Furrow-and-ridge morphology on rockglaciers explained by gravity-driven buckle folding:

A case study from the Murtèl rockglacier (Switzerland)

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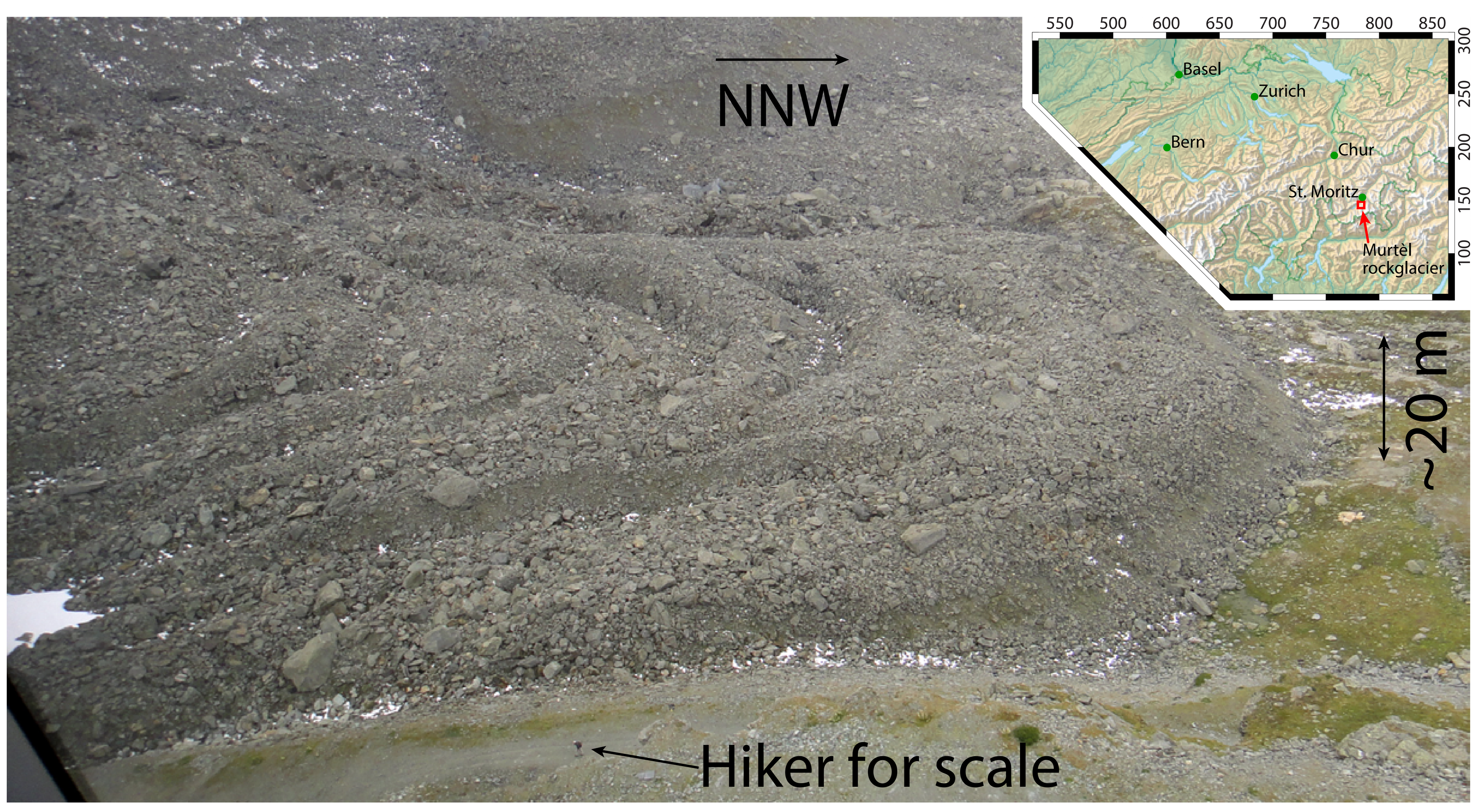
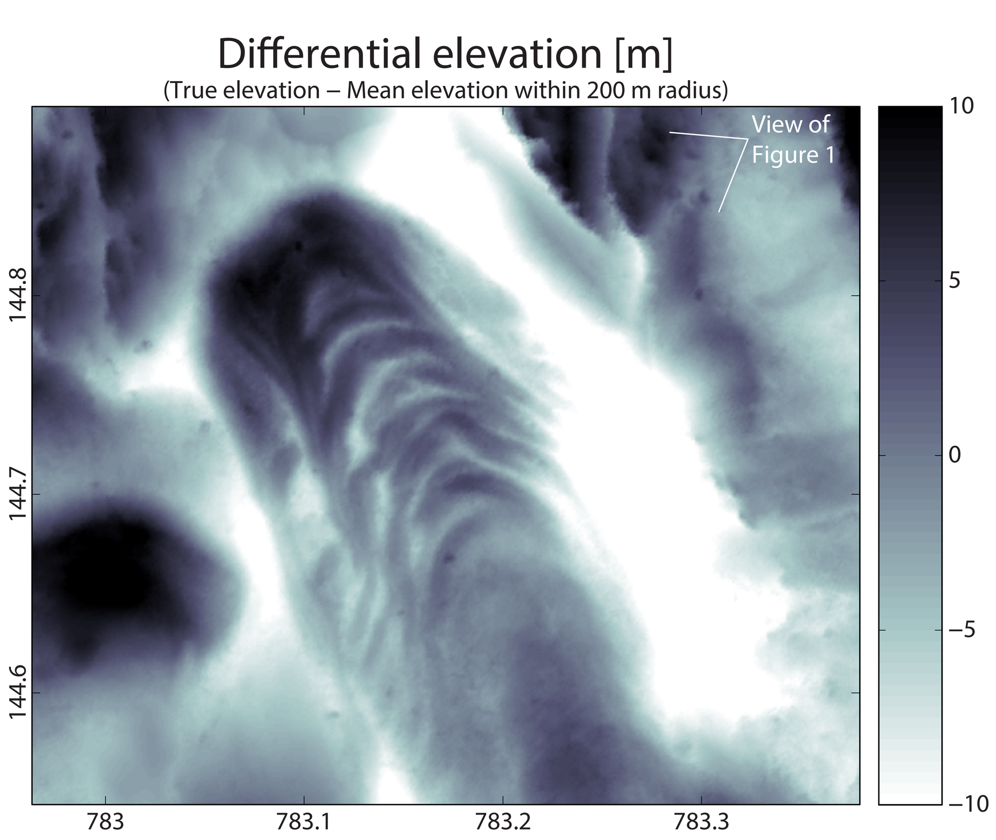
Abstract

