid confusion with solid mechanical plasticity theory which describes the limitation of elastic stresses by plastic yield functions and which can be used as approximation for solids undergoing brittle deformation (e.g. Hill,

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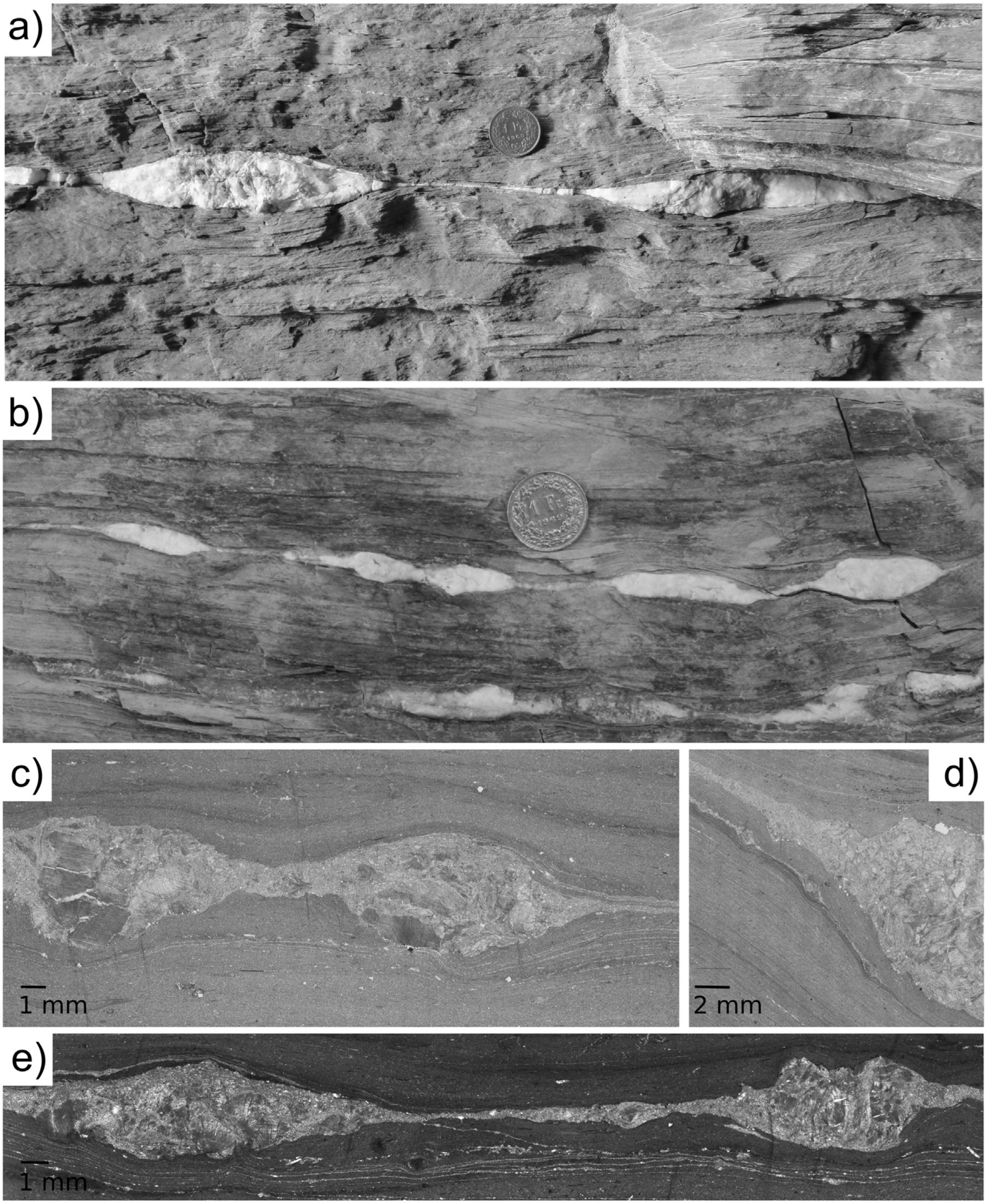

Fig. 1. Natural pinch-and-swell structure in calcite layers embedded in fine grained limestone from the Doldenhorn (a) and Morcles (b) nappes, Helvetic nappe system, Switzerland. c) to e) show thin-section photos of pinch-and-swell in calcite layers from the Morcles nappes (same locality as b). For all micro-scale pinch-and-swell structures the grain size reduces significantly from the swell towards the pinch.

1998; Davis and Selvadurai, 2002). The published viscous flow models for necking show that significant necking in extending layers takes place when (i) the effective viscosity ratio between layer and embedding medium, referred to here as matrix, is large (>~50), and (ii) when the viscous flow law of the deforming layer exhibits a large apparent stress exponent (>~5; see Schmalholz and Mancktelow, 2016; for a recent review). If the effective viscosity ratio and the apparent stress exponents are smaller, then a necking instability is, strictly speaking, still occurring but the instability is so weak that no significant necking and no significant thickness variations develop during extension of a few hundred percent; the deformation is, hence, close to homogeneous pure shear extension. If the apparent stress exponent of the layer is one (i.e. linear viscous or Newtonian viscous flow) then no necking instability occurs no matter how large the viscosity ratio (e.g. Smith, 1977). Large effective viscosity ratios and stress exponents are feasible in layered rocks considering the wide variety of creep flow laws which have been determined in laboratory rock deformation experiments,