TEN YEARS AFTER DRILLING THROUGH THE PERMAFROST OF THE ACTIVE ROCK GLACIER MURTÈL, EASTERN SWISS ALPS: ANSWERED QUESTIONS AND NEW PERSPECTIVES

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Abstract

During the 10 years following the 1987 core drilling through the active rock glacier Murtèl (Swiss Alps), systematic observations in the instrumented borehole and at the surface of the rock glacier opened new perspectives concerning thermal conditions, material properties, rheology, geomorphological evolution and environmental significance of creeping mountain permafrost. The presently available knowledge and process understanding provides the basis for numerical modelling of the partial systems involved (debris production, freezing/thawing, deformation, material redistribution, age structure). Principal open questions concern the energy and mass transfer within and across the boundaries of the creeping permafrost, the various processes involved with ground ice formation in scree slopes, the development of ground thermal conditions and material properties with anticipated atmospheric warming, and the complex flow dynamics at rock glacier fronts and within complex 3-dimensional landforms.

Introduction

During spring and early summer of 1987, the first scientific core drilling through the permafrost of an active rock glacier was completed at the site Murtèl/Corvatsch (Figure 1) in the Upper Engadin, eastern Swiss Alps. The main original goals of this project consisted of (Haeberli et al., 1988):

(1) documenting the thermal conditions within the creeping ice/rock mixture and their evolution with time in view of potential effects of atmospheric warming on mountain permafrost;

(2) investigating the creep processes at depth as a function of material properties such as ice content, rock particle size, etc.; and

(3) analyzing the physico-chemical characteristics of the ice existing in the perennially frozen material and constituting an old but still undeciphered environmental archive of cold mountain areas.

These goals required long-term investments to be made for borehole measurements accompanied by a number of surface studies. After 10 years of observation, important answers can be given to some key ques-
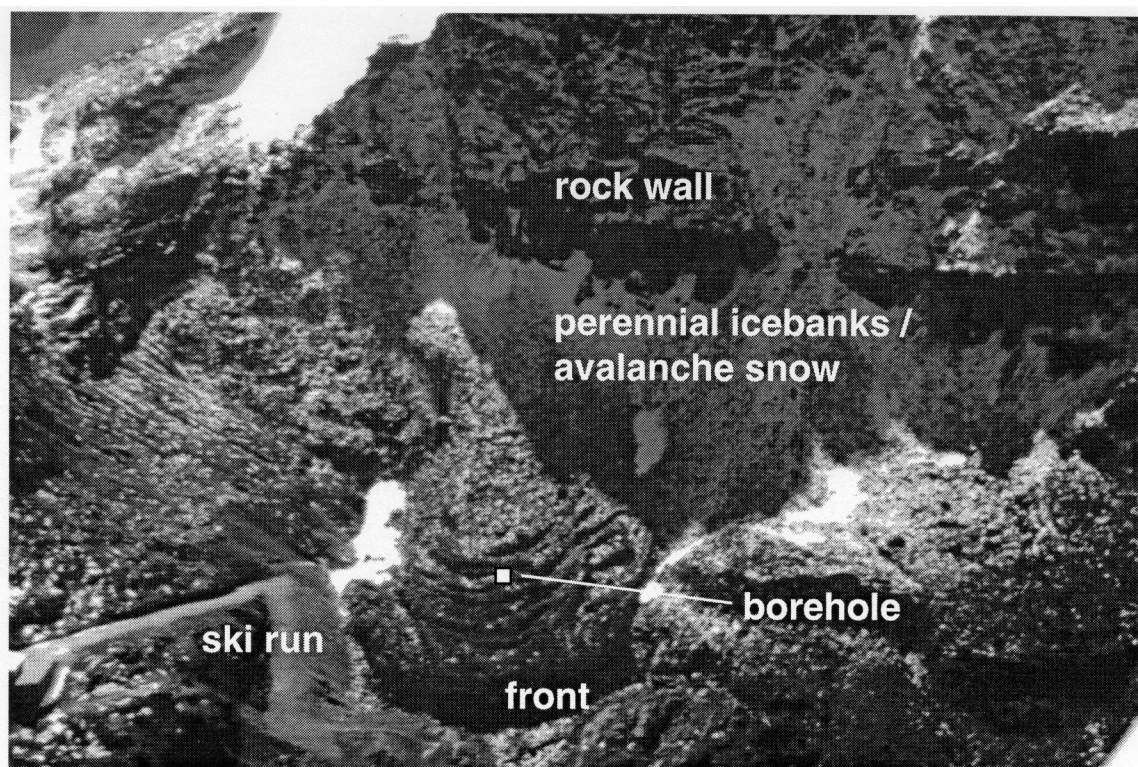
Figure 1. Oblique view (DTM) of rock glacier Murtèl/Corvatsch

