# Furrow-and-ridge structures on active rockglaciers explained by gravity-driven buckle folding: A finite-element study applied to the Murtèl rockglacier

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Rockglaciers, typical permafrost landforms, often feature a prominent furrow-and-ridge topography. The Murtèl rockglacier in the Upper Engadin valley is a very spectacular example for such morphology, with amplitudes and wavelengths in the order of 5 m and 20 m, respectively (Figure 1). Previous studies have suggested that these structures develop under the influence of a longitudinal compressive flow regime in the lower part of a rockglacier (Haeberli et al., 1998; Kääb and Weber, 2004). However, these hypotheses have mostly been based on descriptive observations and therefore remained speculative.

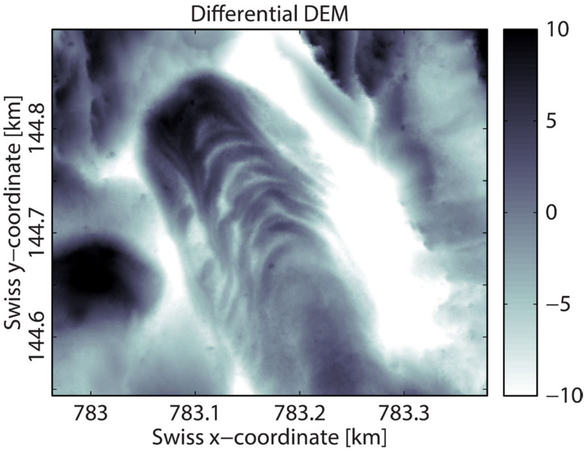

Figure 1: Difference between the Murtèl rockglacier DEM and the moving average of the same DEM. The latter is calculated at each pixel as the mean within a 200 m radius circular area.

Buckle folding is the mechanical response of a layered viscous material to compression if the mechanical contrast between the layers is significant. The resulting buckle folds are common structures in rocks and have been studied extensively in field outcrops, experimentally, numerically, and analytically (see Hudleston and Treagus, 2010 for a review). We believe that buckle folding is also the main responsible process for the formation of the transverse furrow-and-ridge topography on rockglacier surfaces. In this cross-disciplinary study we use the buckle folding theory, which is well-established in the field of structural geology, and apply it to the field of rockglacier geomorphology.

The Murtèl rockglacier is an ideal case study due to its well-studied internal structure (Arenson et al., 2002), which can be approximated with two layers: an upper mixed rock-ice layer and a lower pure ice layer, both exhibiting a viscous rheology. Such a simple structure is a prerequisite for the analytical buckle folding expressions, which assume a single layer embedded in a weaker material. A 1 m-resolution digital elevation model (DEM; Figure 1), based on low-altitude aerial photographs of the Swiss Permafrost Monitoring Network, is analyzed using the Fold Geometry Toolbox (FGT; Adamuszek et al., 2011). This software uses analytical buckle folding expressions and as such provides a quantitative relationship between the observed wavelength, layer thickness, and the effective viscosity ratio between the folded layer and the underlying ice.

We developed a numerical finite element (FE) algorithm to simulate dynamical 2D buckle folding of a layered viscous medium (Frehner et al., 2012) and apply it to the gravitational flow of a two-layer rockglacier (Figure 2). For the lower pure ice layer we use standard density and viscosity values for glacier ice; for the upper mixed rock-ice layer we use material parameters obtained from the previous FGT-analysis of the Murtèl rockglacier DEM. The initial setup is inspired by the Murtèl rockglacier geometry. The simulated gravitational flow leads to a buckling instability of the upper layer due to the mechanical contrast to the underlying pure ice layer (Figure 2). The resulting wavelengths and amplitudes are similar to the Murtèl rockglacier. In addition, the modeled strain rate field highlights the basal shear zone, which is also observed in boreholes.

Our study promotes buckle folding as the dominant process for the formation of transverse furrow-and-ridge structures on rockglacier surfaces.

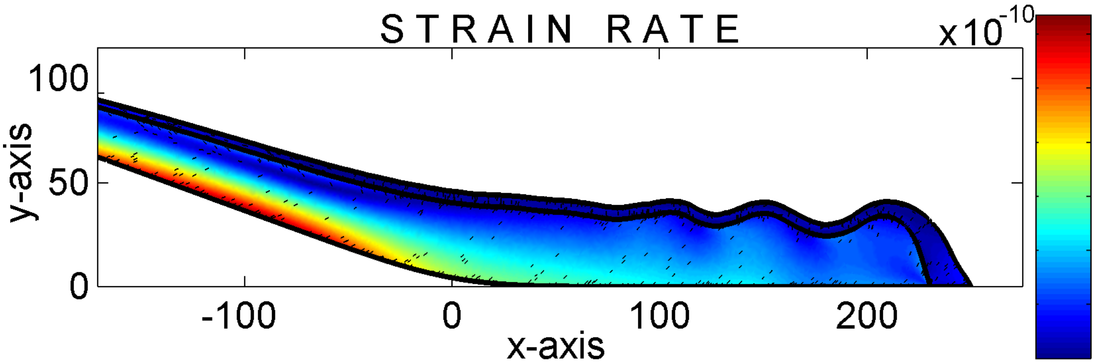

Figure 2: 2D FE-simulation snapshot of a rockglacier flowing downslope due to gravity. The upper mixed rock-ice layer exhibits a higher effective viscosity than the underlying pure ice layer. Colors represent the second invariant of the strain rate tensor; short black lines indicate the long axis of of the strain rate ellipse. The bottom boundary is fixed in accordance with borehole measurements.

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