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Rock Glacier Degradation and Instabilities in the European Alps: A Characterisation and Monitoring Experiment in the Turtmanntal, CH

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Abstract

Global climate change is impacting sensitive alpine cryogenic regions, through slope instabilities in rocks and soils. Significant temperature increase at the air-ground surface interface may be accompanied by increased rainfall, more extreme storms and additional severe rise in mean global temperatures in the coming decades, enhancing risk of mass movement hazards to human life and infrastructure. Rock glaciers and degrading permafrost on steep Alpine slopes are particularly susceptible to warming and phase change in either massive or interstitial ground ice, which may lead to release of water, accelerated motions, initiation of landslides and instabilities. Accumulated failure in soil elements, determined on artificial frozen specimens of rock glacier materials at temperatures below 0 °C, is linked to these processes at field scale. A geophysical and geotechnical field characterisation and monitoring experiment is being conducted on a rock glacier that is undergoing thermally induced creep and growth of thermokarst. Preliminary investigations are described in this contribution.

Keywords

Alpine permafrost • Rock glacier • Landslide • Thermal degradation • Characterisation • Geophysics

Introduction

Global climate change is estimated to impact mountainous cryogenic regions more than the global average (Vonder Mühll et al. 2008). IPCC reported temperature increase on top of the Arctic permafrost layer by up to 3 °C between 1980 and 2007, and thawing of the permafrost base at up to 0.04 m/year. Climate scenarios for the Swiss Alps (time horizon of 2050) indicate changes in temperature/precipitation by +2 °C/+10 % in winter and +3 °C/−20 % in summer, with predicted loss of ~75 % of glacier surface and deep warming of mountain permafrost, impacting landscape cover, hydrology and slope stability (Hohmann 2007; Haeberli and Hohmann 2008).

Rock glaciers and degrading permafrost on steep Alpine debris slopes are becoming more susceptible to melting of ice and initiation of landslides, debris flows and other instabilities associated with accelerated land motions, which introduce various forms of hazard to human life and infrastructure. The risk of mass movements due to degrading permafrost can be expected to increase over the next decades.

Permafrost is defined as soil/rock at, or below 0 °C for at least two consecutive winters and the intervening summer.

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Fig. 1 Photograph of the Furggwanghorn rock glacier and environment (VS)

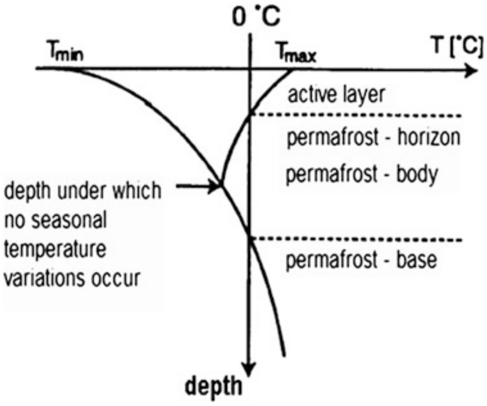


Fig. 2 Definition of permafrost (see also http://nsidc.org/fgdc/glossary) (After Brown et al. 1981)

Land mass on Earth (20 % area) and in Switzerland (~7 %) is covered by continuous and discontinuous permafrost, with extent varying with latitude, altitude, aspect and climate change. Alpine permafrost exists at high altitudes in lower latitude regions through rock glaciers (Giardino et al. 1987; Martin and Whalley 1987; Barsch 1996) creeping downslope and exhibiting evidence of a viscous geomorphological form (Fig. 1). An active layer lies above the permafrost layer (Fig. 2), cycling seasonally above and below freezing temperatures, with depth acutely sensitive to surface temperature and climate variability (Lachenbruch and Marshall 1986; Haeberli et al. 2006).

Mass Movements Triggered by Permafrost Degradation

Catastrophic slides have been triggered due to the reduction in strength as the ice phase warms, induced by climate change (e.g. Haeberli 1992; Zimmermann and Haeberli 1992; Haeberli et al. 1993a; 1997; Davies et al. 2001; Wuilloud, 2008, private communication). Many debris flows were attributed to have occurred due to melting ice at Val Pola (northern Italy south of Bormio, Crosta et al. 2004). Hundreds of landslides and severe flooding occurred between 15th and 22nd July 1987, causing loss of life and large scale economic damage. The temperature was reported to be unusually warm during this period, while the 0 °C isotherm shifted from a typical alpine value of 2,500 m (Vonder Mühll and Haeberli 1990; Arenson 2002; Maurer and Hauck 2007) to between 3,500 and 4,000 m. As well, abnormally high rainfall was noted (600 mm from 15–22/07/87: mean annual rainfall is generally 1,200 mm). The combination of heavy rainfall and exceptionally warm temperatures led to melting of frozen soil and interstitial ice, which in turn led to pore pressure build up, loss of strength, high runoff, severe flooding, which triggered landslides that were characterised by shallow failures, mostly becoming debris flows as they mobilised.

