MULTIDISCIPLINARY INVESTIGATIONS ON THREE ROCK GLACIERS IN THE SWISS ALPS: LEGACIES AND FUTURE PERSPECTIVES

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ABSTRACT. This paper recognizes the contribution of Professor Wilfried Haeberli for his inspiration and leadership in the field of permafrost science and his generous encouragement, both direct and indirect, to the ETH Researchers who have, through him, endeavoured to contribute to this fascinating research area. The multidisciplinary investigations described in this paper have focused on three rock glaciers, Muragl, Murtèl-Corvatsch and Furggwanghorn, all of which have been subject to a varying degree of prior study, and which are continuing to attract new generations of researchers to understand and explain the processes and predict future behaviour. This paper marks a stage at which it is possible to summarize some advances in the state of the art and associated innovations that can be attributed to early motivation by Wilfried Haeberli and offers a tribute as well as gratitude for his ongoing feedback and advice. Some thoughts on the development of thermokarst due to water ponding and flow, and a conceptual model of geotechnical mechanisms that aim to explain some aspects of rock glacier kinematics, are also introduced.

Key words: alpine permafrost, rock glacier, degradation, characterization, monitoring, modelling

Introduction

Wilfried Haeberli instigated modern Swiss research into mountain permafrost by combining field observations, meteorological inputs and energy balances, geomorphological investigations, permafrost mapping and assessment of likelihood of occurrence (Haeberli 1975, 1985). Subsequently he elucidated many aspects of seasonal alpine response and rock glacier dynamics (e.g. Haeberli *et al*. 1993a). Measurement campaigns, results and interpretations (e.g. Vonder Mühll and Haeberli 1990; Haeberli and Hoelzle 1995; Hoelzle *et al*. 2002) were described and papers predicting the impact of warming on climate change were published. Accelerated rock glacier creep movements and shear along 'weaker' layers were cited as an indicator of the thermal state of rock glaciers (Haeberli *et al*. 2006), which would be exacerbated in the future by responding to global warming within years to decades (Haeberli *et al*. 1993b).

In the extreme state, slope instabilities and catastrophic slides, such as debris flows, would be triggered by reduction in strength as the ice phase warmed (Haeberli *et al*. 1990, 1993a, 1993b, 1997; Haeberli 1992; Zimmermann and Haeberli 1992; Haeberli and Hohmann 2008) and rupture occurred along a shear surface. In consequence, potential instabilities of alpine permafrost in Switzerland have been identified as being an issue of national importance (Haeberli *et al*. 1997; Haeberli 1999).

The permafrost community has demonstrated sound understanding of the phenomenon of creep, which is often modelled by three regions, primary, secondary and tertiary (Andersland and Anderson 1978). However, existing mathematical models are unsatisfactory in predicting the transition to tertiary creep and quantifying whether and when rupture will develop in an element of frozen ground, which can then impinge on large-scale stability. The influence of general stress on the changeovers between these regions has been clearly summarized by Phukan (1985) and is both less well quantified and extremely important in the context of whether an

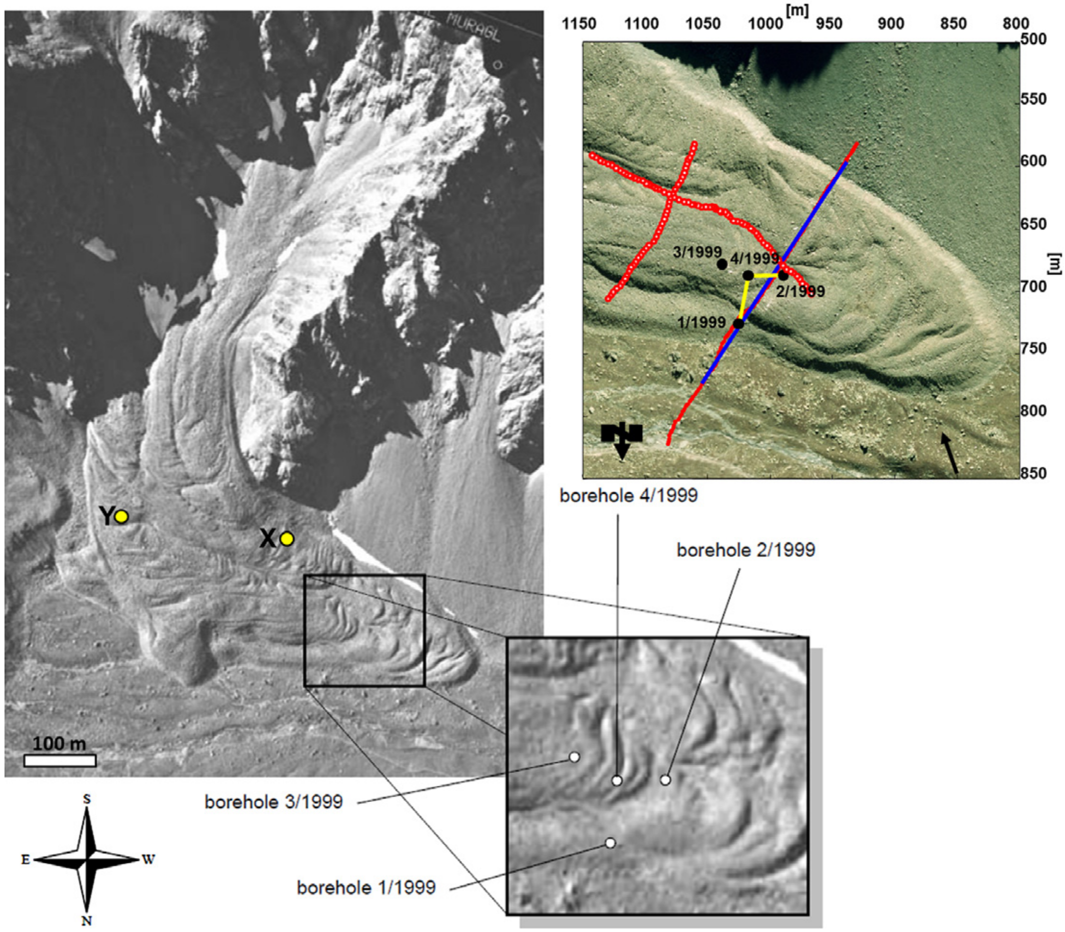

Fig. 1. Aerial photograph of the Muragl rock glacier (taken by the Federal Directorate of Cadastral Surveying in 1994). The yellow dots denoted by X and Y refer to Fig. 15. The boreholes 1/1999 to 4/1999 are marked by white dots in the enlarged inset (Arenson 2002). Location of the geophysical profiles (see also Fig. 5) are indicated in red (seismics) and blue (geoelectrics) in the coloured orthophoto taken by Swisstopo in 2003.

element of ground will reach rupture. Furthermore, temperature and water play a major role in this response. In short, effective coupled thermo-hydro-mechanical nature of the modelling from creep to failure in frozen ground does not exist at present.

The European Alps have provided a natural field scale laboratory for multinational groups researching all aspects of mountain permafrost, as described in an overarching fashion through task groups led by Haeberli *et al.* (2006) and Harris *et al.* (2008), which comment on the necessity of a suitable modelling framework. In parallel, the integration of functioning monitoring systems into the establishment of the Swiss Permafrost Monitoring Network PERMOS (Delaloye and Vonder Mühll 1998; Vonder Mühll *et al.* 2008; PERMOS 2010) has been a signal achievement that has implications for people and infrastructure affected by any future permafrost degradation and associated hazards. Only a small selection of the broad and deep contributions made over the past 35 yrs can be mentioned in this brief introduction, which focuses on research conducted by the authors on three Swiss rock glaciers: Muragl, Murtèl Corvatsch and Furggwanghorn (Figs 1–3).

Stimulated by Haeberli, expertise was combined between the disciplines of geotechnics (Arenson 2002), geophysics (Musil 2002; Maurer *et al.* 2010) and glaciology (Leysinger Vieli 2003) to investigate the Muragl rock glacier in the Engadine

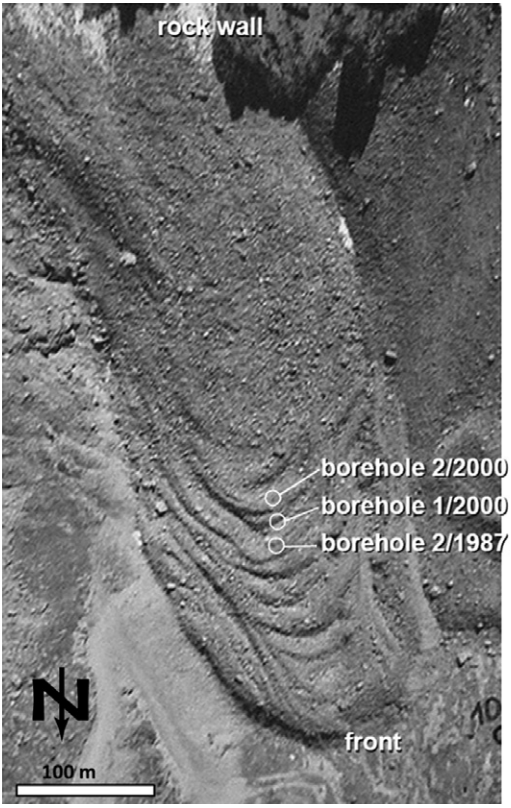

Fig. 2. Aerial photograph of the Murtèl-Corvatsch rock glacier (Arenson 2002) taken by the Federal Directorate of Cadastral Surveys in 1996, showing delineation of the original borehole 2/1987 and the new boreholes 1–2/2000.

in the Swiss Alps (Fig. 1) as the first of two ETH-funded multi-investigator projects to promote better process understanding, to lead to more effective future modelling and prediction of behaviour. Non-destructive (geophysical) and destructive (geotechnical) methods guided the *characterization* of the frozen ground. *Monitoring* of temperatures and deformations with depth led to insights into the way in which rock glaciers deform, through to development and use of *modelling*.

Field investigations were centred around boreholes drilled into the permafrost for multi-purpose use in the potentially degraded reaches at the lower elevations of the Muragl rock glacier. The drilling campaigns were later extended to the Murtèl-Corvatsch rock glacier (Fig. 2; Springman and Arenson 1998; Arenson and Springman 2000; Vonder Mühll *et al*. 2001, 2003) and, more recently, to the Furggwanghorn rock glacier (Fig. 3; Springman *et al*. 2011) in the Turtmann valley. Geophysical characterization (Musil *et al*. 2002; Maurer *et al*. 2003; Arenson *et al*. 2010), undisturbed sampling of permafrost (Arenson 2002) for advanced stress path testing on frozen soils (Arenson and Springman 2005a; Yamamoto and Springman 2010, in press), *in situ* pressuremeter testing (Arenson and Springman 2001; Arenson *et al*. 2003a), and monitoring of meteorological conditions, temperature and deformation (Arenson *et al*. 2002; Vonder Mühll *et al*. 2003) were conducted in parallel.

Innovative multidisciplinary (and especially geotechnical) aspects of, and findings from, this research have enhanced existing knowledge and will be reviewed and summarized in the subsequent sections by focusing on characterization, monitoring and modelling. Future perspectives will be identified and an appreciation of any remaining gaps will be given at the end of the paper.

Rock glacier characterization

During the characterization of a rock glacier, it is essential to establish the following:

- the internal spatial distribution of layers or zones;
- their relative components of ice and rock debris and the distribution of the grain sizes (Fig. 4), which strongly influence the creep, strength and permeability;
- the seasonal hydrology and the state of the permafrost, including the active layer depth and the permafrost base; and
- the relevant strength and stiffness parameters to represent the time-dependent response of each layer or zone.

