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Using dynamic modelling to simulate the distribution of rockglaciers

Regula Frauenfelder [a,*], Bernhard Schneider [b], Andreas Kääb [a]

[a] *Department of Geography, University of Zurich, 8057 Zurich, Switzerland*
[b] *Department of Geosciences, University of Basel, 4056 Basel, Switzerland*

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Abstract

Rockglaciers — permafrost creep features on mountain slopes — are common landforms in high mountain areas. The present contribution reports about the exploration of a dynamic modelling approach using cellular automata to assess their regional distribution patterns. The designed prototype model allows the numerical simulation of the spatial and temporal occurrence of talus-derived rockglaciers in the Upper Engadine (eastern Swiss Alps) during the Holocene. The dynamic model considers processes in the spatial and temporal domain and accounts for both external and internal processes, implemented by means of six modules (A to G). The external processes are: (A) rock-debris accumulation, (B) hydrology, (C) climate, (D) glacier extent. The internal processes are: (E) creep initiation, (F) advance rate, (G) creep termination. Comparison between field evidence and modelling results shows that the dynamic model enables the simulation of spatio-temporal creep processes on a regional scale, but that the model is highly dependent on the accurate modelling of the relevant (input) parameters. These deficiencies have been recognized and analyzed, and it is planned that future research activities will address these issues.

Keywords: Creeping mountain permafrost; Dynamic modelling; Cellular automata; Swiss Alps; Holocene landscape history

1. Thematic background and aim

Rockglaciers are periglacial debris accumulations produced, deposited, and deformed over time scales of centuries to millenia. They are efficient transport systems of rock-debris in the periglacial alpine environment. Rockglaciers originate from talus ('talus-derived' rockglaciers, see Fig. 1) and/or glacier-transported debris.

Talus-derived rockglaciers are located at the foot of headwalls with a high supply of debris and represent a process chain linking frost weathering and rockfall (low magnitude/high frequency events), and rock slides and debris flows (high-magnitude/low frequency events) from headwalls with debris displacement by permafrost creep. In general, the occurrence of these landforms is influenced primarily by climatic, topographic and geological preconditions.

Measured ice contents in active rockglaciers are in the order of 50 and 90% (e.g. Haeberli et al., 1998; Konrad et al., 1999; Vonder Mühll et al., 2001; Arenson, 2002), i.e. the ice content is significantly larger than the pore volume. This implies that active rockglaciers are supersaturated in ice, including massive ice lenses. Ice-supersaturated debris bodies deform under the influence of gravitational stress. This process leads to the formation of rockglacier landforms over time. Two main thermo-mechanical differences to the deformation of

* Corresponding author. Department of Geosciences, University of Oslo, P.O. Box 1042 Blindern, 0316 Oslo, Norway.
E-mail address: regula.frauenfelder@geo.uio.no (R. Frauenfelder).