Numerous debris flows have also been recorded at Ritigraben in the Valais, CH (Rebetez et al. 1997), threatening roads, bridges, a railway line and two villages (Grächen and Sankt Niklaus). The Ritigraben torrent system is oriented WNW, is 3.5 km long and ranges from an altitude of 3,100 m at the ridge to 1,050 m in the valley floor. The upper part of the unstable system is in the alpine periglacial zone, with discontinuous frozen ground (King and Akerman 1993). Past studies (Pfister and Hächler 1990; Röthlisberger 1991; Mani 1994) have provided a record of floods from the Valais/Ritigraben area for the majority of the twentieth century, which indicate that the Ritigraben has been subject to nine large debris flows between 1921 (Schnydrig 1952) or 1922 (Mani 1994) and 1996 (Rebetez et al. 1997). These debris flows have become more frequent since the late 1980s (four major events have occurred between 1987 and 1994). A large scale debris flow occurred on September 24, 1993 at the Ritigraben torrent, and had a devastating effect on local infrastructure as it cut across two roads, a railway line and destroyed a bridge. All these debris flows (with the exception of the 1962 event) occurred at the end of summer/beginning of autumn, when the active layer of the permafrost is unfrozen in the periglacial belt. Seven of the nine debris flows were triggered by excessive rainfall events in the Alps, with the remaining two debris flows (1962 and 1994) being triggered by snowmelt. The flow has been shown to have begun at altitudes of above 2,400 m in the Alpine periglacial zone and within the zone of discontinuous permafrost

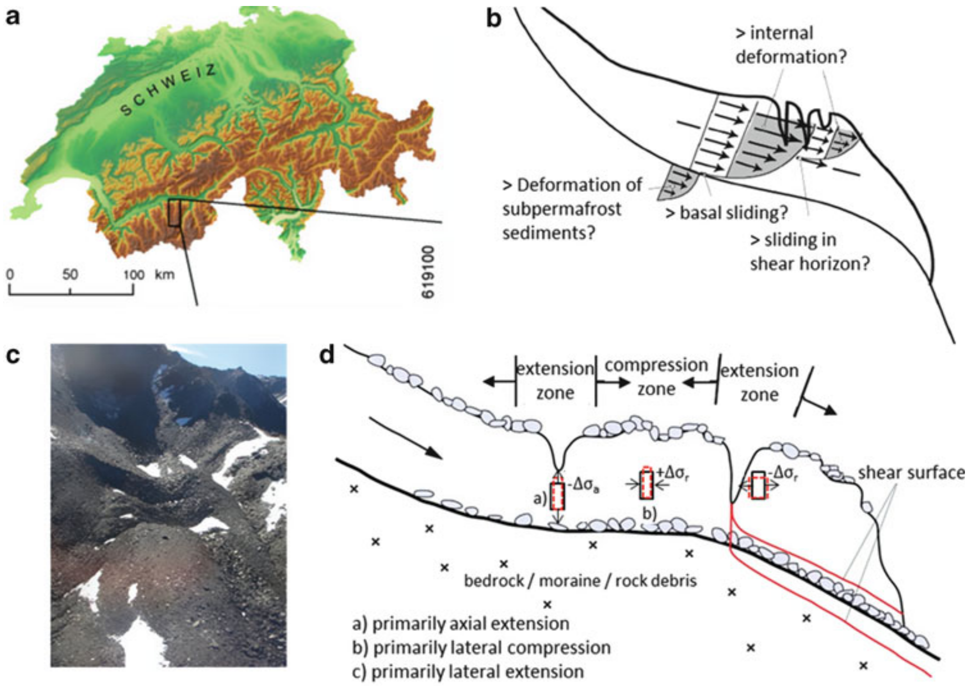


Fig. 3 (**a**) Turtmanntal enclosed within the rectangular box superimposed on the South West Alps (after Nyenhuis 2005); (**b**) cross sections during thermal degradation of mountain permafrost including formation of 'crevasses' (Roer et al. 2008); (**c**) Photograph of the rooting zone in the Furggwanghorn rock glacier in Turtmanntal, Valais (Sarah Springman); (**d**) possible zones of extension and compression with shear planes extending from the base of a crevasse as it deepens, as well as at the surface (within the active layer)

(Haeberli 1990) in the 1921/1922, 1953 and 1993 events (Mani 1994).