Rockglaciers often feature a prominent furrow-and-ridge topography. Previous studies suggest that this morphology develops due to longitudinal compressive flow during rockglacier creep; however, no mechanical/physical explanation for the observed characteristic wavelength has been provided. Our study promotes buckle folding as the main process forming the transverse furrow-and-ridge morphology on rockglaciers. As a case study we chose the Murtèl rockglacier (Switzerland), which exhibits a spectacular furrow-and-ridge morphology. We analyse a high-resolution digital elevation model using analytical buckle folding expressions, which provide a quantitative relationship between the observed wavelength, layer thickness, and the effective viscosity ratio between the folded active layer and the underlying ice. We feed this geometrical and rheological information into a numerical finite-element model to simulate gravity-driven 2D rockglacier flow. A buckling instability develops and amplifies, self-consistently reproducing several key features of the Murtèl rockglacier, such as wavelength, amplitude, and distribution of the furrow-and-ridge morphology, as well as the quasi-parabolic flow profile observed in boreholes. Comparing our model with published flow velocities allows estimating the time necessary to produce the furrow-and-ridge morphology to about 1000–1500 years.

The Murtèl Rockglacier





↑*Fig. 1: The Murtèl rockglacier with its surface furrow-and-ridge morphology. The photograph is taken out of the Murtèl-Corvatsch areal cableway. Inset: Map of Switzerland showing the location of the Murtèl rockglacier.*

←*Fig. 2: Differential elevation model (diffDEM) of the Murtèl rockglacier. The employed 1 m-resolution DEM is based on photogrammetry.*

Geometry and Rheology

Geometrical Information (DEM, boreholes, geophysics)

- Wavelength of furrow-and-ridge structure: 20–25 m
- Average amplitude: ~2 m
- Two layers: Lower almost pure ice layer (~27 m); Active layer (3–5 m), mixture of ice and rock (Fig. 1)

Rheological Information (Fold Geometry Toolbox, FGT)

- Both layers are assumed to be viscous
- The FGT uses analytical buckle folding expressions to calculate the viscosity ratio between the folded layer and its substratum from a given fold geometry (Fig. 3)

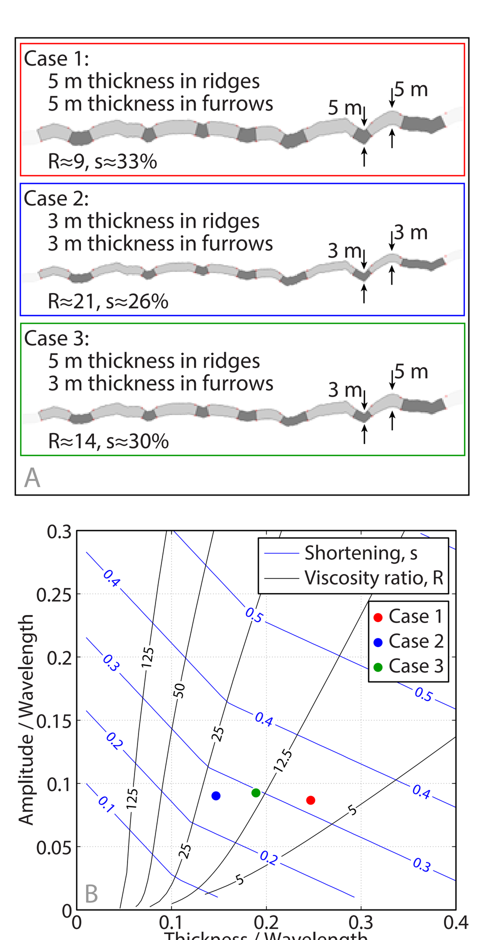


Fig. 3: Geometrical input data (active layer) and inferred rheological information of the Murtèl rockglacier. All sub-figures are modified screenshots from the FGT software.

Numerical Finite-Element Model

Based on the geometrical and rheological information, a FE-model is designed:

- Newtonian rheology
- Two layers with viscosity ratio R=21
- 2D FE-method using Lagrangian mesh
- Mixed velocity-pressure-penalty formulation (Galerkin method)
- Isoparametric triangular T7/3 elements
- Uzawa-type iteration to enforce incompressibility