tions of research on mountain permafrost and rock glaciers (cf. Barsch, 1996). The information and general understanding now available form the basis for future numerical modelling of the complex processes involved. Such numerical modelling may be the most important step to be undertaken in this research field. In order to facilitate this task, the present contribution summarizes the main results collected so far, develops a qualitative scheme of rock glacier evolution, defines some critical questions to be addressed and, finally, sketches perspectives for future research.

Principal insights obtained

Results from core analyses, borehole measurements (Figure 2) and surface investigations at Murtèl/Corvatsch have previously been presented and discussed in detail (Bernhard et al., 1998; Haeberli et al., in press; Hoelzle, 1996; Hoelzle et al., 1998; Keller and Gubler, 1993; VAW, 1990; Vonder Mühll, 1992, 1996; Vonder Mühll and Haeberli, 1990; Vonder Mühll and Holub, 1992; Vonder Mühll and Klingelé, 1994; Vonder Mühll et al., 1998; Wagner, 1992). The purpose of the following summary is to draw the main conclusions from the collected results and to integrate the new insights in order to improve the understanding of the processes/materials involved and to establish a base for future numerical modelling.

The flow field of the entire rock glacier (cf. Kääb et al., 1998)) as determined from computer-aided photogram-

metric techniques (Kääb, 1996) clearly reveals an upper zone of longitudinal extension within the debris cone where the rock glacier originates and a lower zone of longitudinal compression where the rock glacier advances over flatter terrain and forms a striking ogive-like pattern of transverse furrows and ridges. An uninterrupted continuity of slow movement exists from the rock walls at the head of the rock glacier down to its oversteepened front. This flow continuity is obviously related to the viscous-type appearance of the creeping debris body and leaves no doubt that the primary source of the rock-glacier material must be traced back to the debris cone mantling the foot of the rock walls. The continuity of subsurface layers observed in recent georadar soundings (Vonder Mühll, unpublished) confirms this view. Based on photogrammetric analyses of other rock glaciers (Hoelzle et al., 1998; Kääb et al., 1998; Kääb, in press; Kaufmann, 1996), such conditions appear to be quite generally representative.