More recently, the Bèrard rock glacier in the Parpallion Range in the Southern French Alps has been subjected to a combination of slumping and debris flow due to extreme storm and rains, demonstrating the effect of permafrost degradation on mountain slope stability. It was described as quasi-complete destabilisation of the landform by Krysiecki et al. (2008), releasing about 1.5 million m^3 of material into the adjacent valley in summer 2006. Geomorphological studies revealed that the collapse was probably related to an underlying rockslide in the schist below (Krysiecki et al. 2008), which may have been activated by storms. Current studies are focusing on monitoring ongoing rock glacier movements using Electrical Resistance Tomography, Seismic Refraction Tomography and GPS measurements accompanied by a thermal monitoring weather station. No significant movement of the displaced mass was obtained during the first 3 months. The remaining rock glacier was subject to large movements (displacements of more than 5 m in 3 months). Studies are still being carried out, and once published, should give an interesting insight into mechanisms affecting rock glaciers in the warming French Alps.

The Grabengufer rock glacier is small, steep, 500 m long and 100 m wide. It is located close to the lower limit of the regional discontinuous permafrost belt in the Swiss Alps in the Valais. Analysis of 1-day ERS-1/2 differential SAR interferograms showed a displacement rate of 0.5–1 cm/day during 1993–1997. More recently, this rock glacier has accelerated, in common with many other small rock glaciers in the region (Delaloye et al. 2008; Roer et al. 2008). Several measurements series have been conducted since July 2009 (Delaloye et al. 2010), including lateral pictures, permanent GPS (June 2009–February 2010) and a ground-based InSAR survey. Results after 8 months of survey include extremely high surface velocities, ranging from 30 to more than 200 m/year in some rock glacier sections. Rapid erosion of the front has occurred in mid-February 2010, as new scarps developed, with surfaces tending to dip backwards, evidencing the development of rotational failures at the foot of the rock glacier combined with slumping. This is predicted to continue until a total amount of about 250,000 m^3 of rocky debris erodes into the gully beneath the rock glacier snout.

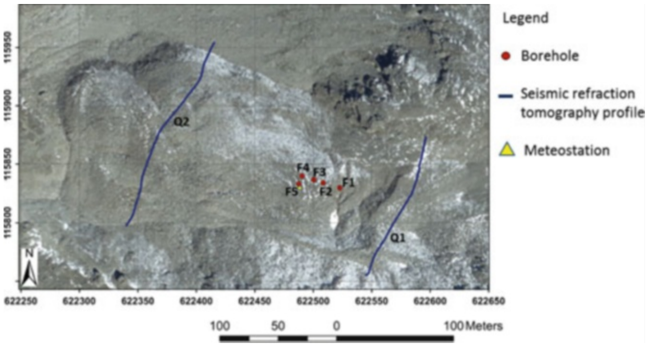


Fig. 4 Orthophoto with the position of boreholes, meteostation and seismic sections along profiles Q1 and Q2 (after Swisstopo)

Rising temperatures have also induced rapid motion of other rock glaciers in the Turtmann valley in the Valais (CH), exposed through recent photogrammetric studies (Roer et al. 2005, 2008; Kääb et al. 2007) (Fig. 3a, c), which are compounding the urgency for improved understanding and predictability of rock glacier stability in the face of climate warming and will be investigated subsequently in this paper.