Preliminary spatial delineation derived from surface geophysical techniques was critical in selecting borehole locations and drilling depths, based on surface refraction seismic investigations, distance between boreholes for the cross-hole experiments, consideration of geomorphology and annual surface deformation vectors. Logging borehole samples, carrying out in-hole logging and photography have been helpful where it was possible to achieve this. Deriving tomograms from various forms of cross-hole geophysics has assisted in interpreting the ground between the boreholes. Finally, stress path tests for determination of creep

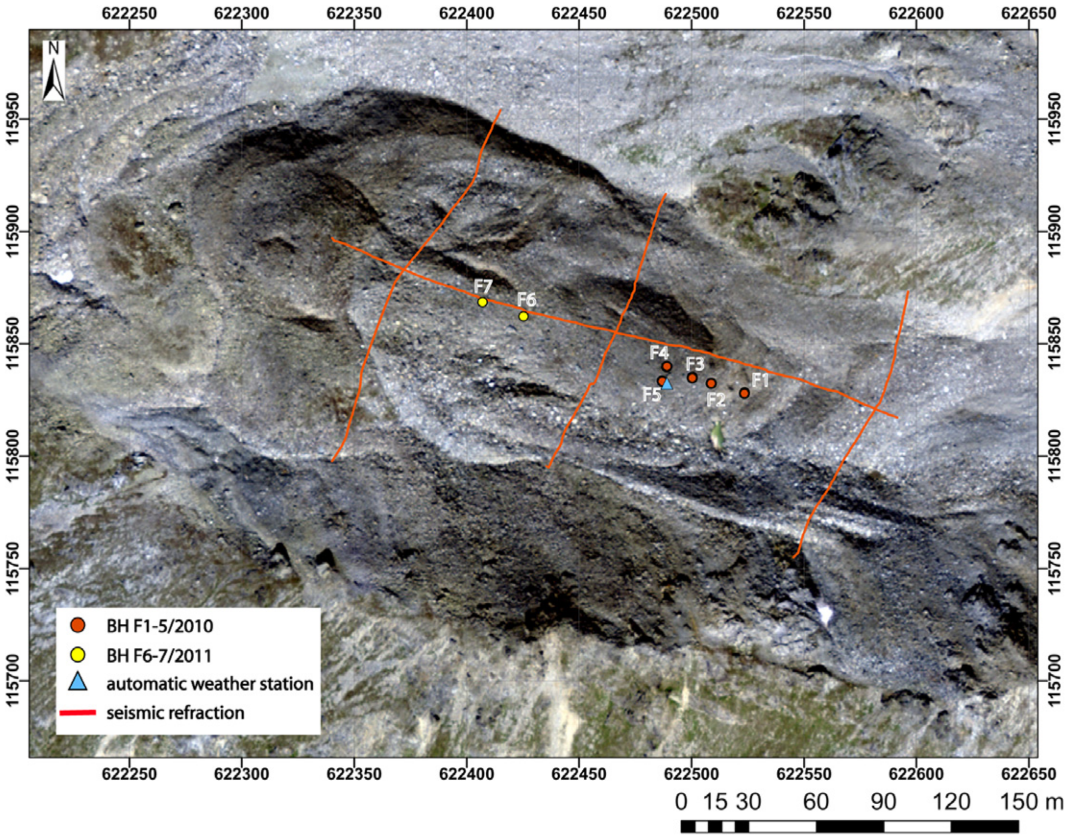

Fig. 3. Orthophoto of the Furggwanghorn rock glacier taken by Swisstopo in 2009 with the position of boreholes F1–5/2010, F6–7/2011, automatic weather station and seismic refraction sections.

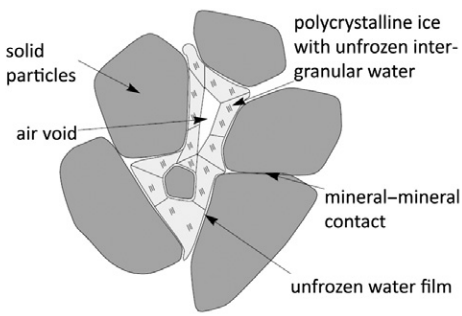

Fig. 4. Two-dimensional schematic of the structure of frozen soils (after Ting *et al.* 1983).

and strength properties for the permafrost provide detailed data about the *in situ* response of the ground around the borehole, and from a series of specimens tested under controlled laboratory conditions.

Geophysical surveying

Geophysical techniques offer powerful options for characterizing the internal structures of rock glaciers. In particular, tomographic inversion techniques proved to be extremely useful, since rock glaciers can be quite heterogeneous and may include critical small-scale spatial variations. As discussed by Hauck *et al.* (2011), the essential components of rock glaciers are ice, water, air and the solid particles of parent rock (Fig. 4). Consequently, geophysical methods that can distinguish between the physical properties of these four ingredients should be employed. Unfortunately, a single method is generally not capable of solving the problem. Therefore, it is necessary to combine the results from different geophysical data types to obtain meaningful results. Experience from the past has shown that a combination of seismic, geoelectric and *ground penetrating radar* (*GPR*) techniques often produces satisfactory results. An overview of all the advantages and limitations of the individual techniques (in the context of rock glacier investigations) can be found in Maurer and Hauck (2007) and Hauck and Kneisel (2008). In brief, seismic methods are sensitive to changes of the elastic properties, and are thus well suited for delineating bedrock topography underneath rock glaciers. Geoelectrical techniques lead to determination of electrical conductivity distributions, which can be useful for identifying ice-rich regions. Finally, GPR methods are primarily sensitive to variations of dielectric permitivities. The high spatial resolution of GPR allows small-scale features within a rock glacier to be imaged.

The interplay of the different geophysical methods can be well demonstrated with measurements performed on the Muragl rock glacier (Fig. 1). Surface-based seismic and geoelectrical measurements have been combined with cross-hole GPR results. Fig. 5a, b show the geoelectric and seismic tomograms obtained along a profile acquired across the Muragl rock glacier (see Fig. 1). The surficial active layer is distinguished by moderately high resistivities and low velocities (features DC1 and S1 in Fig. 5a, b). Bedrock topography could be identified only with seismic tomography (interface S3 in Fig. 5b). Additionally, the geoelectric and seismic tomograms reveal interesting internal structures. The resistive region DC2 indicates the ice-rich part of the rock glacier. This interpretation is also supported by seismic velocities of about 3500 m/s in the same region. The highly resistive body DC3 (Fig. 5a) represents a zone with a particularly high ice content. Finally, the conspicuous low-velocity feature S2 (Fig. 5b) identifies potentially degraded permafrost, where the interstitial ice has thawed and left large air voids.

The surface-based geoelectric and seismic measurements were complemented by cross-hole radar surveys performed between boreholes 1/1999, 2/1999 and 4/1999 (Fig. 1). The resulting tomograms of the GPR velocities are shown in Fig. 5c. It is instructive to compare the high and low radar velocity zones (R1–R4; Fig. 5c) with features observed in the borehole logs and in the surface-based resistivity and seismic velocity tomograms (Fig. 5a, b). The high GPR velocities in the R1 and R2 zones have different explanations: R1 projects to the ice-rich sands in 2/1999 and 4/1999 that also explain the very high resistivities in the region DC2, whereas R2 intersects ice-free boulders in 2/1999 and ice-free sand in 4/1999. The high velocities in R1 are a consequence of the presence of ice, whereas the high velocities in R2 are likely to be caused by a mixture of rock and large air voids (see Musil *et al*. 2006 for more details). Significant shear displacements measured from an inclinometer in 4/1999 (white cross in Fig. 5c; Arenson *et al*. 2002) are concentrated near the base of R1. Interpretation of the high GPR velocity zone R3 is ambiguous, because it could represent a zone with pores filled with ice (borehole 4/1999) or air (1/1999). Finally, the low radar velocities of the R4 zone may be associated with one or more water-bearing layers intersected in all three boreholes (Fig. 5c).

Boreholes

The boreholes on the Muragl rock glacier were located in the zone in which ground ice was expected, based on the surface geophysical surveys (see Musil *et al*. 2002 for the longitudinal sections through 3/1999 and 4/1999) and have served several multidisciplinary purposes, in addition to providing the lineal ground truth for the characterization. The extraction of undisturbed frozen specimens into a 75 mm diameter triple tube sampler, by cooling the crown (bit) adiabatically during drilling, was achieved on both the Muragl and Murtèl-Corvatsch rock glaciers (Arenson 2002; Vonder Mühll *et al*. 2003). This was the first time mechanical and thermal disturbance was specifically minimized while drilling in mountain permafrost and this remains the sole method of obtaining representative small-scale samples that replicate the microstructure and field conditions as closely as possible in the laboratory. However, there were some significant challenges to sampling as the strata changes between hard large rocks and ice or frozen soil matrix, requiring repeated switching between drilling bits (Arenson 2002). Further, the frozen state of the samples had to be maintained on site after recovery, as well as during the transport from the site to the laboratory. Some of the boreholes were subsequently used for *in situ* testing using a high pressure dilatometer, geophysical cross-hole analyses and for monitoring of temperature and deformation with depth. Unfortunately, it was not possible to drill the boreholes at Furggwanghorn to permit undisturbed samples to be extracted so that both percussion and rotary techniques were used to produce boreholes with 139 mm diameter in which to place the monitoring devices and instruments.

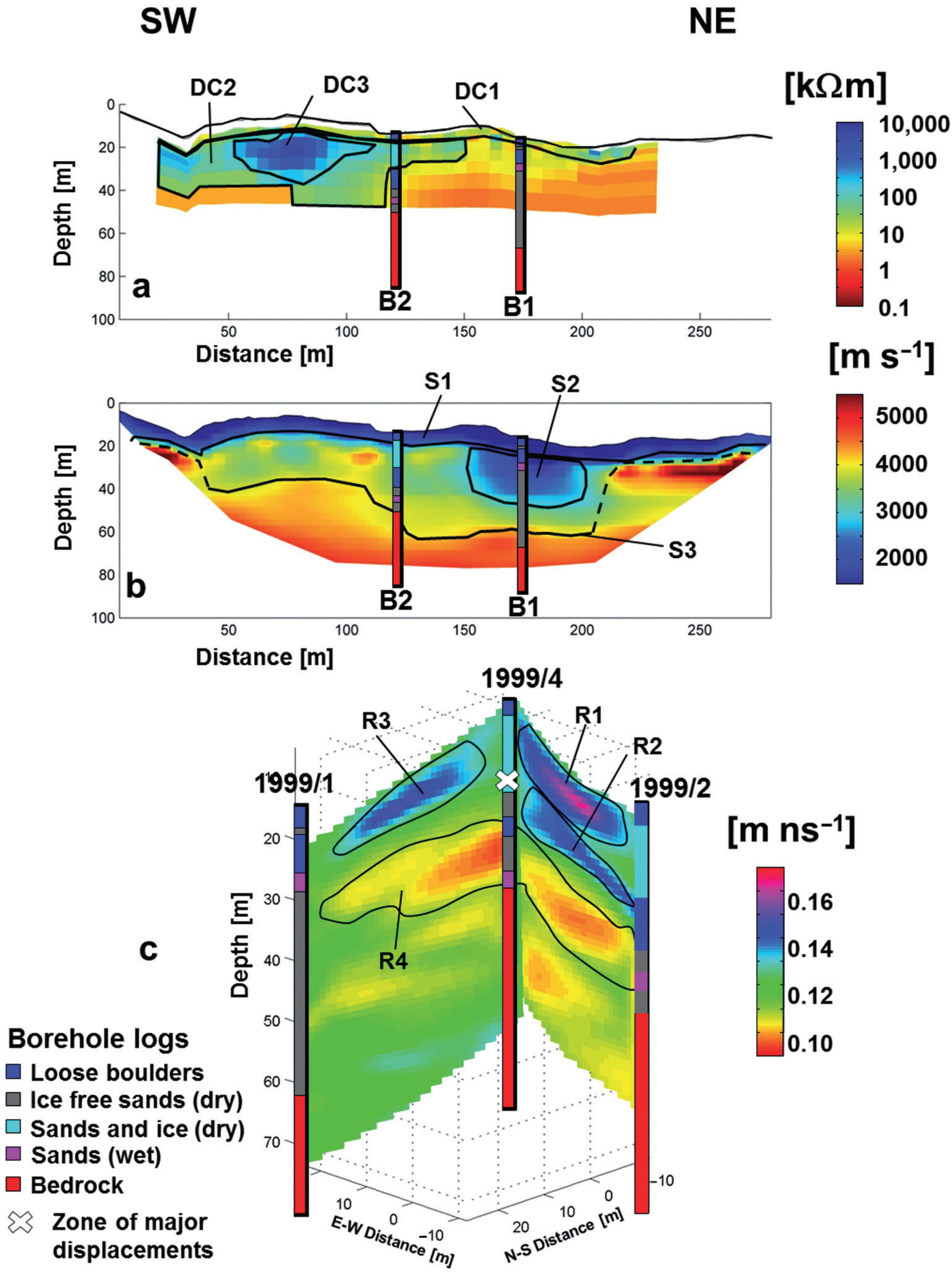

Fig. 5. Cross sections derived from (a) geoelectric, (b) seismic and (c) cross-hole radar data acquired on the Muragl rock glacier. Fig. 1 shows survey locations. See text for the features of DC 1–3, S 1–3, R 1–3.

Ground models

Ground models are developed based on information obtained at different scales. A whole rock glacier occupies several million cubic metres and may be interrogated through non-destructive surface geophysical investigations in various forms. A zone of intense characterization is achieved around the boreholes in which cross-hole studies increase the effectiveness of the model, for example to about 20 000 m^3 at Muragl. These will be used to verify the large-scale ground model of the complete rock glacier as well.

At much smaller scales, it is possible to produce a detailed record of the properties and behaviour of an annulus around the borehole, including density and the stress–strain response with time under *in situ* thermal conditions through the in-borehole studies (*c.* 4000 cm^3). Finally, specimens used in laboratory stress path tests have a volume of 650 cm^3 and can be tested to produce the relevant stress–strain parameters and then examined afterwards to determine the precise classification.

Scale effects include:

- the influence of large blocks of the order of several cubic metres in volume, which either cannot be included or give comparable response in the small-scale tests, as they would in reality at full scale; and
- the inclusion of gravel sized particles within a 74 mm diameter triaxial sample, which would strengthen the matrix.