Temperature beneath the roughly 3 meter thick active layer remains negative throughout the year. At 11.6 m depth within the Murtèl/Corvatsch borehole, mean annual ground temperature increased from -2.3°C (1987) to -1.4°C (1994) but cooled intermittently due to thin snow cover in the winters of 1994/95 and 1995/96 (Vonder Mühll et al., 1998). Permafrost in Alpine rock glaciers is relatively warm and typically tens of meters thick. At Murtèl/Corvatsch, temperature variations around 0°C are observed at depth, in a thin seasonal talik between 52 and 58 m below surface (Figure 2), but
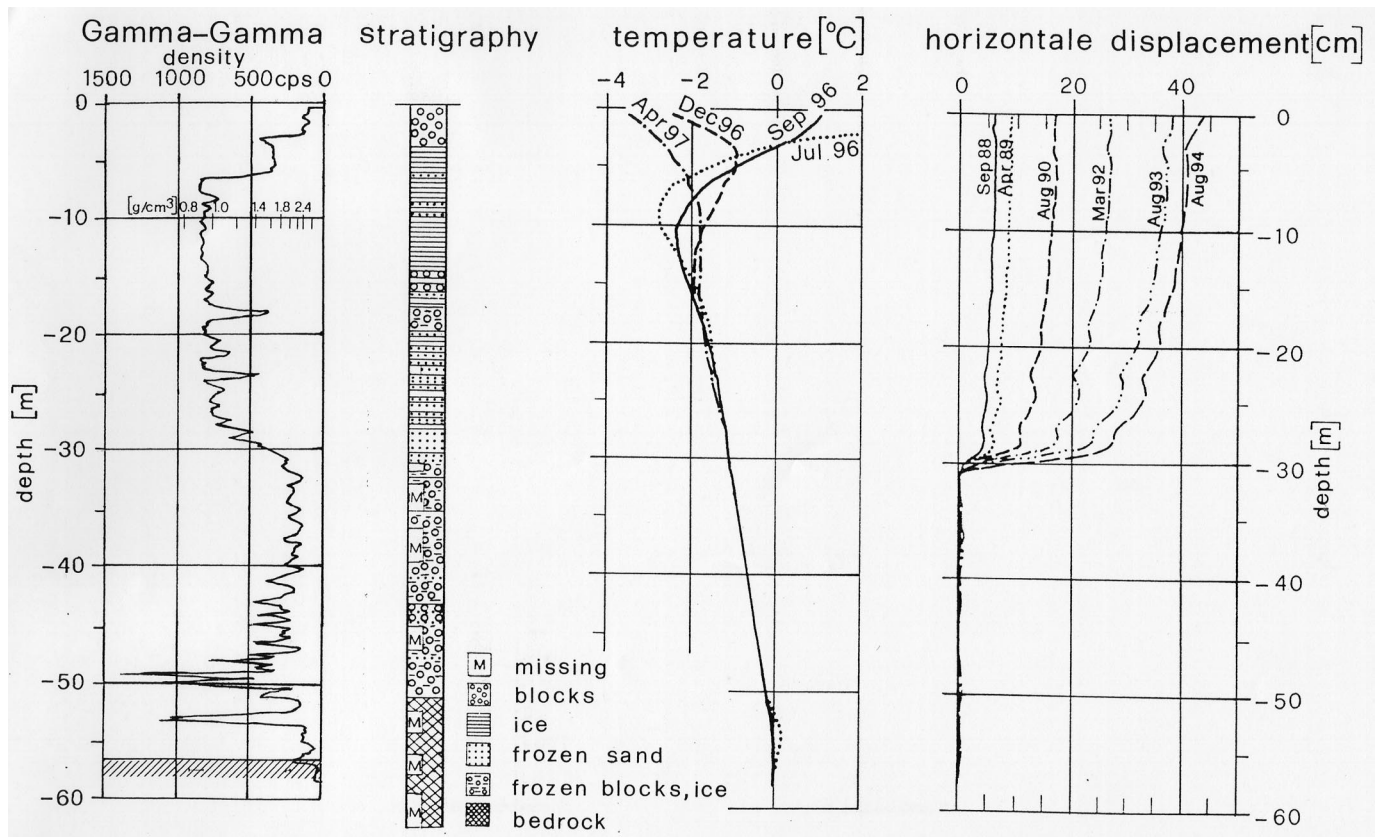
Figure 2. Principal results from core analyses and borehole measurements at the active rock glacier Murtèl-Corvatsch. Underneath the 3 m thick active layer with coarse blocks, the density log (g-g) and the stratigraphy show two main layers: (1) massive ice (90 - 100% ice content by volume) with thin layers of ice-rich sand down to 28 m and (2) coarse blocks with ice-filled pores but almost completely without fine rock particles down to bedrock at about 50 m depth. Three-quarters of the total horizontal displacement (6 cm per year at the surface) takes place within a pronounced shear horizon in the transition zone between the two layers at a depth of 28 - 30 m as revealed by the borehole deformation. The upper (strongly supersaturated) layer undergoing steady-state creep thereby overrides the non-deforming (structured) lower layer. Seasonal temperature variations are well developed within the uppermost about 20 m and mean annual permafrost temperature at the permafrost table (3 m depth) is estimated at -2.5 to -3°C.

total permafrost thickness is estimated at about 100 meters and reaches far into the underlying bedrock. Considering the thermal inertia of ice-rich permafrost (Lunardini, 1996) together with the fact that the observed borehole temperatures relate to the warmest decade within an especially warm century of the Holocene, it is reasonable to assume that permafrost conditions existed at the drill site - and probably within rock glaciers in general - since the end of the last ice age. Snow-cover effects, however, have an important effect on ground temperature and make relationships between air and permafrost temperatures highly uncertain. Moreover, ventilation and cold-air circulation within the blocky active layer probably play an important role with respect to coupling the atmosphere with the permafrost on mountain slopes and rock glacier surfaces (Bernhard et al., 1998).