The existence and dynamics of unfrozen water in frozen soils within permafrost (Boike et al. 1998; Romanovsky and Osterkamp 2000) affect the hydro-thermal regime within rock glaciers (Rist and Phillips (2005) and Rist (2007)). They found that values for hydrological and thermal parameters in the ground, estimates of slope stability and meteorological parameters were closely correlated in time during thawing periods. Instantaneous increase in ground temperature was caused by convective heat transfer and latent heat was released due to phase change of infiltrating meltwater from surficial snow. Downslope displacement begun simultaneously. Their laboratory experiments showed that a slope failure is most likely in summer, when the thawing active layer deepens into finer grained materials, which is saturated, mainly due to heavy rainfall. Snowmelt was found to be less critical, because a large amount of the infiltrating water froze in the active layer, which was still cold, and the surficial deposits were stabilised by the ice. Ice formed during this period determined the water content during active layer thawing, which was found to be important for the disposition of slope failure in summer, as was the three dimensional nature of the active layer in degrading zones of rock glaciers (e.g. in Muragl, CH, after Arenson 2002).

The Furggwanghorn Rock Glacier Test Site

The Turtmann valley is located in the Western Swiss Alps. Numerous rock glaciers are found on its Eastern slope (Figs. 1 and 3a) (e.g. van Tatenhove and Dikau 1990; Nyenhuis 2005; Roer 2005) with the 0 °C isotherm at about 2,550 m.a.s l. Long period observations of air temperature and horizontal movements show clear correlation between air temperature variations and accelerated flow of assorted rock glacier units (e.g. Roer et al. 2005; Kääb et al. 2007). The increased flow rates, most probably combined with thermal degradation, have led to deep crevasses forming in the rock glacier bodies, which may lead to destabilising processes (Fig. 3b, Roer et al. 2008). Investigations are required to locate potential shear surfaces that could lead to formation of a detachment slide, either along the active layer or a deeper shear surface through the crevasses to the base of the rock glacier (Fig. 3d). Significant volumes of degrading frozen debris would be mobilised; either causing collapse (volume loss into existing thermokarst), translational sliding or debris flows, as probably occurred at the Bérard rock glacier.

Preliminary Geophysical Investigations

Several geophysical investigations have been performed to characterise critical subsurface structures, and primarily to locate permafrost, so that boreholes could be positioned and drilling depths decided. Two seismic refraction tomography profiles were acquired in spring 2010 to delineate the bedrock topography of the rock glacier and to map large-scale internal structures. The location of the profiles is shown in Fig. 4.

The active layer and the snow cover can be identified in both profiles by the 3–10 m thick layer with relatively low shear wave velocities between 500 m/s and 1,500 m/s near the surface of the rock glacier. Zones with velocities >4,500 m/s are indicative of bedrock or very large boulders, whereas the permafrost is expected to have velocities around 3,000–4,000 m/s. Zones with degraded permafrost show velocities around 2,000 m/s.

The thickness of the permafrost is less than 5 m with bedrock occurring at a depth of about 10 m in the southern part of profile Q1 (Fig. 5a). The bedrock is not clearly defined in the northern part. A permafrost body might exist and extend to a depth of around 15–20 m.

Profile Q2 in (Fig. 5b) shows a very heterogeneous internal structure of the rock glacier. A bedrock barrier in the centre of the profile seems to divide the rock glacier into two flow branches. High velocity anomalies within the rock glacier may indicate the presence of large boulders. Zones with lower velocities near the southern end of the profile are an indication of beginning of degradation of the permafrost.

In order to obtain more comprehensive subsurface information, additional geophysical measurements (ground-penetrating radar, electrical resistivity tomography, nuclear magnetic resonance) are currently being carried out and interpreted. A three-dimensional subsurface model will be established based on this information, as input to the geotechnical models.

Boreholes, Instrumentation, Meteorological Station

Two major zones of interest had been identified from field observations. Thermal degradation was apparent due to deepening troughs at the rock glacier root, running NNE-SSW (around 622,520 E, 115,830 N). The first drilling campaign was designed to investigate thermal response along a transect. The second area extends from the rooting