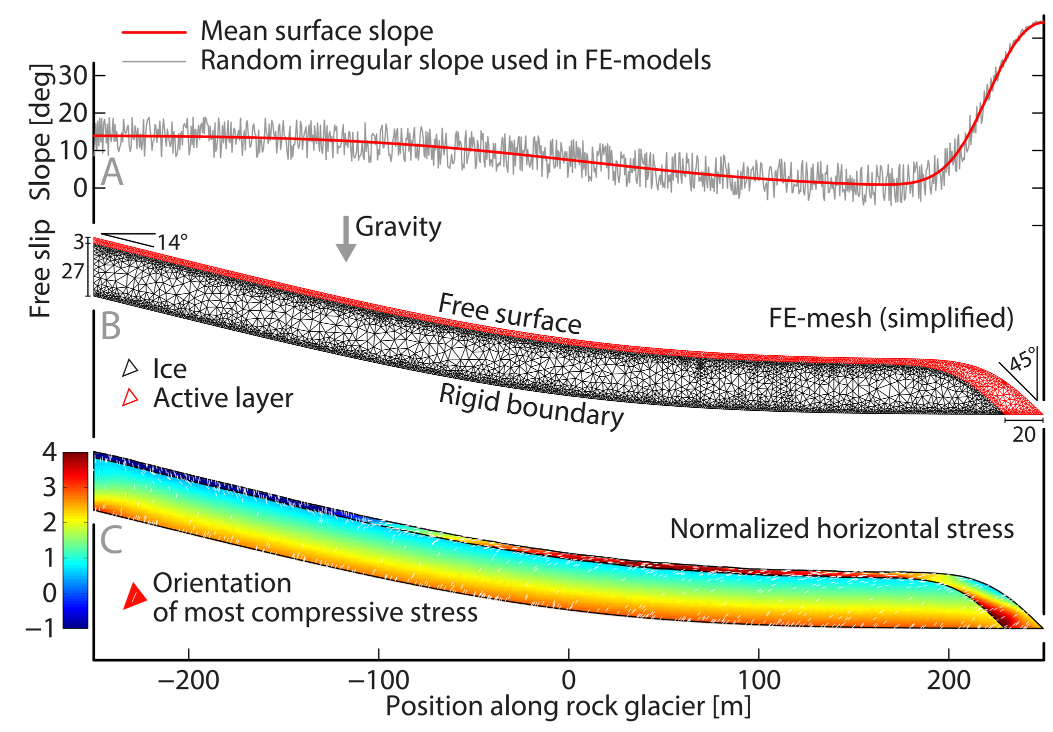


Fig. 4: Initial state and boundary conditions of FE-model. Initial surface slope (A), internal two-layer structure, and layer thicknesses (values in meters in B) are inspired by the Murtèl rockglacier. The numerical mesh (B) is simplified as the real employed mesh is too dense to be shown here. C: Normalized horizontal stress after one time step and orientation of the most compressive stress (white lines).