Micromechanical sketches show the granular nature of the matrix of solid particles surrounded by unfrozen water films, ice granules and air bubbles (Fig. 4). It becomes clear that it will not be possible to develop uniform pressure in any interstitial water in any frozen specimen under load, which means that the only volume change occurring under load will be due to volume change in the air phase.

Identifying the spatial location of, and discerning a frozen sandy, relatively impermeable matrix from massive ice and a coarse highly permeable coarse granular matrix is the purpose of the ground model. Haeberli *et al*. (1998) showed that the frozen sandy layer hosted the shear zone in the original 2/1987 in Murtèl-Corvatsch with areas of more massive ice above this zone. A highly permeable coarse granular matrix was located at about 15–20 m depth in the Muragl rock glacier, which enabled under-drainage to occur from degrading permafrost (lateral talik). This was an irreversible process under the ongoing warming regime, which cannot be compensated for by gravitation effects as in the active layer, when the permafrost provides an impermeable base to prevent surface runoff from penetrating into the frozen ground. The key impact on the degrading permafrost is the combination between the matrix, ice content, permeability and the location of these layers within the rock glacier. Convective heat transfer in the voids under the ice in the well drained medium may have a significant influence on future degradation.

The stratigraphy of the Muragl rock glacier (Fig. 6a) shows the edge of the rock glacier with 1/1999 located outside the active part of the rock glacier. No permafrost was recorded in this borehole, but penetration of cold air during the winter due to natural convection indicates coarse sands and gravels with a high permeability. The frozen layer in the active part (2–4/1999) is approximately 15 m thick overlaying a very coarse gravelly and blocky layer before bedrock is reached at a depth of about 30 m. This blocky layer is highly permeable and it is likely that it is connected to the atmosphere. Seasonal temperature variations have been recorded below the permafrost base. It is also likely that the material found in this layer was originally transported on top of the rock glacier, deposited at the front and later covered by the advancing rock glacier (Haeberli *et al*. 1998). Although no such layer was clearly identified and described at the Murtèl-Corvatsch rock glacier (Fig. 6b), it is most probable that the bedrock reported in 2/1987 was not actually reached, given that bedrock was not found in boreholes 1–2/2000 that were located at each 15 m spacing upslope from one another (Fig. 2). The permafrost base seems to correspond with the presumed talik. Vonder Mühll *et al*. (1998) report on the possible thermal disturbance likely to have been caused by water flowing on top of the bedrock and forcing the permafrost base to degrade at a rate higher than a typical thermal gradient would predict. Without this heat source, the natural permafrost base would probably be slightly deeper. In addition to a greater permafrost thickness, the volumetric ice content (volume of ice/total volume w_i) of rock glacier Murtèl-Corvatsch is larger than that at Muragl, where ice-rich and massive ice zones were encountered closer to the depth of the shear zone.

Only preliminary characterization has been possible for the Furggwanghorn rock glacier: 5–7 m of coarse grained material overlies 8–13 m of fine

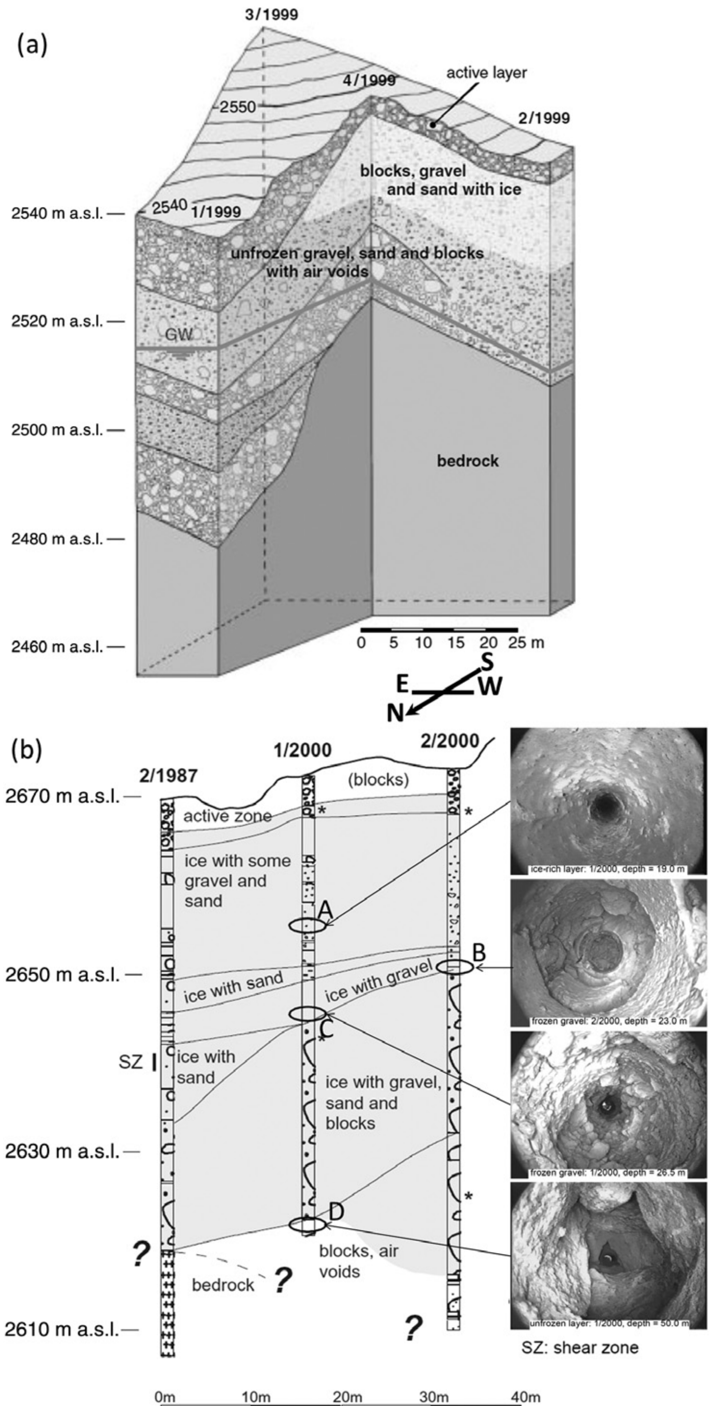

Fig. 6. (a) Stratigraphy of the Muragl rock glacier through boreholes 1–4/1999, as shown in Fig. 1. (b) Stratigraphy of the Murtèl-Corvatsch rock glacier through boreholes 2/1987 and 1–2/2000, as shown in Fig. 2. Water leakage into the borehole (*) was observed during drilling (Arenson 2002).

Table 1. Summary of data for three Swiss rock glaciers.

Test field	Muragl	Murtèl-Corvatsch	Furggwanghorn
Canton	Graubünden	Graubünden	Valais
Aspect	W/SW	NW	NW
Slope (°)	15	10	15–20
Elevation (m a.s.l.)	2700–2480	2800–2630	2900–2760
Drilling dates	1999	2000	2010–2011
Geology	Underlying rocks and rock wall are characterized by strongly foliated, layered paragneisses with minerals: plagioclase, quartz, zircon and apatite. Biotite gneisses are typically 1–5 cm thick biotite-rich layers and prone to weathering, whereas 3–10 cm plagioclase and quartz-rich layers are mostly weathering resistant.	Rock wall consists of granodiorite of the Corvatsch nappe and the Chastelets unit of chalky marbles (mica, chlorite, albite and quartz), and carbonatic mica-schists (source of fine-grained material), both of which supply the rock glacier.	Rock glacier partially fills a cirque below a head rock wall with flanks predominantly comprising biotite- muscovite bearing gneiss with chlorite, amphibolite and chlorite-rich green schist facies, which supply the rock glacier.
Boreholes and elevation	1/1999[P/RC] (2536.1 m a.s.l.), 2/1999[P/RC] (2538.5 m a.s.l.), 3/1999[P/RC] (2558.2 m a.s.l.), 4/1999[P/RC] (2549 m a.s.l.)	1/2000[P/RC] (2672.9 m a.s.l.), 2/2000[P/RC] (2672.3 m a.s.l.)	F1/2010[P] (2859.4 m a.s.l.), F2/2010[P] (2855.8 m a.s.l.), F3/2010[P] (2849.9 m a.s.l.), F4/2010[P] (2850.9 m a.s.l.), F5/2010[P] (2851.0 m a.s.l.), F6/2011[P] (2827.6 m a.s.l.), F7/2011[R] (2822.6 m a.s.l.)
Active layer (m)	2–6	BH2/1987 3.5[a] BH2/2000 2.5[a]	1.5–5[b]
Depth of base of permafrost	1/1999: no permafrost, 2/1999: 18 m, 3/1999: 20 m, 4/1999: 18 m	2/2000: 52 m	F1/2010: 22 m, F2/2010: 25 m, F3/2010: >25 m, F4/2010: >25 m
Instrumentation	Thermistor string 25 m (1, 2, 3, 4/1999), snow depth measurement, air temperature, inclinometer (3, 4/1999), SINCO settlement USBR-probe	Thermistor string, 62 m thermistors (2/2000), TDR deformation monitoring (1, 2/2000), HP dilatometer tests (1/2000), University of Zurich/PERMOS: meteorological data	Thermistor string, 30 m (F1-4, 6, 7/2010), surface thermistors (F1-4/2010), 1 × 24 m (F5/2010) and 2 × 28 m (F6-7/2011) inclinometers, air temperature, precipitation, humidity, wind direction/speed, snow depth, radiation

[P] Percussion, [R] Rotary, [RC] Rotary cooled.
[a] Arenson *et al*. (2010).
[b] Only 1 yr of data.

sand, with bedrock located below in F1–3/2010 (Table 1). A hole of over 1 m in size was identified in F3/2010, which was located in a depression at the base of the coarse grained layer with several water inflows recorded below this. The permafrost was determined to occur beneath the active layer below 3 m, entirely in the coarse grained material in F4/2010 with fine sand at 18 m depth.

In situ testing: high-pressure dilatometer

High-pressure dilatometer (*HPD*) tests were carried out in borehole 1/2000 at the Murtèl-Corvatsch rock glacier, which was pre-drilled by the cooled rotary bit, with the 95 mm diameter cylindrical dilatometer. The 575 mm long rubber membrane can be expanded against the side of the borehole while pressure and deformation of the annulus around the borehole were measured in a constant strain rate (*CSR*) test. Alternatively, a constant pressure can be maintained and radial deformation measured as a multi-stage constant *constant stress creep* (*CSC*) test.

A combination of two CSR and five multi-stage CSC stress paths, carried out at various depths between 15 and 25 m, exhibited all three stages of

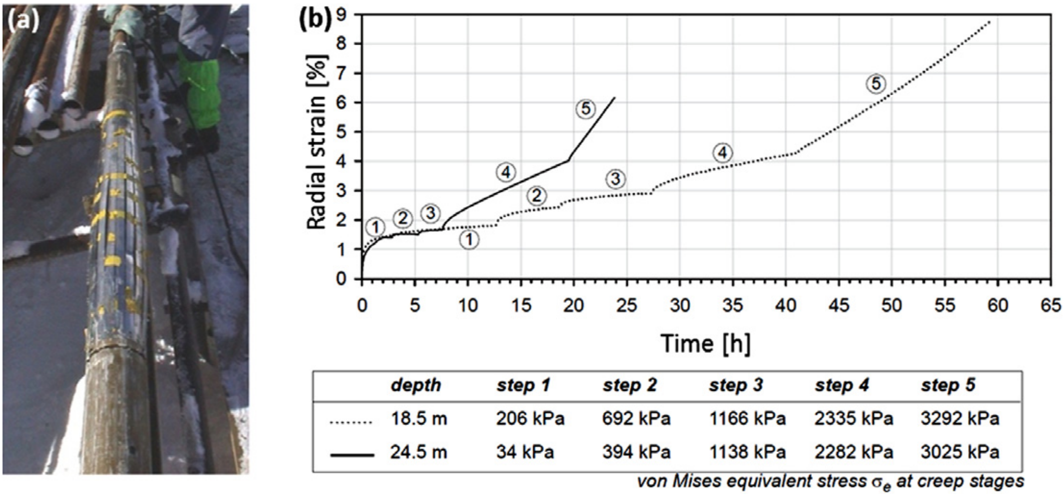

Fig. 7. (a) High-pressure dilatometer. (b) Test results at 18.5 and 24.5 m depth in borehole 1/2000, Murtèl-Corvatsch rock glacier (Arenson 2002).

creep (Fig. 7) and confirmed that primary and secondary creep were clearly identified at all stages with faster strain rates measured for each increase in radial stress (von Mises equivalent; Arenson 2002). Tertiary creep developed *in situ* under a high deviatoric stress over vertical stress equivalent to a depth of about 150 m (3000 kPa) with comparable stress–strain response noted in dilatometer and triaxial stress path tests (Arenson *et al*. 2003a).

A major challenge in carrying out *in situ* testing is attributable to the thermal disturbances introduced through the drilling. Often it takes months for any thermal disturbance to abate, independent of the drilling technique used. In addition, the thermal disturbance is the largest in the annulus directly around the borehole and will reduce with increasing distance from the borehole wall. Therefore, the temperature in the frozen ground sample tested *in situ* is not constant at the same depth, as would be expected in thermally undisturbed ground, and the strength response may not be completely representative for real conditions. However, since thermal disturbances occur throughout the whole borehole, cross comparisons and information on trends in changes with depth are still very valuable parameters for the characterization of the frozen material.