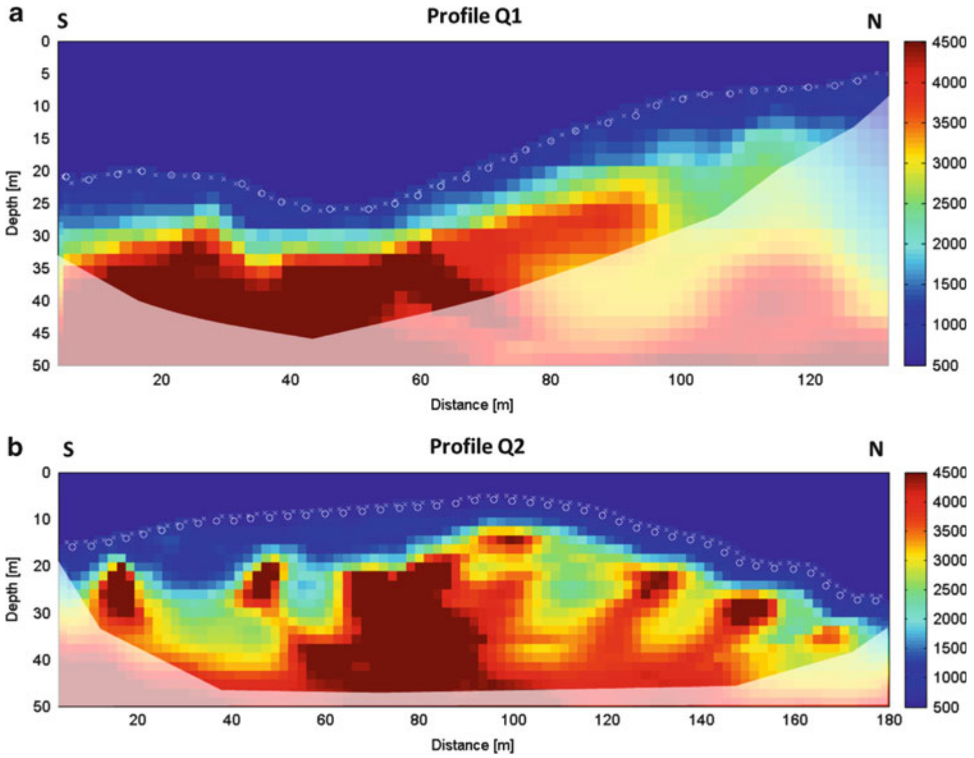


Fig. 5 Seismic sections along (**a**) profile Q1 and (**b**) profile Q2. The locations of the profiles are shown in Fig. 4. Source positions are indicated by *circles*, receiver positions by *crosses*. *Faint areas* are not well resolved by the data

zone to the WWN, where annual surface movements of over 3 m had been observed, and the causes of this high rate of strain were of interest.

Figures 5 and 6a show the position of five boreholes (F1–F5). Based on the data presented in Fig. 5a and b, these were drilled to 25 m depth in summer 2010 to try to locate active layer, permafrost and bedrock. The irregular surface indicates the different flow regimes in the rock glacier.

An inclinometer was manufactured from four chains, each with eight sections of rods of 0.5 m length and with rotary joints at each end, and installed in F5. Orthogonal tiltmeters in the vertical plane measured rotation of each section to determine displacement of the rock glacier with depth (www.terramonitoring.ch).

Monitoring results over the half year (Oct. 2010–Apr. 2011) show that the boreholes F3, F4 and F5 have moved downslope from F1 and F2. A movement of 1.5 m was measured at the surface during this time, accompanied by visible surface deformations. Several cracks were identified between F3 and F5, which may indicate seasonal movements of the active layer (Fig. 6b). Large displacements of the rock glacier, more or less at constant strain rate, were measured by the inclinometer as well, with a concentrated shear zone located between 14 and 15 m depth.

Thermistor chains have been installed in boreholes F1 to F4, with 30 temperature sensors spaced at either 0.5 or 1 m. The temperature distribution in F1 is shown in Fig. 7a for the first 6 months. The cooling effect during winter can be seen 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. 7b). The temperature below 8 m depth remained close to 0 °C in all four boreholes during the measuring period. Measurements on the rock glacier were supplemented by a meteorological station that recorded wind speed and direction, long and shortwave radiation, water equivalent of snow and rain, humidity, air temperature and snow depth (Fig. 8). All data were registered by a logger located next to F5.

The meteorological data presented in Fig. 8 indicate a winter period 2010–2011 with early and continuous snow cover since mid-October, which decays, perhaps exponentially during periods in which mean air temperature exceeds 0 °C. Snow depths have persisted notwithstanding several -multi-day periods during which the air temperature exceeded 0 °C and increased up to just over 1 m on two separate occasions. The apparent loss in snow depth shortly after 10th March reflects anthropogenic effects due to excavation of snow around the meteorological station.