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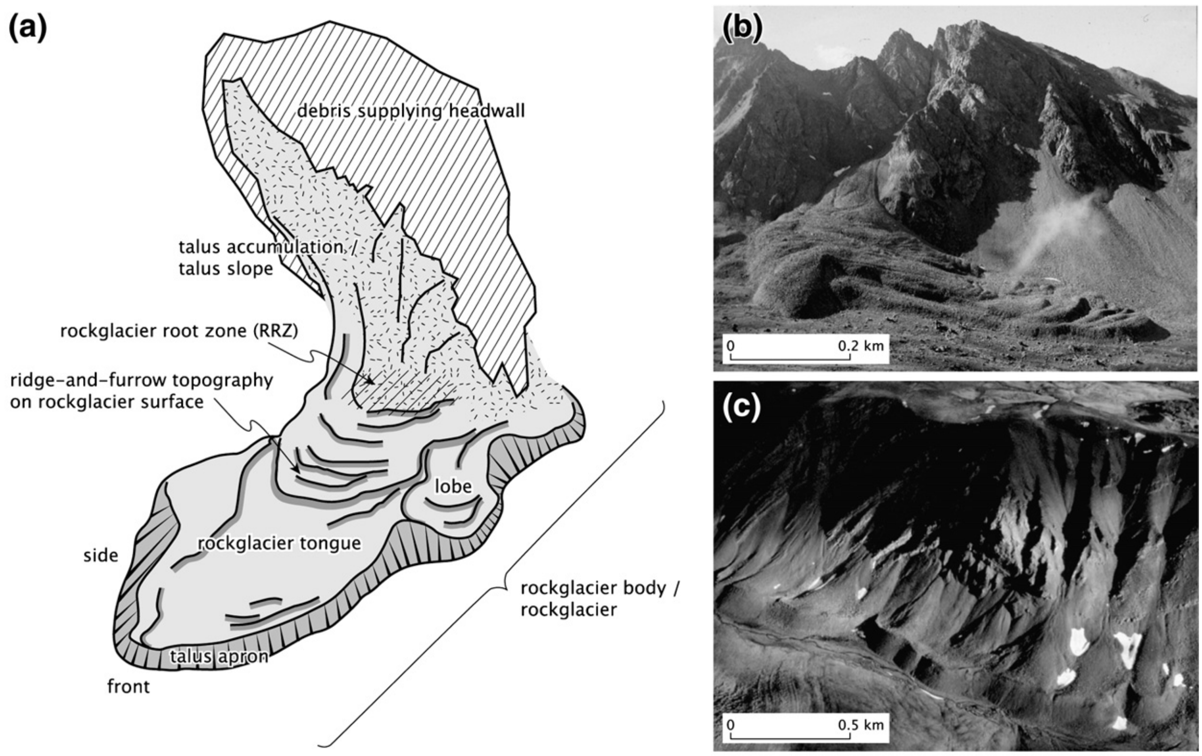

Fig. 1. (a) Schematic plot of a talus-derived rockglacier, (b, c) two examples of active talus-derived rockglaciers: (b) Muragl rockglacier in the Upper Engadine, Eastern Swiss Alps (photograph by R. Frauenfelder), (c) rockglaciers at Nordenskiöldkysten, Svalbard Archipelago (photograph by A. Kääb).

glacier ice should be noted: (1) the ice in rockglaciers is colder than 0 °C throughout the year, i.e. it is permanently frozen (= permafrost), and (2) the creeping body consists of a mixture of ice and debris. Although rockglacier matrices differ, therefore, significantly from glacier ice, first model attempts and sensitivity studies (e.g. Olyphant, 1983; Olyphant, 1987; Whalley and Martin, 1992; Arenson, 2002; Leysinger Vieli, 2004) suggest that the deformation of rockglacier bodies can be approximated quite well using Glen's flow law, though with rate factors very different to pure glacier ice.

Numerous inventory studies about rockglaciers yielded valuable information about their characteristics such as form, geology, location, etc. In addition, detailed studies on individual rockglaciers helped to build up a profound knowledge basis about these landforms. However, a comprehensive understanding of intra-regional variability of rockglacier occurrence is still lacking. The aim of the present study is, therefore, to help evaluate and increase knowledge about dynamics and distribution patterns of rockglaciers by means of dynamic modelling (cf. Bras et al., 2003, for an in-depth discussion of mathematical modelling in geomorphology).

2. Methodical background

Dynamic modelling builds upon static modelling by incorporating the time component (e.g. Van Deursen, 1995; Wesseling et al., 1996, Karssenberg, 2002). A dynamic model describes, thus, how a parameter system can transform from one qualitative state into another, where each qualitative state is described by a static model. The dynamic spatio-temporal behaviour of the system is modelled as an interaction between spatial and temporal processes. The word 'spatial' refers to the geographic domain which the model represents (i.e. the two- or three-dimensional space), while 'temporal' refers to simulated changes through time by using rules of cause and effect (Lundell, 1996).

The presented dynamic model (cf. Section 4) is based on the approach of cellular automata (Von Neumann, 1966). Cellular automata are dynamical systems in which space and time are discrete. A cellular automaton consists of a regular grid of cells, each of which can be in one of a finite number of k possible states, updated synchronously in discrete time steps according to a local, identical interaction rule. The state of a cell is determined by the