The HPD (Fig. 7) was also used in boreholes F6–7/2011 at Furggwanghorn, with three multistage CSC and two CSR tests conducted between 5 and 30 m depth in F6/2011 and two further tests at 2.5 m and 16.5 m (CSC) in F7/2011, of which the upper one ended prematurely through severe fracture development. The data are even more extensive than for those conducted at Murtèl, and will provide information about *in situ* lateral stresses, time, stress- and strain-dependent stiffness and strength in the ground in the future.

Laboratory stress path testing equipment

Triaxial testing apparatuses (Fig. 8) were designed and constructed inhouse to perform fully automated stress and strain controlled tests on laboratory specimens at specific stress levels and along stress paths selected to replicate the stresses in the ground. These were placed in a temperature-controlled cold chamber for testing (to ±1.0°C), with a range of ±0.1°C achieved in the specimen, as described by Arenson (2002). Subsequent developments upgraded the triaxial apparatuses to achieve even finer control of specimen temperature (to ±0.03°C). Volume change determination of specimens was included with devices to measure the radial deformation from lasers mounted on a travelling carriage to move vertically along the specimen length inside the triaxial cell and targeted towards the specimen surface (Fig. 8b; Messerklinger and Springman 2007).

Acoustic waves emitted by shearing and bond breakage (Fish and Sayles 1981) indicate impending rupture during CSR tests. Yamamoto and Springman (in press) report the insertion of acoustic sensors in the end platens and the corresponding

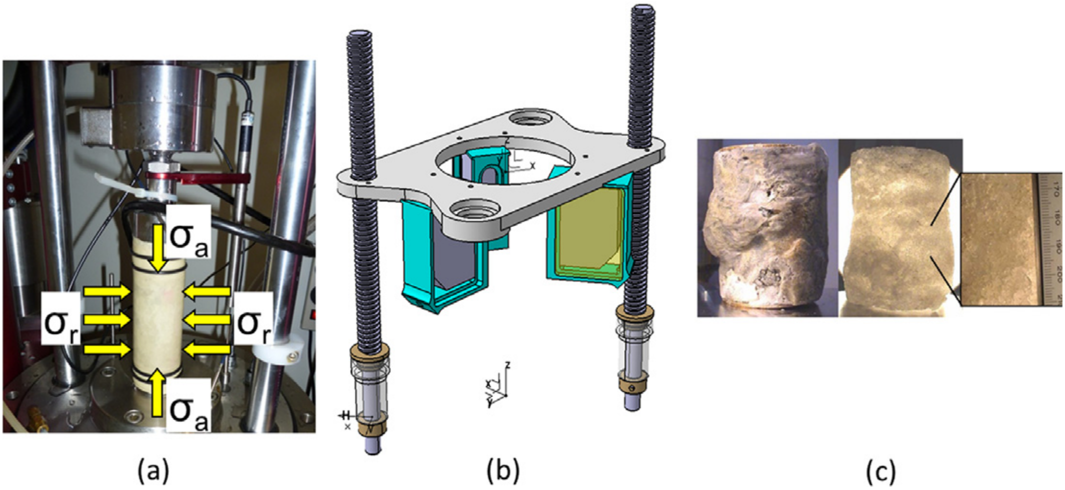

Fig. 8. Triaxial stress path testing on artificial specimens of alpine permafrost. (a) Apparatus and specimen with arrows showing axial and radial total stress directions. (b) Laser measurement system (after Messerklinger and Springman 2007). (c) Left, post-test dense artificial specimen showing shear zone dilation at 30° to the horizontal plane; and right, post-test specimen of granular ice, showing rearrangement and bulging in the lower third of the specimen (Arenson 2002).

high emissions recorded as peak deviatoric stresses were approached. Future developments could combine this with computed tomography scanning to investigate the change in microstructure during loading to failure.

Sample preparation Sample preparation techniques were developed inhouse before triaxial compression tests were performed on artificially frozen soil specimens (Arenson *et al*. 2004) and were also adopted by Yamamoto and Springman (2010). A unique dataset was obtained from over a hundred natural undisturbed samples extracted from the Muragl and Murtèl-Corvatsch rock glaciers (Fig. 8c; Arenson *et al*. 2003b, 2004; Arenson and Springman 2005a). The effect of volumetric ice-solid-air fractions (Fig. 8c), temperature, strain rate and confining stress on mobilized shear strength and creep strain rates was investigated.

Many types of laboratory tests, for example shearing in *axial compression* (*AC*) at CSR, or maintaining CSC, to measure the resulting creep deformations, or under given strain modes, have been performed on frozen soils or Arctic permafrost (Goughnour and Andersland 1968; Sayles 1974; Parameswaran and Jones 1981; Weaver and Morgenstern 1981; Savigny and Morgenstern 1986; Vyalov *et al*. 1989; Ladanyi 1997) to advance and verify theoretical models. Microstructural aspects have been examined and quantified to establish their influence on mechanical properties by Cole (2001).

CSC tests CSC triaxial compression tests were carried out at constant temperature (±0.1°C) to obtain axial creep strain rates as a function of difference between the axial and radial total stresses, the deviatoric stress ($q = \sigma_a - \sigma_r$; Fig. 8a), and temperature (Fig. 9a–c, Arenson 2002). Axial creep strain rates increased with the increasing applied deviatoric stress, temperature, and volumetric ice content (when this was lower than ~65%). Minimum creep strain rate was strongly related to peak and residual shear strength of soil, and was dependent on temperature and composition of samples. Tertiary creep was only achieved for some samples within the duration of the tests, for deviatoric stresses higher than would have been expected within a rock glacier under natural stress conditions (Arenson and Springman 2005a). The most critical zone close to 0°C is the hardest to investigate due to the impact of Gibbs free energy (e.g. Stadler 1996) as thawing continues, accompanied by raised pore water pressures, which contribute to an increased risk of reaching the threshold defining the transition to tertiary creep.

CSR tests CSR triaxial compression tests were carried out to determine failure parameters as a function of volumetric ice content and strain rate, whereby shear strength mobilized increased with greater axial strain rate. Significant percentages of air within the frozen matrix (up to 20% by volume) of natural samples affected mobilized stiffness,

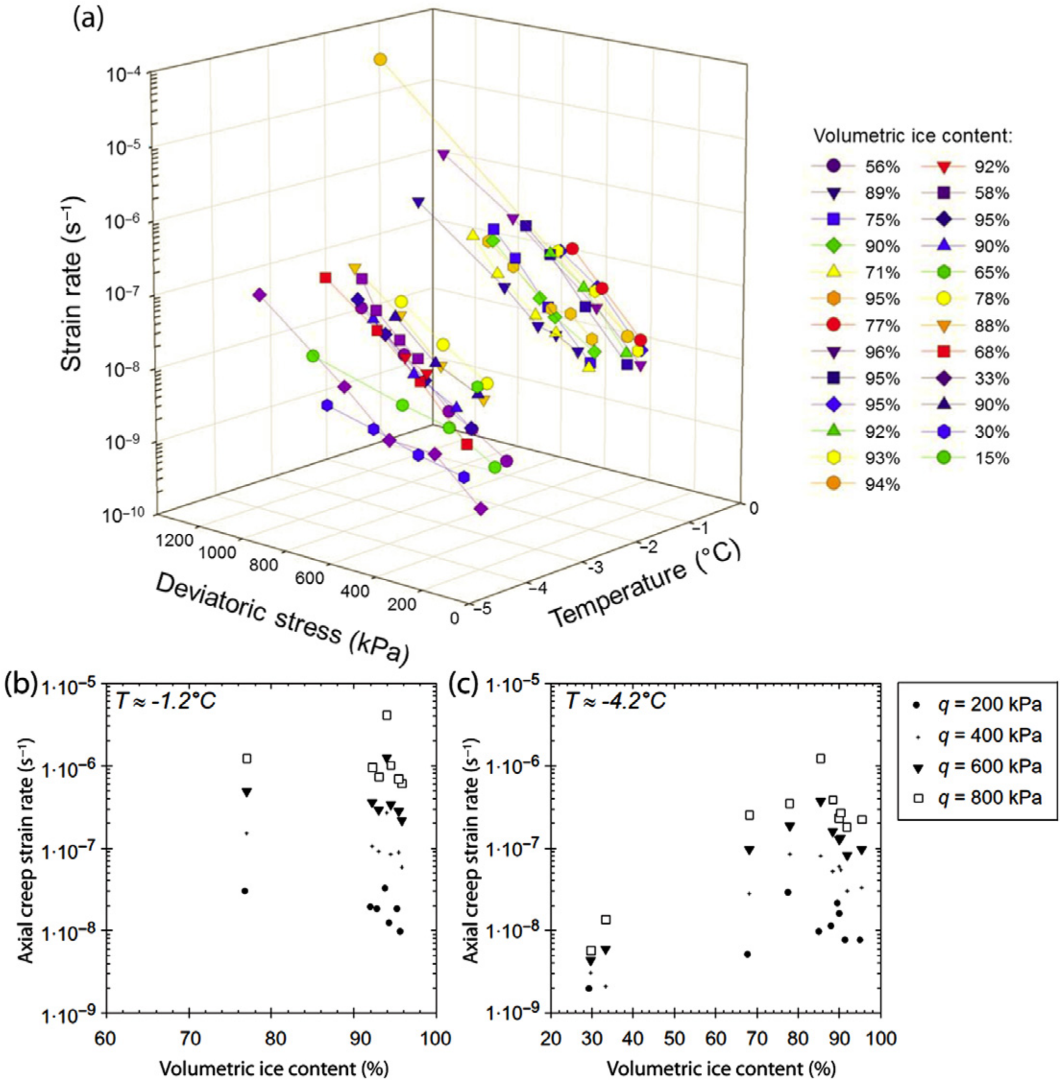

Fig. 9. Constant stress creep (CSC) test data for natural samples from the Murtèl-Corvatsch rock glacier, (a) with axial creep strain rate as a function of the deviatoric stress and the constant temperature maintained with a range of volumetric ice contents. Axial creep strain rate as a function of the volumetric ice content for two different temperatures: (b) $T \sim -1.2$°C, (c) $T \sim -4.2$°C (Arenson 2002).

strength and volumetric response (Arenson *et al.* 2004) from ongoing dilatancy, interlocking particles, higher stiffness and strength, in conjunction with increasing volume (see also Yasufuku *et al.* 2003) to lower stiffnesses and strength, with ductile contraction (Arenson and Springman 2005a).

The peak deviatoric stress, q_{peak}, which is the difference between axial (σ_a) and radial stress (σ_r), $q_{peak} = (\sigma_a - \sigma_r)_{peak}$, obtained from a selection of tests by Arenson (2002), is shown in Fig. 10a and is compared with data acquired more recently by Yamamoto on smaller artificial specimens with more than 53% volumetric ice content and 2.0–5.5% volumetric air content (Table 2). Peak deviatoric stress clearly decreases with increasing temperature and decreasing axial strain rates. Yamamoto's data (Fig. 10b) shows more consistent trends and indicates marginally higher values of q_{peak} compared with those obtained from the

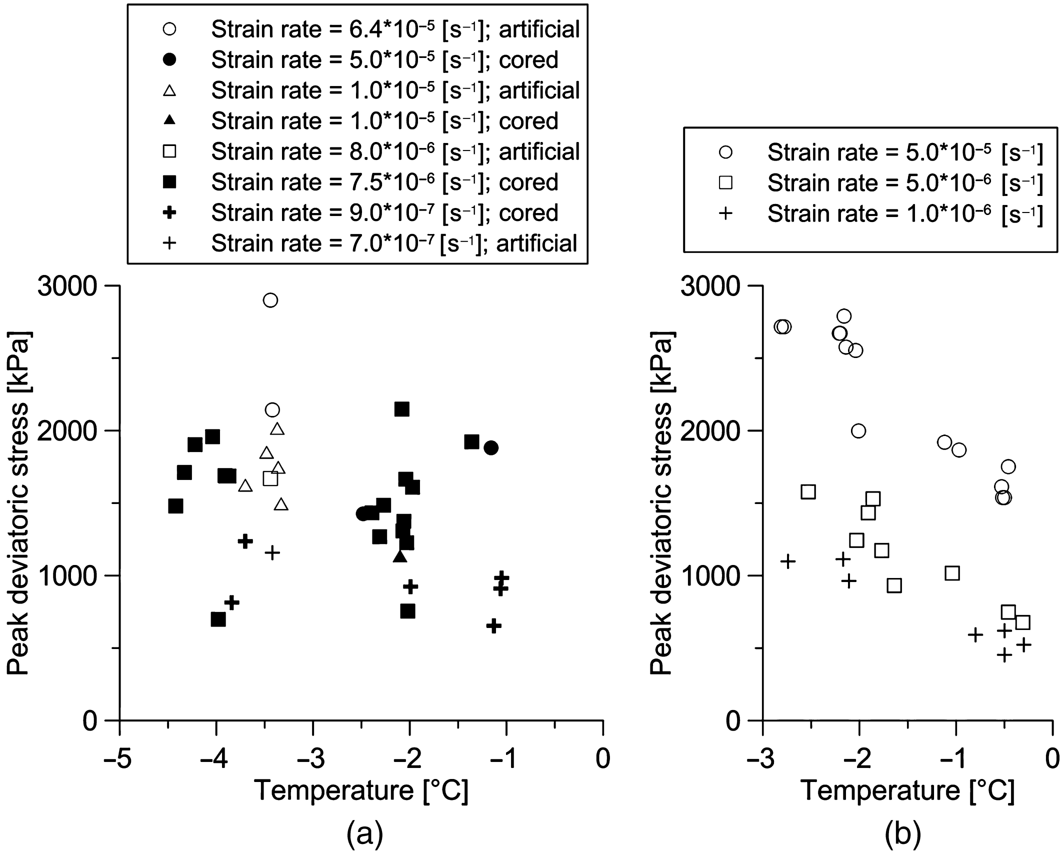

Fig. 10. Comparison of peak shear strength results for specimens (with range of w_i given in Table 2) obtained by (a) Arenson (2002) (b) Yamamoto.