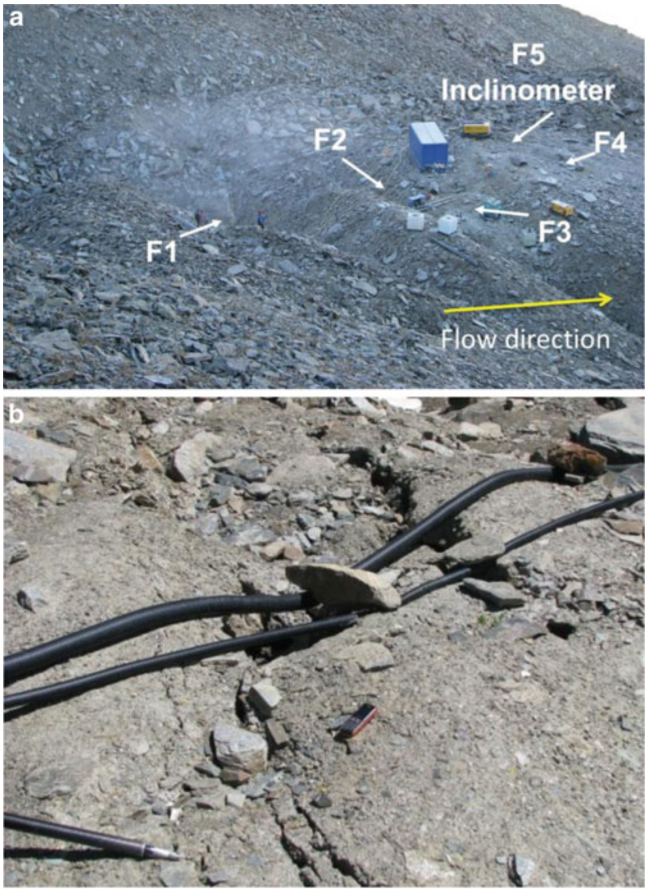


Fig. 6 (**a**) Irregular surface in the area of the field campaign; (**b**) surface tension cracks between boreholes F3 and F5

Future Fieldwork

Since running water has been heard in the snow-filled depression 30 m due south of F1 (Fig. 4), the importance of investigating the hydrology is acknowledged. Measurements will be carried out in the active layer and around the flanks of the rock glacier.

Now that the monitoring is well underway, it should be possible to obtain multi-season data including the key meteorological records combined with spatial and temporal output from temperatures and displacements on the surface, and at depth in the boreholes.

Ongoing geophysical investigations using ground penetrating radar (GPR), electrical resistance tomography and nuclear magnetic resonance form a major part of the characterisation and monitoring threads of this project. GPR was most helpful in locating the next two boreholes to be drilled by a mixture of rotary coring and percussion midway between section Q2 and borehole F4 in August 2011 to 30 m depth. The focus will be to delineate any shear zones that have been implied by the preliminary GPR analyses (Notivol Lazaro, 2011, private communication) as well as determine strain rates with depth.

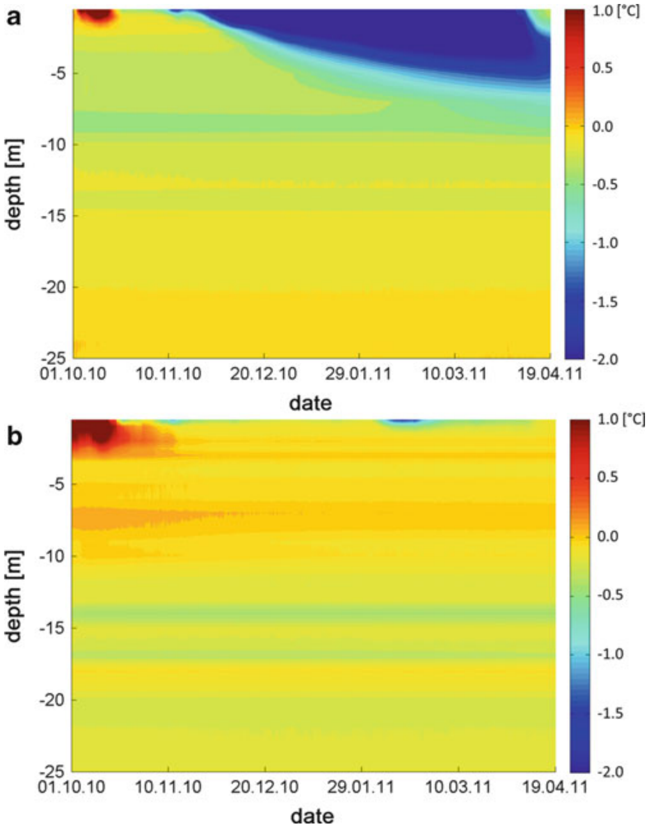


Fig. 7 Temperature distributions from October 2010 to April 2011 in boreholes (**a**) F1 (**b**) F4