Extreme supersaturation in ice characterizes the thick layer resting underneath the blocky active layer at the surface (Figure 2). In the case of the Murtèl/Corvatsch drilling, massive ice predominates. Electrical resistivity soundings on many rock glaciers indicate that such thick massive ice is the exception rather than the rule, but extreme supersaturation (50 to 90% ice by volume)

appears to generally exist in rock glaciers (Haeberli and Vonder Mühll, 1996). Such high ice contents probably result from freezing of suprapermafrost (snowmelt-) water involving primary and secondary frost heave mechanisms in the upper parts of the debris cone, where frost-susceptible fine material (sand and silt) is abundant. Burial of perennial snowbank ice may also be involved. Such massive ice of probably polygenetic origin is most likely to be preserved within the creeping mass of frozen sediments when reaching zones of longitudinal compression which induce dynamic active-layer thickening. In any case, the general ice-supersaturation of rock glaciers explains the cohesive behaviour of the debris and indicates that perennially frozen debris cones in cold mountains may often contain more ice than debris.

Deformation corresponding to a steady-state creep mode takes place within this ice-supersaturated layer of typically a few tens of meters thickness (Figure 2). A power-type flow law with a low value for the exponent seems to fit the observed borehole deformation as a rough first-order approximation only. In detail, pronounced heterogeneities within the ice/rock-mixtures cause important variability in apparent viscosity and in

Creep and related aggradation / degradation of permafrost

syngenetic debris / ice accumulation

melting at permafrost table ?

longitudinal
extension

freezing at permafrost table ?