Table 2. Specimen details and test conditions.

Researcher	Specimen					Test condition
	Diameter (mm)	Height (mm)	Maximum grain size (mm)	Origin of solid grains	Volumetric ice contents w_i (%)	Temperature (°C)
Arenson (2002), cored sample	74	150	–	Murtèl-Corvatsch, Muragl	55–97[a] 39–96[b]	–4.42 to –1.05
Arenson (2002), artificial sample	74	150	16	Murtèl-Corvatsch, Muragl	65–97[a] 61–100[b]	–3.70 to –3.33
Yamamoto, artificial sample	50	100	4	Murtèl-Corvatsch	53–90[a] 20–95[b]	–2.81 to –0.32

[a] Dataset used in Fig. 10(b).
[b] All samples.

equivalent cored samples. This was attributed to the greater likelihood of specimen heterogeneity and relatively higher volumetric air contents of 10–25% (Arenson *et al*. 2004) in the field samples, with attendant reduced q_{peak} and secant Young's modulus.

A unique relationship for mobilized friction angle in terms of volumetric ice content, w_i

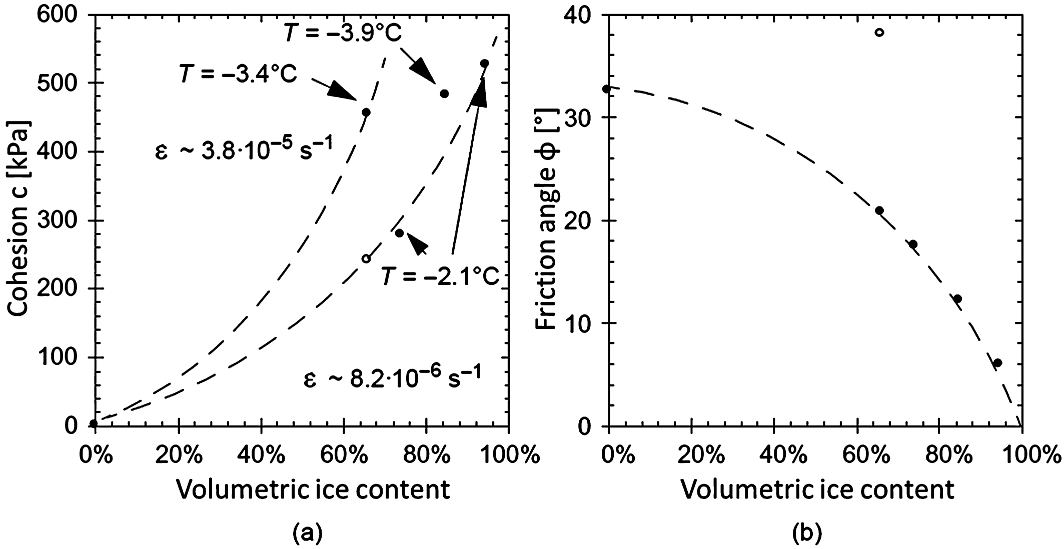

Fig. 11. Constant strain rate (CSR) triaxial compression tests to produce the Mohr Coulomb parameters: (a) cohesion, (b) friction angle (Arenson and Springman 2005a).

(Fig. 11b) was produced from Arenson's (2002) data (Fig. 10a), whereas cohesion was found to be a function of temperature and strain rate as well (Fig. 11a). These data, although somewhat sparse, have proved to be useful in practice, even though the Mohr Coulomb failure criterion and associated parameters are relatively simple and make no allowance for hardening or softening after yield; they may also be derived from the HPD tests.

Importance of the stress path method in laboratory testing The stress path method has been established in geotechnical engineering practice in order to understand and solve stability problems (Lambe and Marr 1979). Stress paths that represent field conditions in the ground should be replicated in an appropriate laboratory test programme in order to determine soil parameters (Holtz *et al.* 2011). The development of deep crevasses and the existence of the extension and compression zones within a rock glacier suggest that instabilities may be triggered (Fig. 12). AC triaxial tests are the most common type used in engineering practice, and have been adopted for the tests conducted by Arenson (2002). However, three new stress paths (Fig. 12) can be assumed to act on a soil element in different zones of the rock glacier. A soil element under, or adjacent to, a crevasse will be unloaded axially or laterally, because the deepening of a crevasse results in a reduction of overburden and lateral earth pressure acting on the soil, whereas, a soil element is loaded laterally in a compression zone.

These four different stress paths can be modelled using triaxial apparatus as *axial extension* (*AE*), *lateral compression* (*LC*), *lateral extension* (*LE*) and AC, respectively. Amendments to the triaxial apparatus have been made to carry out AE, LC and LE tests and details of the tests conducted on artificial samples are mentioned in Table 2. Radial confining stress $\sigma_r = 100$ kPa represented *in situ* stress conditions between 5 and 10 m depth. The results (Fig. 13) confirm past trends in AC and show, tendentially, that an increase in strain rate leads to increased shear strength at failure, defined either by axial strains over 20% (AC, LE) or by axial strains of more than 2% after the peak strength was observed for LC and AE paths. Stress paths following $q < 0$ do appear to mobilize considerably less strength than those with $q > 0$ (Fig. 13). This has important implications for rock glacier stability, although the results are still preliminary.

The results from a multi-phase CSC-AC test are shown in Fig. 14. The radial stress was held constant at 100 kPa with $q = 400$ kPa and the axial strain rate increased by a factor of 4 as the temperature was raised from –1 to –0.5°C.

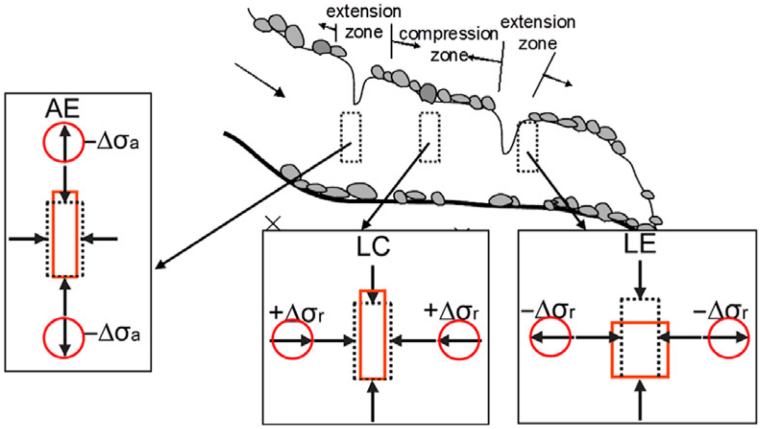

Fig. 12. Equivalent laboratory stress paths in a rock glacier. AE – axial extension; LC – lateral compression; LE – lateral extension.

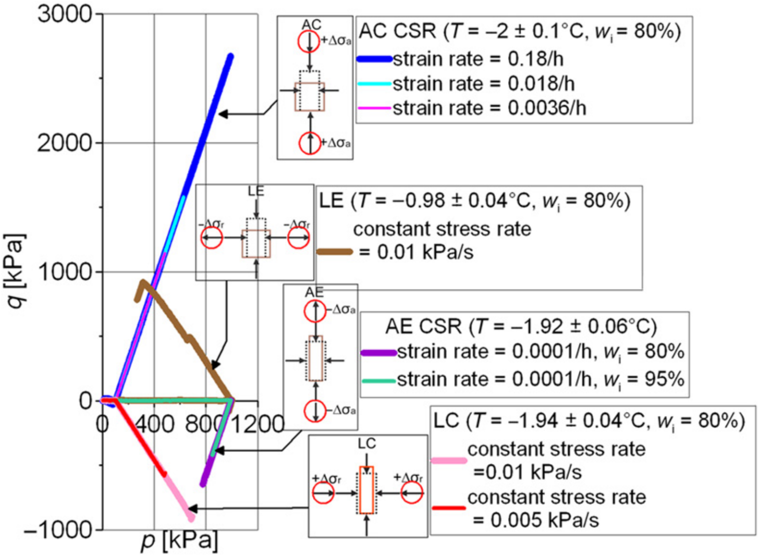

Fig. 13. Total stress paths in deviatoric ($q = \sigma_a - \sigma_r$) versus mean ($p = (\sigma_a + 2\sigma_r)/3$) stress (after Springman *et al*. 2011).

Field observations from 2011

Visits to all three rock glaciers in summer 2011 revealed a common thread of observations linking the role of water flowing on the permafrost table in accelerating active layer deepening and local thaw. This has impacted on local volume loss and settlement. Fig. 15a shows a photograph taken at point X (Fig. 1) through the snow cover on the Muragl rock glacier. Water was heard and observed to be flowing fast at a depth of <1 m before it drained into some thermokarst and emerged in a stream, most probably on the orographic left flank (Fig. 1). Runoff was also heard and seen at places (e.g. point Y in Fig. 1) along a series of local linear depressions to drain from the permafrost in the overlying lobes shown on the right of Fig. 15b. Signs of these local depressions can be identified in Fig. 1, marking the boundary of each generation of lobe development.

Likewise, Derungs (2011) observed and/or heard water flowing downslope beneath the boulder layer and on top of the permafrost table at Murtèl-Corvatsch rock glacier (zone 1, Fig. 16a), where ice could be seen, especially in the furrows.

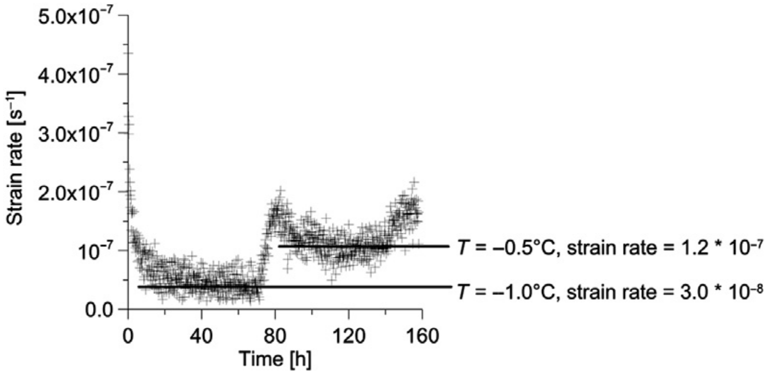

Fig. 14. Constant strain creep–axial compression (CSC–AC) triaxial stress path test subjected to a warming thermal regime (from –1°C to –0.5°C).

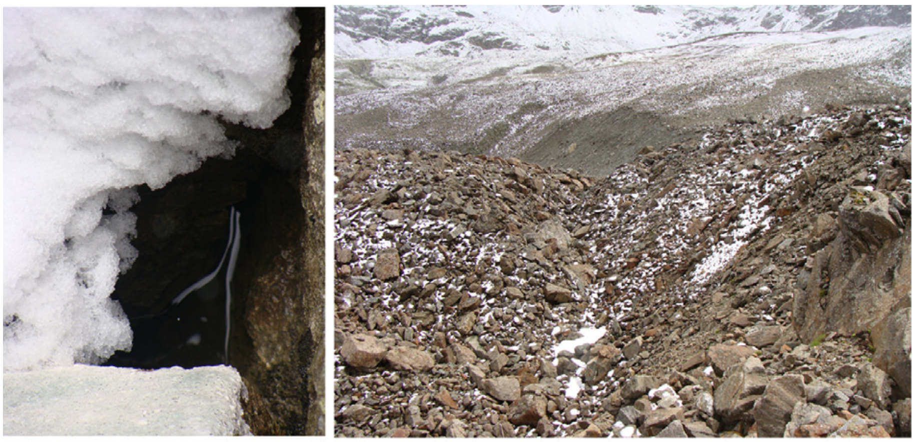

Fig. 15. Muragl rock glacier, July 2011. (a) Water flowing on permafrost at <1 m depth in the active layer at point X in Fig. 1. (b) View to WNW from point Y in Fig. 1.

