Non-linearity of rockglacier flow law determined from geomorphological observations:

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Introduction

The creep behavior ( rheology) of rockglaciers may deviate from the well-known flow-law for pure ice. Here we constrain the non-linear flow law governing rockglacier creep based on borehole deformation data and map-view data. The Murtèl rockglacier in the Upper Engadin valley, SE Switzerland serves as a case study, for which high-resolution DEMs, time-lapse borehole deformation data, and geophysical soundings exist that reveal the exterior and interior architecture and dynamics of the landform.

Borehole inclination data of the Murtèl rockglacier (Arenson et al., 2002) reveal a curved deformation profile. In map view, the prominent foreset and ridge morphology also exhibits a curved geometry. Hence, the surface morphology and the borehole deformation data together describe a curved 3D flow geometry. Frehner et al. (2015) reproduced the curved vertical flow profile and the upper part of the borehole deformation profile using a 2D linear viscous (Newtonian) flow model. Linear viscous models result in perfectly parabolic flow geometries, non-linear creep leads to localized deformation at the bottom and sides of the rockglacier while the deformation at the top and in the interior are less intense. In other words, non-linear creep results in non-parabolic flow geometries. By comparing the observed flow geometry with theoretical 3D flow geometries, we determine the most adequate flow-law that fits the natural deformation geometry best.

The Murtèl rockglacier

In Frehner et al. (2015), the applied buckle folding theory for linear viscous (Newtonian) materials to explain the furrow and ridge morphology on the Murtèl rockglacier. Based on the spacing of the furrows and ridges (5–20 m) we determined the effective (Newtonian) viscosity ratio between the upper layer (h=3 m) and the main rockglacier body as n=2.

Motivation: Our previous work

Buckle folding theory in a nutshell: Buckle folding in the mechanical replication of layered viscous materials to layer parallel compression. The wavelength (7) depends on the effective viscosity ratio (h) between the stiff (middle) and soft layer, and on the thickness of the stiff layer (h).

First results for borehole data

So far, we analyzed two borehole curves (Fig. 6 & 7, Table 1). Considering the entire borehole, the power-law fits perform significantly better (R²>0.92) than the quadratic fits (R²<0.75) and we find power-law exponents of 3.14>m>7.30. Considering only the middle section of the borehole, all different fitting curves perform equally well (R²=0.96) and we find power-law exponent close to m=2.

First results for furrow-and-ridge geometry

The borehole deformation data suggests that creep of the Murtèl rockglacier as a whole is governed by a non-linear viscous flow law with a stress exponent (m) between 4 and 6 in Fig. 6 & Table 1. Hence, the rockglacier may be divided into a lower part with highly viscous (main rockglacier body) with an almost linear (m=1) rheological flow law. The curvature of the furrow-and-ridge morphology suggests an almost linear (m=1) rheological flow law.

Discussion, Conclusions & Outlook

This may indicate that the development of the furrow-and-ridge morphology is independent of the basal shear zone and only governed by the flow of the main rockglacier body. Such an explanation has been made by Frehner et al. (2014).

Outlook

Our work continues and will be finalized during the BSc Thesis of D. Amshwandt. Next, we will feed the best-fit rheological laws into a 3D finite-element model (Fig. 11) as example to study the internal dynamics (stress & strain rates) of rockglacier flow.

References:

Arenson L. et al., 2002: Borehole deformation measurements and internal structure of some rock glaciers [...]. PPP 13, 117–135.

Flow of non-linear viscous materials leads to curved, but not perfectly parabolic flow structures. Ideally, the power-law exponent of the curved flow structures (m) is one unit larger than the power-law stress exponent of the non-linear rheological flow law (m). Hence, the following relationship applies:

\[ \tau \propto \varepsilon^m \]

where \( \tau \) is shear stress, \( \varepsilon \) shear strain rate, \( m \) stress exponent in power-law functions and \( m \) fixed gradient(s) at the end(s) of the structure (e.g., at the top of the borehole).

Rheological flow law (Glen’s (1952) flow law):

\[ \tau = C \varepsilon^3 \]

Gradient of flow law: \( \alpha = \frac{\varepsilon}{\tau} \)

Horizontal borehole deformation with depth

Therefore, geometrical analysis of curved furrow-and-ridge morphology in map view (Fig. 4) and the borehole deformation data in vertical view (Fig. 5) should allow determining the power-law exponent (m) governing the viscous flow. Various assumptions and boundary conditions may be applied:

- In map-view consider the entire furrow and ridge structure or reject few meters on each side in the borehole: include or reject the top 5 m and/or bottom few meters (shear zone)
- Fixed value(s) or or fixed gradient(s) at the end(s) of the structure (e.g., at the top of the borehole)

Fig. 1: Regional overview (Google Earth) of Piz Corvach and the Murtèl cirque. Grab a pair of red-blue 3D glasses. Important: Relax your eyes, e.g. focus on the furthest peaks right of the center of the image.

Fig. 2: Digitalized ridges superimposed on the 8 cm DEM (hillshade). In this hillshade representation of the DEM the furrow and ridge morphology is particularly well visible, enabling digitization.

Fig. 3: Different views of 3D deformability simulations. A DEM (Fig. 4) defines the model topography. The base is equal to the 3D model (Fig. 2).