active layer

vertical thinning

PERMAFROST

permafrost base

longitudinal compression

epigenetic basal freezing
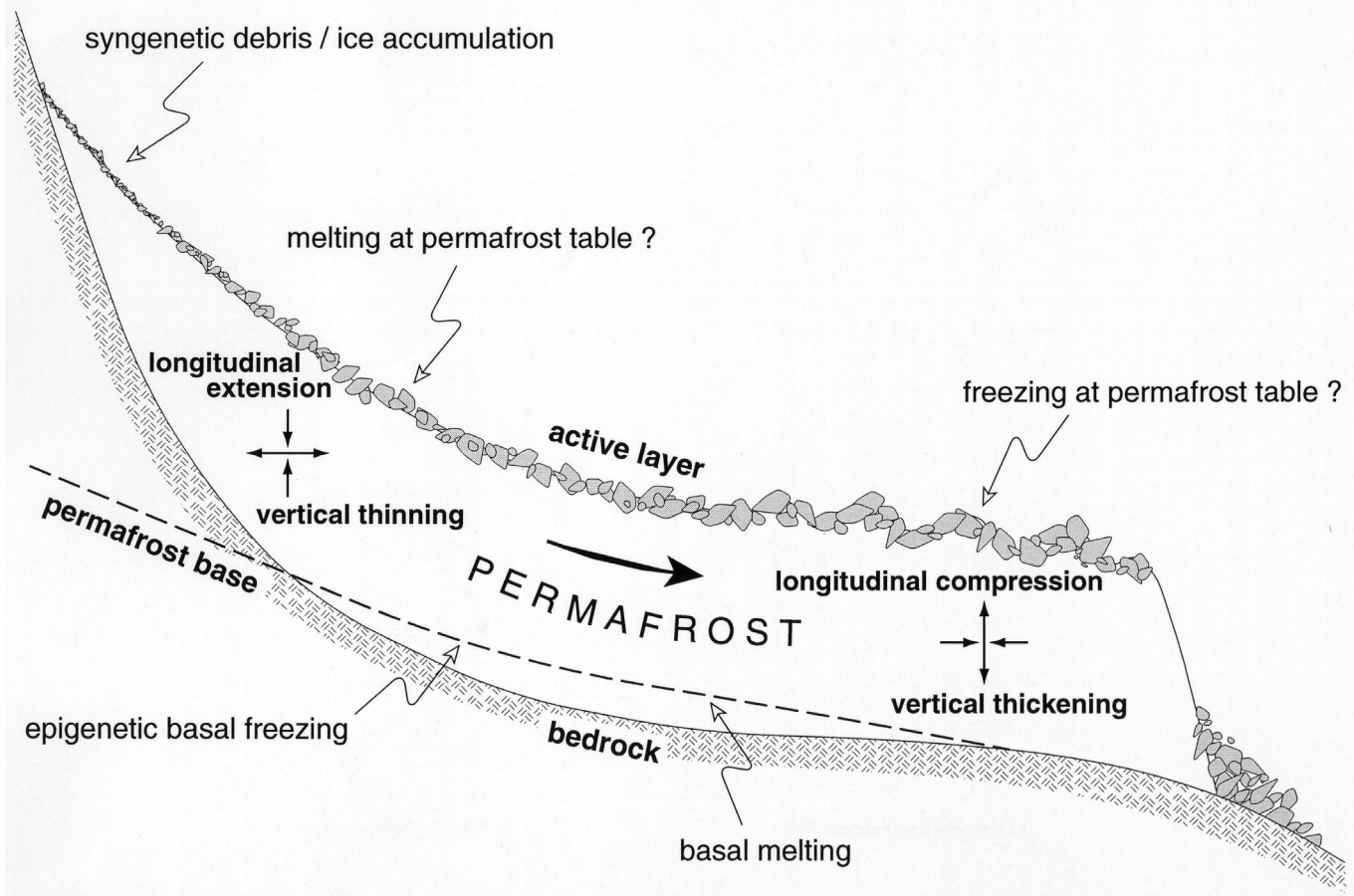
bedrock

vertical thickening

basal melting

Figure 3. Schematic representation of 2-dimensional flow and related permafrost aggradation/degradation.

the change of horizontal/vertical strain rates with depth (Wagner, 1992; Kääb et al., 1998). The most striking effect is due to the existence of a thick, stiff layer at the base of the deforming ice-supersaturated layer. This layer is only saturated with ice (impermeable to borehole water); it consists of coarse blocks similar to the ones found at the rock glacier surface, almost completely lacks fine material and does not deform - despite higher stresses and warmer temperatures at this depth - because of the damped creep mode occurring in such structured permafrost. The existence of a stiff basal layer had been predicted earlier (Haeberli, 1985), based on the assumption that the blocks falling from the top of the rock glacier at its front must subsequently be overridden in order not to pile up and completely cover the rock glacier front. The main lesson to be learned from these findings is that permafrost creep on mountain slopes is complex and may not always involve the whole thickness of perennially frozen debris.

The documented flow velocities, the relatively stable climatic conditions during the Holocene and the ther-

mal inertia of ice-rich permafrost indicate that rock glaciers in general develop over thousands of years. This idea could be confirmed by the first ^{14}C-dating of organic material from massive ice within the Murtèl/Corvatsch permafrost core (Haeberli et al., in press). The development of most rock glaciers probably started around the onset of the Holocene, when the area they now occupy definitely became deglaciated. Characteristic rates of long-term ice and sediment accretion on the debris cone from which the rock glacier develops as well as characteristic retreat rates of the cliff which provides the debris to the debris cone and rock glacier are millimeters per year. The bulk of the ice/rock-mixture within creeping rock-glacier permafrost must be several thousand years old but a different age structure must be expected in the creeping supersaturated layer and in the stiff blocky layer at the base, respectively. This will be discussed further in the following section.
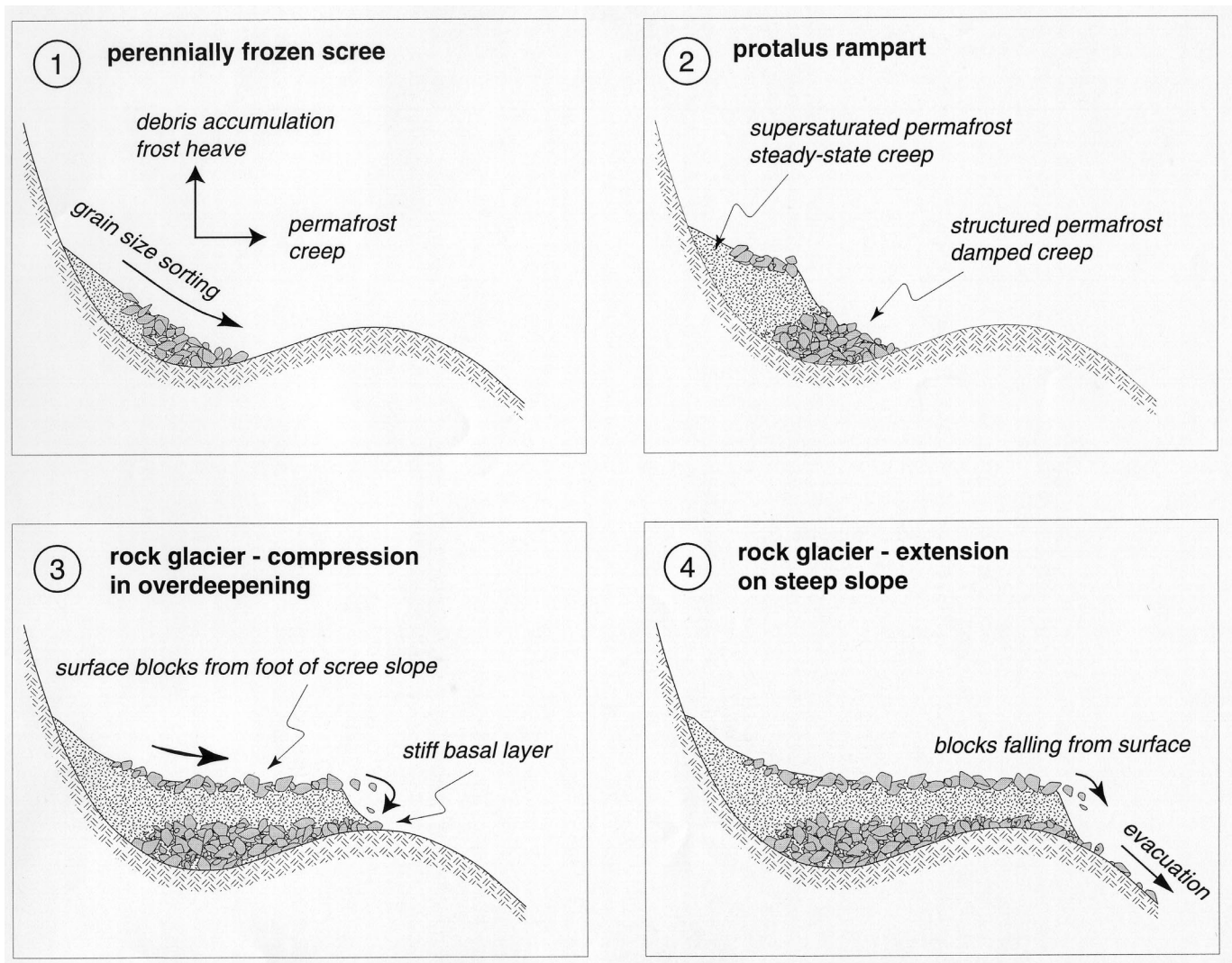
Figure 4. Scheme of the evolution of the layered structure within rock glaciers.