This runoff either drained into thermokarst formed by the many channels that were identified in the permafrost body in the 2000 boreholes (Vonder Mühll *et al*. 2003) or off the flanks or front of the rock glacier (zone 2, Fig. 16a) into several converging streams.

A snow-filled depression, 50 m south of F1/2010 (Fig. 3) on the Furggwanghorn rock glacier was observed to hold water to a depth of 30 cm above the deepest point in August 2011. At the same time, water was heard flowing down the orographic left flank and along the lower right flank. There were further indications of an advanced drainage regime to the NNE (Fig. 3) in the root, near F1–3/2010, where the accelerated crevasse deepening reported by Roer *et al*. (2008) can now be attributed to convection thaw and ongoing formation of thermokarst.

Temporal and spatial monitoring of deformation and temperature at depth

Characterization is only partial because of the temperature dependency of the creep and cohesion parameters. Consequently, the state of the thermal regime must be coupled with the preliminary characterization from regular monitoring. Installation of monitoring systems in boreholes in former, degrading and creeping permafrost, with continuous logging of temperature and shear (Arenson 2002), is the ideal. A brief summary of the monitoring systems will be presented in this section.

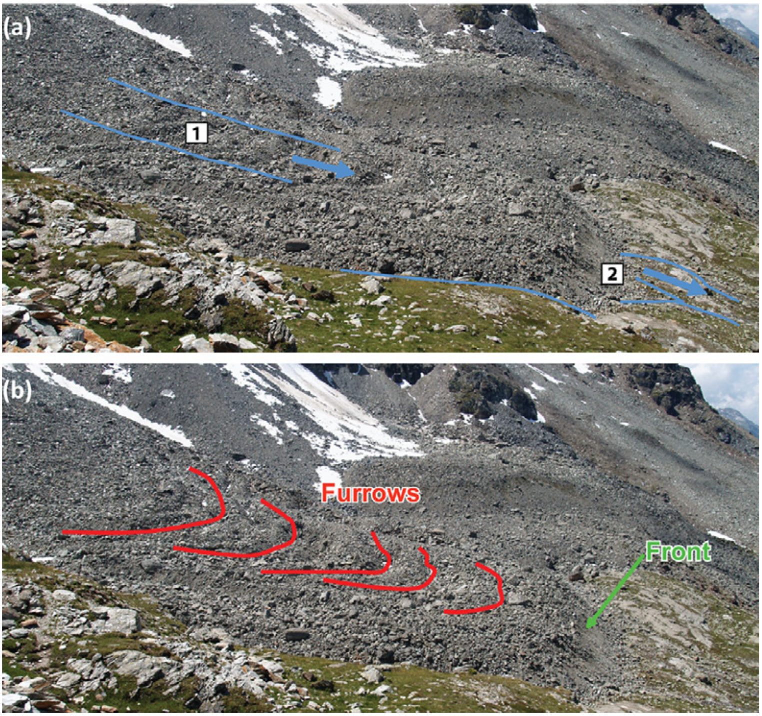

Fig. 16. Overview of Murtèl-Corvatsch rock glacier. (a) Shows the locations of water flowing downslope on top of the ice rich layer [1], and at the bottom of the front of the rock glacier [2]. (b) Overview of Murtèl-Corvatsch rock glacier showing the furrows (red lines) and the front (green) (Derungs 2011).

A solar powered on-site automatic weather station was installed at Muragl to monitor surface heat fluxes and external *thermohydraulic* (*TH*) driving forces, such as precipitation and snow cover (including snow density), as well as air temperature, wind speed, wind direction (eddy covariance), and solar radiation (short and long wave). It is important that all of these parameters are monitored and recorded continuously, because it is very challenging to model surface energy balance on rock glaciers accurately otherwise.

Surface deformations

Aerial photogrammetric investigations have been conducted on several rock glaciers in order to analyse surface topography and surface kinematics. Kääb *et al*. (1998) show the appearance of the transverse ridges (up to 7 m) on the lower part of the Murtèl-Corvatsch rock glacier. Roer *et al*. (2008) illustrate the existence and development of 'crevasses' (up to 14 m deep) in several rock glaciers in the European Alps. These formations differ between rock glaciers, but slope angle and rheological properties of the permafrost layer may determine the initiation and development of a crevasse. For example, the Murtèl-Corvatsch rock glacier shows higher surface velocity in the upper zone due to the steep slope than in the lower zone (Kääb *et al*. 1998), which results in the compression zone in a lower part leading to the formation of the transverse ridges because of the reduced resistance in the vertical direction (e.g. Fig. 16b, Derungs 2011). In contrast, the Furggwanghorn rock glacier shows higher surface velocity in the lower zone than in the higher zone, which results in an extension zone followed by a formation of the crevasses in the rooting zone (Roer *et al*. 2008).

A much more complex surface flow pattern is observed for the Muragl rock glacier (Kääb 1998). The middle part, with the steepest slope, showed maximum deformations of up to 0.5 m yr^{-1} in the late nineties. Different generations of active rock glaciers have contributed to the current combined outline.

Future developments

New technologies have become available recently to measure surface deformations continuously over larger areas with high accuracies (<0.1 mm). Differential radar interferometry is a technique for measuring the spatial distribution of mm–cm scale surface displacements, which has been applied to rock glaciers through the use of satellite SAR interferometry (Rignot *et al.* 2002; Strozzi *et al.* 2004), and more recently with a ground-based radar interferometer (Strozzi *et al.* 2009; Strozzi *et al.* 2011). Observation of fast-moving rock glaciers from space is limited however because signal decorrelation occurs within the repeat measurement interval for available satellites, such as ENVISAT (35 days), ALOS (46 days) and TerrarSAR-X (11 days). Despite this, Strozzi *et al.* (2009) analyzed 1 day ERS 1/2 SAR interferograms for the period 1995–1999 and detected 10 rapidly moving rock glaciers in the Swiss Alps, indicating a velocity between 2 and 5 m yr^{-1}. The first known application of a *Gamma portable radar interferometer* (*GPRI*) to overcome the limitations inherent to satellite observation of rock glaciers, and to image surface displacements at high spatial resolution and precision was used to measure displacements, along the radar line of sight on the Dirru and Grabengufer rock glaciers in the Mattertal, Switzerland (Strozzi *et al.* 2009). A real aperture antenna array that rotates across azimuth was used (Werner *et al.* 2008). Maximum displacements on the Grabengufer were measured at 40 cm day^{-1} in August 2009, which reduced to 10 cm day^{-1} in March 2010 (Strozzi *et al.* 2009; Tazio Strozzi, personal communication 20 January 2012). In another application of GPRI radar analysis of surface topographic change, two digital terrain models derived from GPRI radar data on the Grabengufer rock glacier showed a 10 m height increase at the rock glacier front for a 7-month period (Strozzi *et al.* 2011). The first of a series of measurements using an improved GPRI system (Werner *et al.* in press) was deployed on the Furggwanghorn rock glacier in late summer 2011, where continuous measurements were recorded over a 22 h period (radar images acquired every 5 min). Preliminary results show (line of sight) displacements of up to 1.8 cm at the rock glacier front with at least two distinct zones of movement occurring across the rock glacier (Fig. 17).

High-resolution terrestrial laser scanning is also being applied at Furggwanghorn, where periodic repeat scans will form the basis for analysing 3D inter-seasonal surface spatial displacement patterns. In combination with ground-based LiDAR, which provides high-resolution point clouds (<10cm point spacing), real-time surface deformation monitoring of active rock glaciers will be possible at a variety of spatial and temporal scales. Such data will provide valuable insights into the deformation pattern and potential seasonal variations. Further, it will be possible to evaluate the effect of the snow cover on rock glacier movements, in particular those of the active layer.

Borehole deformations

Pioneer work was conducted by Haeberli *et al.* (1993a), Wagner (1996) and Hoelzle *et al.* (1998) in determining the depth, thickness and speed of shearing within extreme shear zones from horizontal downslope borehole deformation data from a hand-measured 71 mm internal diameter vertical slope inclinometer in the Murtèl-Corvatsch rock glacier (Fig. 18). Data revealed average strains in the shear zone and surface deformation rates that were well in agreement with photogrammetric measurements of rock glacier dynamics (e.g. a rate of <0.1 m yr^{-1} at the borehole location at Murtèl-Corvatsch; Kääb *et al.* 1998; Kääb and Vollmer 2000), and constant surface velocity was determined (Arenson *et al.* 2002). Two SINCO Digitilt and USBR inclinometers were installed in the faster creeping Muragl rock glacier, which also conformed by exhibiting surface movements of ~0.5 m yr^{-1} from both measurement systems (Fig. 18). The extreme curvature of the inclinometer tube as it enters and leaves the shear zone controlled the sustainability of the tubes, which survived local shear strains up to 30%.

It is noticeable that there are some discontinuties in deformations, marked by the rings in Fig. 18, at the base of the active layers of each of the rock glaciers, supporting recent concerns expressed by Rist and Phillips (2005) and Rist *et al.* (2012) about increased risk of active layer detachment, which they investigated in an inclined shear box apparatus under controlled thermal conditions. The measurements of deformations with depth initiated by Haeberli also led to a new understanding of the morphology of rock glaciers. Demonstrating the existence of a distinct shear zone, which is very different from the continuous deformation profile found in most glaciers, led to postulation of modern rock glacier genesis.

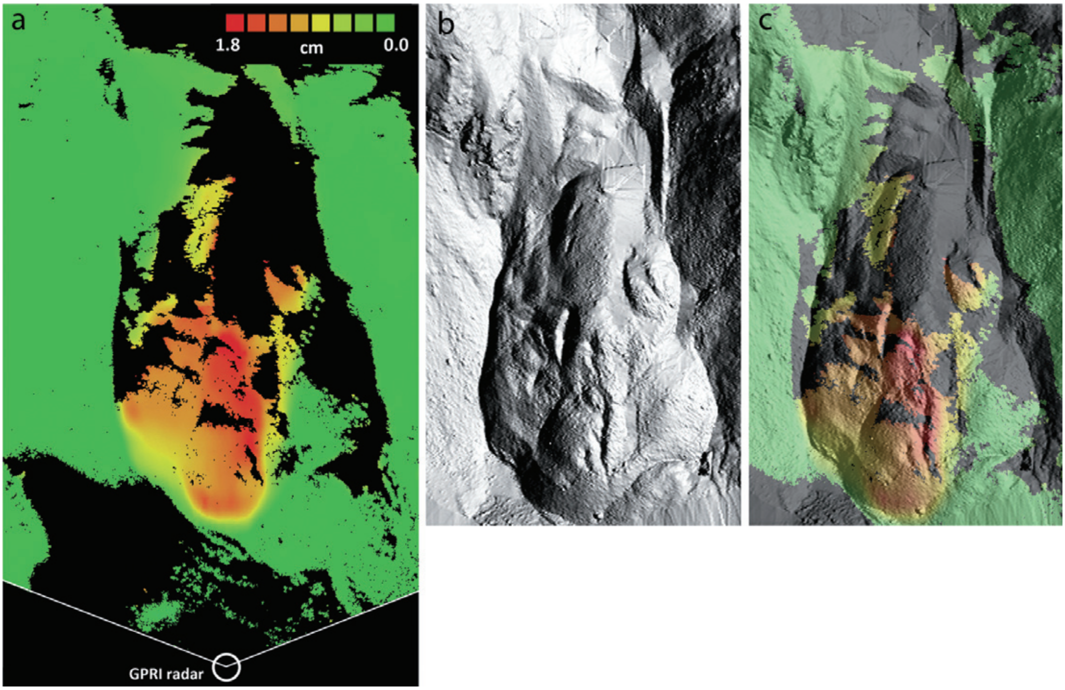

Fig. 17. Preliminary results from radar interferometry from a 22 h continuous survey using a portable radar interferometer on the Furggwanghorn rock glacier. (a) 22 h spatial displacement map (phase unwrapped) showing differential velocities on two lobes of the rock glacier. (b) Preliminary 0.5 m gridded shaded relief map derived from terrestrial LiDAR (<10 cm point spacing). (c) Overlay of radar displacement map and shaded relief.

The deformations measured in the two boreholes at Muragl were unique in that seasonal variations could be shown for rock glacier flow for the first time (Fig. 19). Unfortunately, shear deformations for 4/1999 were so large that the casing sheared off after only 4 months. The deformation profile for 3/1999 indicated the maximum deformation rates during winter, with slower rates during summer. This can be explained by the time needed for warmer temperatures (from summer) to reach the depth of the shear zone. As the ice warms, the creep strength decrease allowed for larger strains to develop. Rates started to decrease again as winter temperatures reached the depth of the shear zone deformation. Seasonal changes in air temperature were found to affect the rock glacier creep because the shear zone is much shallower for the Muragl rock glacier compared with that at Murtèl-Corvatsch (Fig. 18). A sinusoidal curve fit was calculated to quantify the surface velocity (Fig. 19).