Dynamic Rockglacier Flow Model

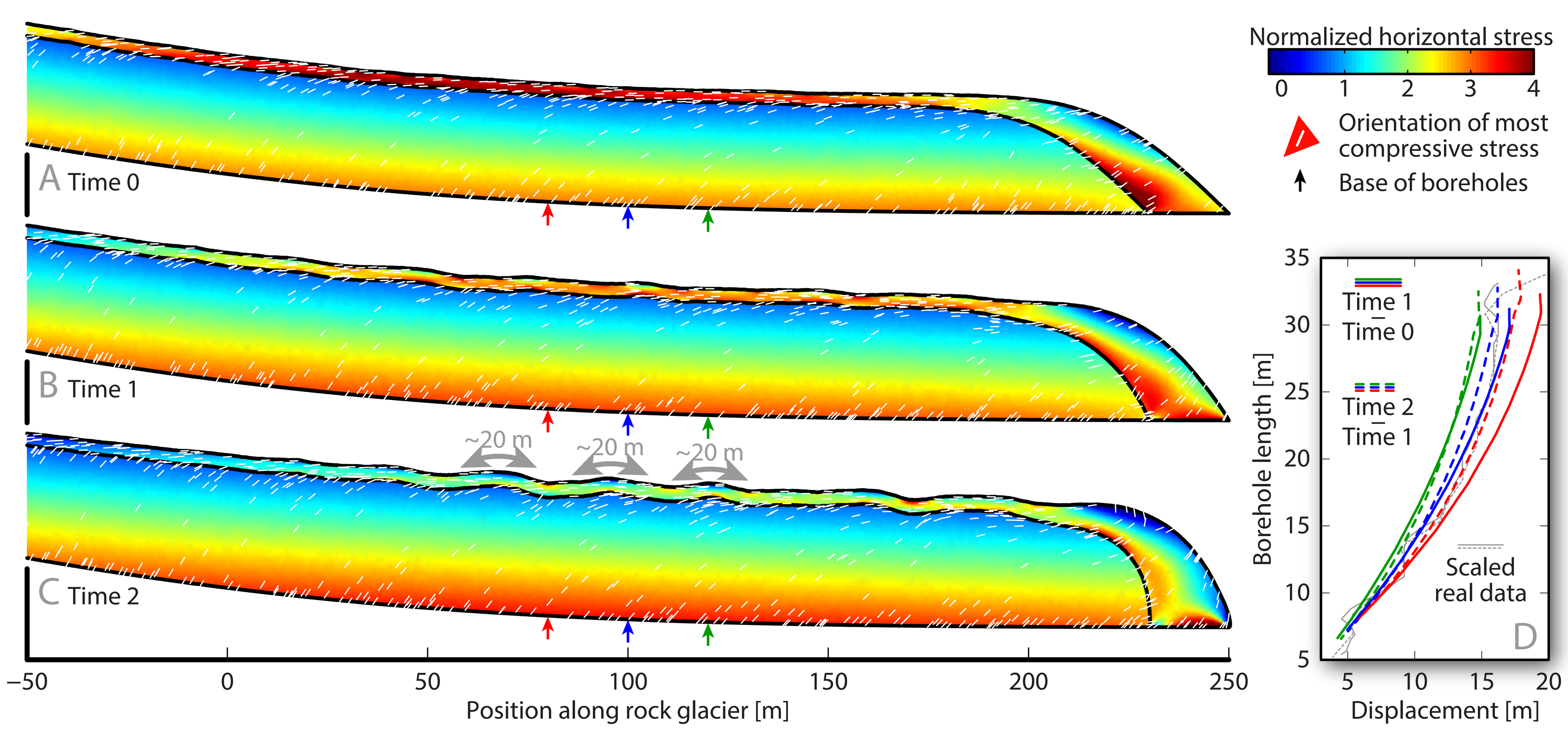


Fig. 5: A–C: Simulation snapshots of the frontal part of the rockglacier. A: Zoom of Fig. 4C. D: Modeled borehole deformation (colored lines) at three locations indicated in A–C. Gray lines: Borehole deformation on the Murtèl rockglacier (Arenson et al., 2002) between 11.1987 and 03.1992 (solid line) and between 11.1987 and 08.1995 (dashed line), both horizontally scaled to match the time scale of the FE-simulation.

Timing of Furrow-and-Ridge formation

- FE-simulations do not capture the shear zone deformation (base of rockglacier); hence only 40% of the total deformation is modeled (Arenson et al., 2002).
- 3D flow field (Fig. 1 & 2) slows down rockglacier flow compared to modeled 2D flow by about 35% (open-channel flow assumption).
- Fitting measured surface velocities (5–6 cm/a), and including both corrections above, our simulation predicts 960–1460 years to develop the furrow-and-ridge morphology. Time 1=480–730 yrs; Time 2=960–1460 yrs after initial state (Fig. 5).

Discussion and Conclusions

- Rockglacier slow-down leads to layer-parallel compression promoting buckle folding due to the mechanical layering of rockglaciers.
- Buckle folding may be the dominant process for furrow-and-ridge development.
- Several first-order features of the Murtèl rockglacier are reproduced: wavelength, amplitude, and location of furrows and ridges, and quasi-parabolic flow profile.
- Timing: <1500 yrs are estimated for developing furrow-and-ridge morphology.

References:

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Arenson L., Hoelzle M. and Springman S., 2002: Borehole deformation measurements and internal structure of some rock glaciers in Switzerland, Permafrost and Periglacial Processes 13, 117–135.
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