Towards modelling of rock glacier evolution

First attempts to numerically model rock glacier flow and evolution (Olyphant, 1983; 1988) have treated the creeping ice/rock-mixture as homogeneous and isothermal. More differentiated process understanding and numerical modelling of permafrost creep and rock glacier formation on mountain slopes, requires three main aspects to be considered in combination:

(1) ground thermal conditions in a deforming sediment body governing freezing/thawing processes and being determined by related energy exchange processes at the boundaries involved;

(2) the evolution of the characteristic multilayer structure within the advancing rock glacier by sorting and redistribution of rock particles with different grain sizes and frost susceptibility; and

(3) the development of a specific age structure at depth as induced by redistribution, cumulative straining and thawing/freezing of material.

The coupling of climatically controlled ground thermal conditions with flow-induced thinning/thickening in areas of longitudinal extension/compression has been discussed by Haeberli and Vonder Mühll (1996) and is illustrated in Figure 3. Besides a general warming of permafrost through creep movements from colder to warmer areas due to effects of altitude, mountain shadow and snow-cover duration, there are four main zones of ice formation/disappearance. At the very roots of active rock glaciers, i.e., on debris cones or moraines, syngenetic freezing is likely to take place at the permafrost table which follows the rising surface of the aggrading sediment body; burial of perennial snowbanks is also most likely to take place in this uppermost zone. Further down, in zones of longitudinal extension, dynamic thinning of the active layer tends to induce melting of ice at the permafrost table but freezing may start at the base of the dynamically thinning permafrost. Basal melting is likely to occur in still lower zones of longitudinal compression and corresponding dynamic permafrost thickening. The "ridge-and-furrow-topography" induced by such compressive flow of

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the frozen material creates specific microclimatic conditions. Special conditions and sharp changes in surface boundary conditions must also be expected within the front area, where thick snow deposits are accumulated by wind, and fine material replaces the thermally insulating coarse blocks at the surface.