A coaxial cable was installed in the newer boreholes on the Murtèl-Corvatsch rock glacier to measure deformation using *time domain reflectometry* (*TDR*) (O'Connor and Dowding 1999). However, no conclusive data are available to date that would provide detailed information on the shear zone characteristics of the rock glacier. It is likely that the shear zone is not sufficiently concentrated to generate a dent in the cable that is large enough to be identified using TDR technology.

The latest generation of inclinometers do not require manual reading and comprise increments of eight rigid 0.5 m segments with freely rotating joints at each end, each instrumented with a compact array of smart triaxial MEMS gravity sensors (gtShape, http://www.geotrade.com/index.php?id=229, 19-Apr-12), enabling readings to be compared over much shorter timespans. Several 4 m chains have been connected together and grouted into F5/2010 and F6–7/2011 at Furggwanghorn to investigate the deformation mechanisms with depth and link them to surface settlements and/or lateral movements. Long-term accuracy is reported to be better than 1.5 mm for this set up, and initial results have been extremely prom-

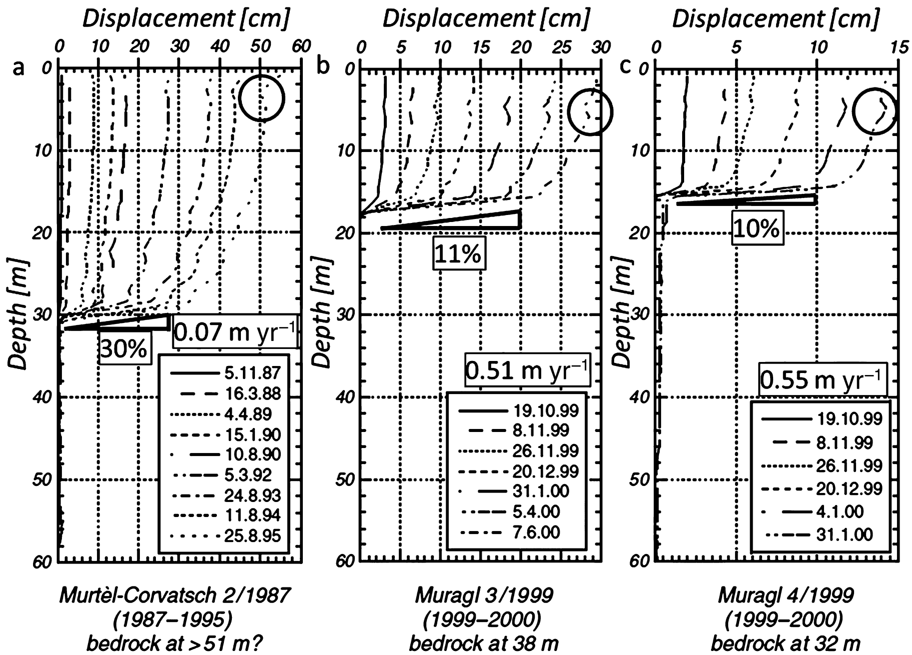

Fig. 18. Horizontal downslope borehole deformation from inclinometers in the Murtèl-Corvatsch and Muragl rock glaciers (after Hoelzle *et al*. 1998; Arenson *et al*. 2002), including annotations of surface deformation rate and average strain in the shear zone.

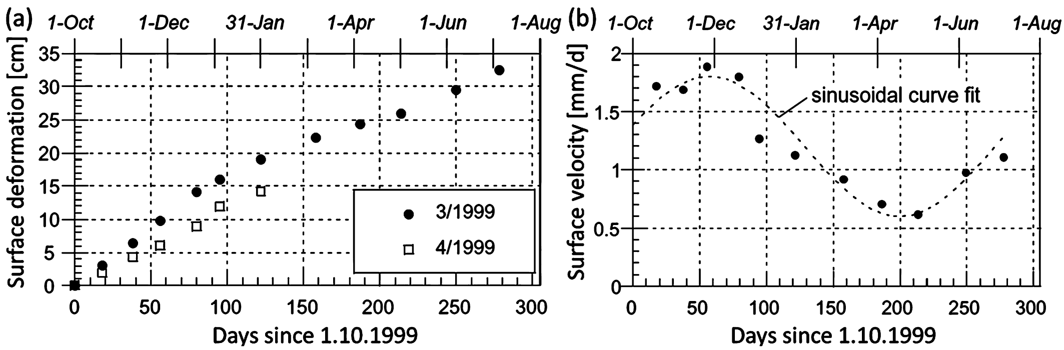

Fig. 19. (a) Cumulative surface deformation (cm) since 1 October 1999 for boreholes 3/1999 and 4/1999. (b) Surface velocity since 1 October 1999 for borehole 3/1999 (Arenson 2002).

ising. Ideally, the joints should also be able to lengthen axially so that the inclinometer would extend and provide readings for a longer period.

Borehole temperatures

Several *in situ* thermistor cables in the active part of the Muragl rock glacier have sheared off and are no longer recording temperatures. The cables in 2/1999 recorded until May 2006, 3/1999 until June 2005 and 4/1999 is still recording temperatures over the top 13.6 m, but the lower part has sheared off since January 2004 and no more data are being produced. Temperatures are still measured in borehole 2/2000 on Murtèl-Corvatsch and present an interesting phenomenon. The temperatures in most of the borehole remain at 0°C during summer and only cool during winter (Fig. 20a). Arenson *et al.* (2010) present a discussion on this behaviour, which is thought to be caused by intra-permafrost

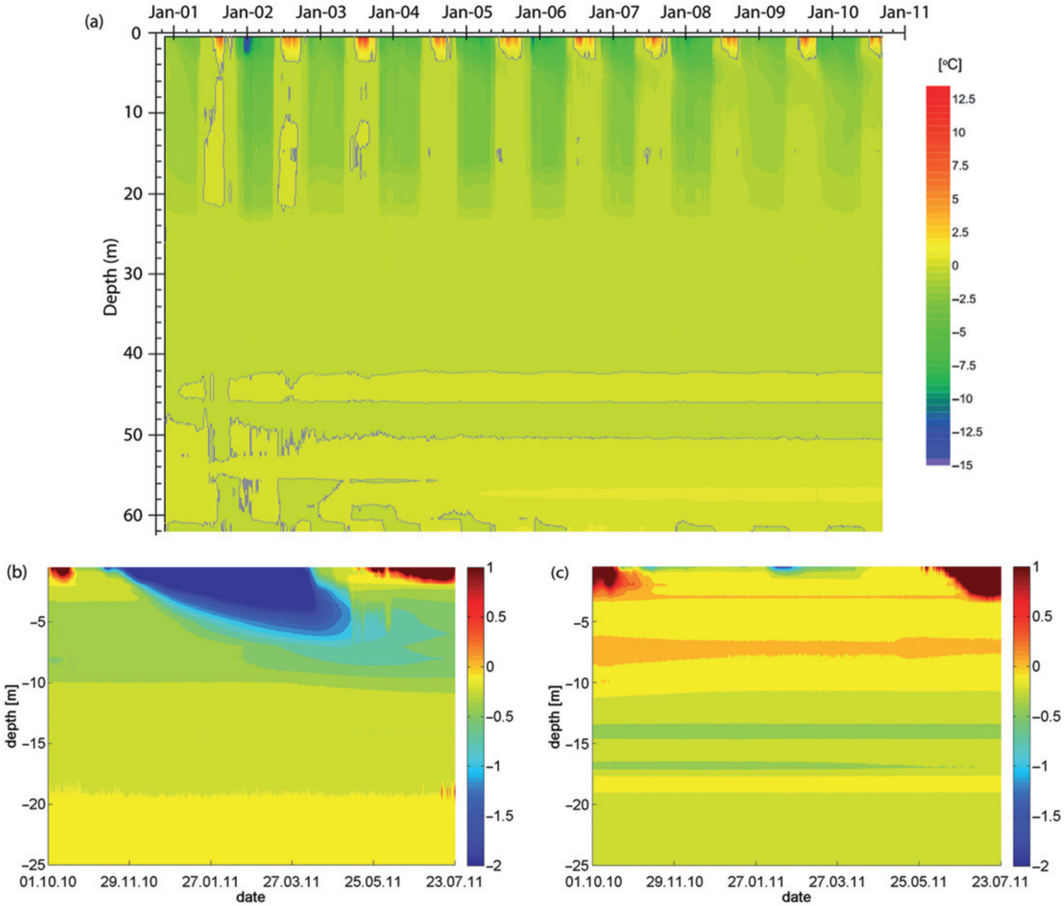

Fig. 20. Temperature (°C)–depth (m) plot in (a) 2/2000, Murtèl-Corvatsch from December 2000 until September 2010. (b) Furggwanghorn rock glacier from October 2010 to July 2011, F1/2010; (c) F4/2010, same period.

groundwater flow. Further, the development of a sub-permafrost talik can be noted at a depth of about 57 m. The temperatures at the permafrost base slowly increased over the past 10 yrs, furthering the view that permafrost degradation has developed from the bottom.

The thermistor chains in all boreholes at Furggwanghorn (except F5/2010) are providing temporal and spatial temperature distributions (Fig. 20b,c) for the first 9 months. The cooling effect during winter can be seen in F1/2010 up to a depth of 8 m, below which the temperature remained just below zero, without significant seasonal change. The boreholes F2 and F3 show a similar temperature distribution as borehole F1 for the first 6 months. The winter cooling effect in F4 is not discernible (Fig. 20c). The temperature below 8 m depth remained close to 0°C in all four boreholes during the measuring period.

Detailed ground temperature analyses are presented bi-annually in the PERMOS reports (PERMOS 2010). The analyses confirm the importance of such long-term ground temperature data when assessing the state and changes in permafrost, as recommended by Humlum and Matsuoka (2004). Only multi-year observations allow for accurate interpretations of the thermal state of rock glaciers.

Mechanistic modelling

A conceptual, mechanistic model, based on the features observed in the Murtèl-Corvatsch rock glacier (Figs 16 and 21a), is discussed in which zones of

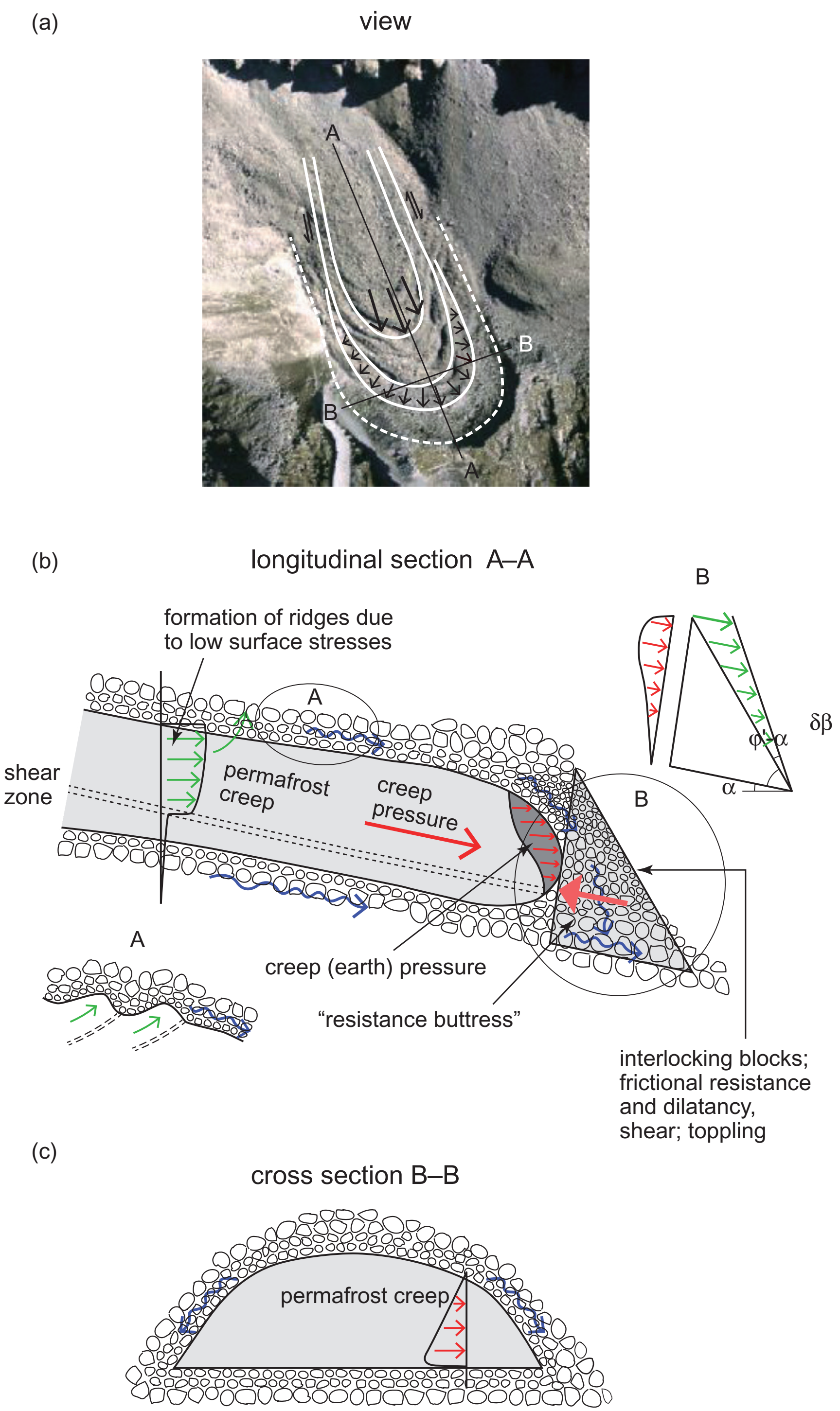

Fig. 21. Pressure-hydraulic-deformation mechanisms derived from this research. Pressure/force (red), displacement (green), water flow (blue). (a) Overview of the mechanistic model; (b) longitudinal section A–A; (c) cross section B–B.

higher w_i at warmer temperatures and higher stresses will creep downslope faster than colder, frozen soil with lower w_i under lower stress conditions (Fig. 9). The three-dimensional active layer, which has formed largely of interlocking blocks at the base, the front and on the top of the rock glacier, with finer grained deposits clearly visible on the front and side slopes due to 'self-sorting' (e.g. Pouliquen and Vallance 1999) (Fig. 16b), will be likely to exhibit no viscous creep at all, creating a significant discontinuity that is manifested in extreme shear along the ice–active layer boundary.