The evolution of the characteristic layered structure of active rock glaciers (Figure 4) as visible on their fronts is easily explained. The most important initial condition is the vertical sorting of grain sizes on debris cones: large, non-frost-susceptible blocks accumulate at the bottom and freeze with low ice contents (saturated or structured permafrost with damped creep behaviour), whereas frost-susceptible fine materials concentrated in the upper parts tend to expand volumetrically during freezing and supersaturation by ice. Frost heave and creep of the ice-supersaturated finer material now starts to form a bulge (protalus rampart), overriding the coarse and stable blocks at the bottom of the debris cone. However, coarse blocks continue to accumulate at the base of the debris cone, now on the bulge or protalus rampart formed in this way, and are being carried along on the back of the further advancing rock glacier until reaching its front. There, they fall down the steep scree of exposed fine material because the surface speed is higher than basal and average front advance, and are subsequently overriden by the creeping supersaturated fine material. Subpermafrost freezing now takes place, thus forming a basal, ice-saturated, stiff blocky layer. Where permafrost is too warm/thin to allow for subpermafrost freezing, the blocky layer remains unfrozen and equally stiff. Basal blocky layers can be assumed to remain thin or even absent on steep slopes where a rock glacier advances quickly and blocks cannot accumulate at the foot of its front.

The development of a specific age structure at depth is now a straightforward consequence of such processes. In the ice-supersaturated creeping layer, the age increases with increasing depth and flow distance. The oldest parts of the ice/debris mixture can be expected at the base of this deforming layer and towards the front of the rock glacier. In the stiff basal layer, on the other hand, equally old parts must exist near the rock headwall, and ages become increasingly younger towards the front. A strong age inversion is likely to occur in vertical profiles (boreholes) at the interface between the creeping and the stiff basal layer.

Conclusions, open questions and research perpectives

The viscous-type flow and cumulative deformation of cohesionless debris typical of rock glacier appearance can only take place under frozen-ground conditions. Active, inactive and relic rock glaciers, thus, are excel-

lent indicators of present and past permafrost occurrence, constitute natural archives of holocene frost weathering and rock fall activity, and relate to especially climate-sensitive slope stability aspects. Some basic principles of permafrost creep and rock glacier formation on mountain slopes are, thus, clear now. In detail, however, a number of difficult problems remain to be solved. In the zone where most rock glaciers originate, the various processes involved with ground ice formation in scree slopes or sometimes moraines are still not satisfactorily understood. Along rock glacier surfaces, the energy balance of blocky material with important effects from ventilation and direct thermal coupling - even through thick winter snow - of the permafrost with the atmosphere must be investigated. An especially complex situation exists at the front of rock glaciers with changing surface and thermal conditions being coupled with permafrost creep, redistribution of debris material and overthrusting effects. All these questions concern constant climatic conditions. Anticipated atmospheric warming, however, could strongly influence ground thermal conditions, thereby introducing changes in material properties with phase changes in the ice component.

In order to quantitatively integrate the most important processes and materials in a model of rock glacier evolution, a number of partial models must be coupled. First, a frost-weathering/debris-production/rock-fall model should be able to simulate debris-cone formation with an appropriate sorting of grain sizes. Then, a freezing/ice-formation model has to provide saturation/supersaturation in blocks/fine material with corresponding volume expansion and frost heave. Next, damped and steady-state creep modes have to be modelled in saturated/supersaturated materials, inducing cumulative deformation of the supersaturated layers and redistribution of surface blocks to fall over and to be overriden by the advancing front. Now, mechanical straining within, heat flow through and freezing/thawing at the upper and lower boundaries of the creeping permafrost must be considered in a thermo-mechanically coupled model reflecting the pronounced anisotropy effects related to variable ice contents and rock-particle/ice-crystal sizes. At a later stage, 3-D effects and intrinsic non-stationarity resulting from complex landform evolution (for instance, younger rock glacier generations overriding older ones) affecting - as a function of time - slope, flux rates, permeability etc., can also be considered.

Investigation of such aspects necessitates full parameterization of models based on systematically collected field evidence. Special problems concern the geophysical detection of the permafrost base and the base of the deforming layer, but also the complex processes at rock-glacier fronts. First attempts to quantify energy and

mass fluxes through the blocky active layer are now being undertaken at the drill site. Anticipated atmospheric warming could lead to thawing of previously frozen fine material with excess ice causing thaw consolidation and slope failure. In addition to the above-mentioned phenomena relating to more-or-less stable climate conditions, a number of corresponding processes, thresholds and trigger mechanisms must therefore be considered with respect to effects from potentially rapid climate change. Such problems are presently being addressed by the PACE project of the European Union.

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