Frictional resistance will be mobilized in the active layer through interlocking, shear and dilatancy that can be overcome at the front by a simple (rotating) shear mechanism (sketch B in Fig. 21b), promoted by the creep pressure at the front of the permafrost lobe, which is likely to cause toppling of the large blocks 'travelling' on top of the creeping mass as the slope angle of the front face reaches an angle of friction φ' plus a critical wedge angle $\delta\beta$ whereupon toppling, rolling, sliding and slumping will return the slope to a front angle of about φ' to the horizontal, as the simple shear displacements begin, again, to create an unstable front wedge.

In the face of a resisting three-dimensional granular 'buttress' at the front, the faster creeping central zone will decelerate by extrusion and vertical displacement will occur (sketch A in Fig. 21b) due to the low vertical stresses near the surface, forming ridges and furrows in the active layer, as were described by Barsch (1977). This is likely to contribute to the discontinuities observed in inclinometer readings around the active layer depth, as identified in Fig. 18.

This construct implies that peak downslope strain rate will be found at some depth (Fig. 21b), where the combination between these factors is favourable to the development of a shear zone that exhibits enhanced straining (Fig. 9). Deformations along the flanks of the rock glacier are largely irrelevant unless there is a local lateral toppling event. Displacement vectors for Murtèl-Corvatsch (PERMOS 2010) tend to indicate primarily longitudinal advance and spreading at the front, as illustrated in Fig. 21b.

Flowing melt-water and runoff from precipitation (Fig. 21b, c) is likely to have a limited impact on local stability given the high drainage capacity in the blocky matrix at the front and base that would preclude full saturation. This is supported by many field observations in that streams flow out at the base of the Muragl (Figs 1 and 15) and Murtèl-Corvatsch (Figs 2 and 16b) rock glaciers, and not through the side slopes.

Arenson (2002) summarized possible slope stability mechanisms that could develop in rock glaciers (Fig. 22) concluding that active layer (Case 1) and local front (Case 2) instabilities would be the most likely form of mass movements. Cases 4 and 5 would present the greatest mass movement event in terms of the volume of material displaced.

Numerical modelling

Numerical modelling of rock glacier behaviour includes three fundamental processes that are each challenging to model because the *in situ* behaviour is not completely understood, hence model calibration is very difficult. Furthermore, these processes are coupled and are changing constantly, i.e. transient modelling is required during which the various interdependencies of the properties can be simulated properly. These processes are soil strength/mechanical stability; ground thermal regime; and water flow.

The strength parameters of the frozen materials are a function of the temperature, which is not constant in time and space. Water flow may occur, for example in a lateral talik, and affect temperature through convective heat transfer, hence thermal erosion, that in turn affects the stability. The surface energy balance in rock glaciers is not well understood (e.g. Hoelzle *et al.* 2003) and simplifications are needed in order to model the effect of climate variables on the ground thermal regime. Since current ground temperatures are controlled by past climate and are likely not to be in equilibrium with current climate conditions, proper calibration is even more challenging.

A simple one-dimensional technique was used by Arenson and Springman (2005b) to model creep strains with depth as a function of temperature and volumetric ice content. Because the relationship used for this model was based on laboratory tests carried out on undisturbed frozen samples from that particular rock glacier, validation against the modelling results was reasonable and assessing different temperature conditions is viable. However, extrapolations to other sites are not recommended because the conditions are likely to be very different.

A decoupled approach for assessing the change in the slope stability (Geostudio: Slope/W) of an ice-rich rock glacier as a function of temperature, was presented by Nater *et al.* (2008), idealized from the Muragl rock glacier (Fig. 23). A two-dimensional

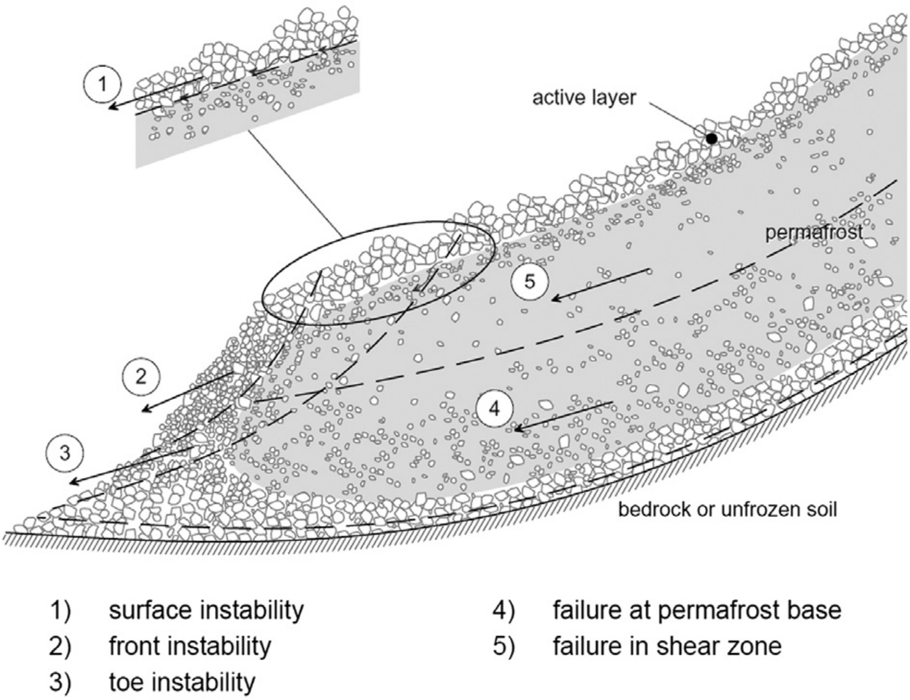

Fig. 22. Possible instability mechanisms in rock glaciers (Arenson 2002).

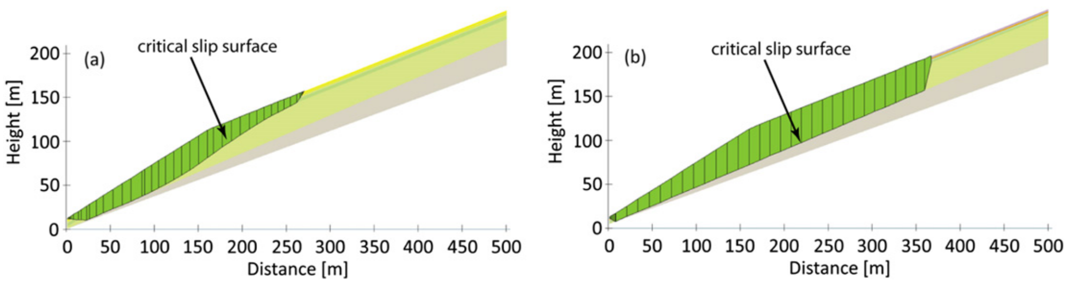

Fig. 23. Failure mechanisms (green) for temperature profiles in slope with active layer (yellow), frozen soil and unfrozen gravel (grey), with a global factor of safety of 1.2 (summer, a) and 1.5 (winter, b), respectively (Nater *et al.* 2008). All units in metres.

thermal finite element model (Geostudio: Temp/W) was used to calculate changes in the geothermal profile as a function of air temperature and time. Temperature-dependent strength parameters (Fig. 11) were later used in a series of slope stability analyses to calculate a time-dependent factor of safety against failure, which varied between 1.2 for summer and 1.5 during winter (Fig. 23). A mixture of deeper failure mechanisms between Arenson's cases 3, 4 and 5 was obtained. However, the effects of creep were not considered.

Derungs (2011) conducted a two-dimensional limit equilibrium analysis on the Murtèl-Corvatsch rock glacier, with the cross section derived from Kääb *et al.* (1998). Notwithstanding thermal modelling of the rock glacier's response to climate perturbations, the critical failure mechanisms passed through the well-drained granular deposits in the front zone. Interestingly, the locally steep slope (Fig. 24) supports the suppositions developed in the conceptual model described in Fig. 21, whereby dilatancy of the blocks, which can reach

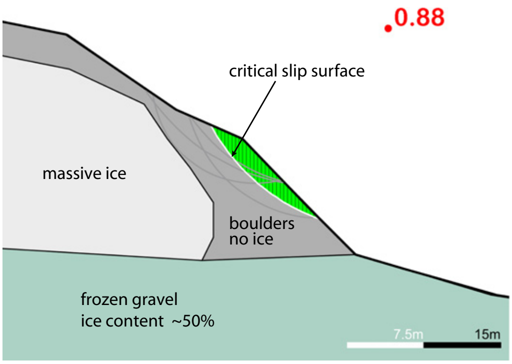

Fig. 24. Failure mechanism (light green), centre of circle and factor of safety (0.88) in the boulders (dark grey, $\varphi = 35°$) at the front of the Murtèl-Corvatsch rock glacier, massive ice (light grey, cohesion, $c = 400$ kPa, $\varphi = 20°$) and underlying frozen gravel (blue, $c = 500$ kPa, $\varphi = 30°$) also shown (Derungs 2011).

10–20° in medium dense soils under low stresses (Bolton 1986), adds to the available shear strength based on the critical angle of friction ($\varphi' = 35°$). The numerical analysis considers neither the dilatancy nor the three-dimensional failure mechanism and therefore predicts a factor of safety <1, centred on the large dot in Fig. 24.

Constitutive models must become increasingly complex to represent the relevant aspects of frozen soil-mixture response in the future. Rigorous three-dimensional, coupled thermo-hydro-mechanical-time models need to be developed, accounting for effects of strain magnitude and rate, relative density, and opposing effects of dilatancy and crushing, although some exist already to cope with three out of the four main controlling influences. A multi-scale approach is essential to benefit from physical data in laboratory tests and physical models, as validation and parameter calibration opportunities. Initially, key aspects should be investigated in small-scale element tests and on medium-scale physical models, and these should be extended, ultimately, to field scale.

Conclusions

Prediction of the effects of significant deep warming of mountain permafrost necessitates access to regular information combined with understanding about the complex, non-linear, interacting processes that lead to permafrost degradation, eventually triggering mass movements initiating from mountain permafrost. Multidisciplinary field research efforts in these challenging environments, stimulated by Haeberli's early work, have evolved from investigations into classic 'slow moving' rock glaciers such as Murtèl Corvatsch (0.1 m yr^{-1}) to 'faster moving' rock glaciers such as Muragl (>0.5 m yr^{-1}), and currently to Furggwanghorn, in which surface creep deformation is of the order of several metres per year. Comprehensive datasets are available, and more information is being added annually, via ongoing research projects and monitoring (platforms PERMOS). Researchers, and those responsible for natural hazard protection in their communities, compare surface, borehole and geophysical records of thermal state, and of movement of the rock glaciers over time, and therefore obtain an invaluable record of rock glacier behaviour.

This paper primarily describes the investigation methods used, characterization carried out and monitoring initiatives on three rock glaciers, together with some preliminary numerical modelling, by combining geotechnical, geophysical and geodetic methods. A key focus of the paper is on understanding the mechanical (geotechnical) behaviour of Alpine permafrost and the response with time to changing temperatures by determining:

- the structure (content, origin and extent);
- the physical properties and state (density, stiffness, strength, *in situ* stress) and how they vary with time and temperature; and
- the surficial deformation (creep) mechanisms and how they vary with depth in the complex three-dimensional environment on the rock glacier.

A few more steps have been taken towards a better understanding of the transient thermo-hydro-mechanical behaviour of permafrost and ice-rich frozen ground, which will be expected to contribute to mitigation of, and adaptation to, natural hazards in the future.

Multidisciplinary research on rock glaciers in the Alps and the role of such approaches in natural hazard assessments is still a young field. The work initiated by our colleague, Professor Wilfried Haeberli, has opened many doors, inspired numerous new collaborative research opportunities and contributed to achieving significant understanding of rock glacier dynamics.

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