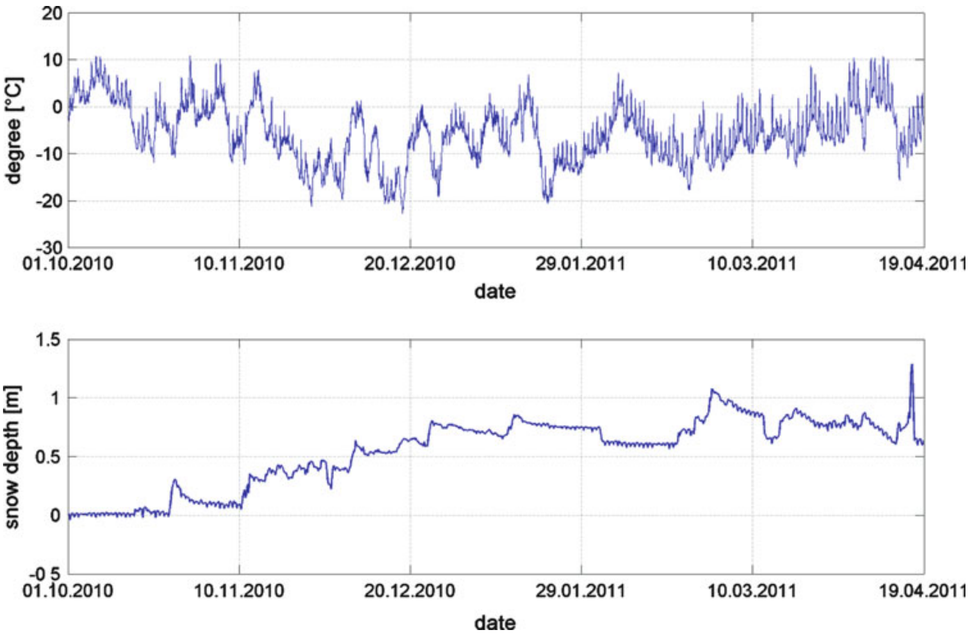
An inclinometer and 30 thermistors will be installed in each borehole after a series of monotonic and constant load (creep) pressuremeter tests have been carried out, similar to those conducted by Arenson et al. (2003). The pressuremeter tests are intended to obtain the local stress–strain response in situ as a function of time, and the limit pressures, for comparison with a study that is currently underway in the laboratory to determine creep and shear strength parameters.

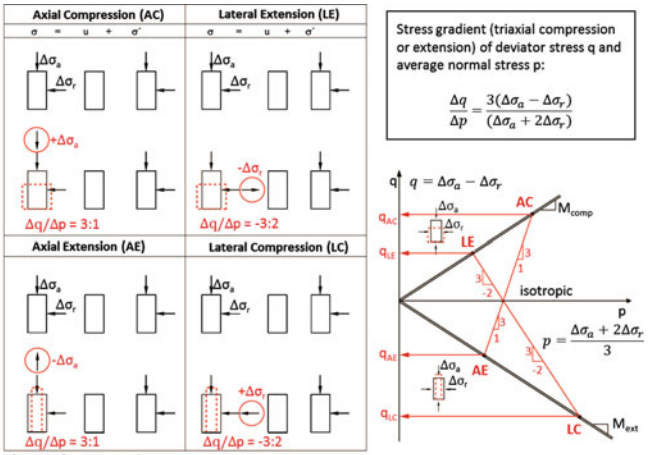
Laboratory Characterisation

Laboratory characterisation is essential to select parameters for thermo-mechanical constitutive models to be used in subsequent numerical modelling. Stress paths experienced by soil elements along the shear planes are entirely different (Fig. 3d) from those in the conventional axial compression, which require investigation to establish whether failure will occur at lower values of deviator stress in radial and axial extension, where $q_{LE} < q_{AC}$ and $q_{AE} < q_{LC}$ (Fig. 9).

Yamamoto and Springman (2011) confirm that this concern should be taken seriously. Artificially frozen soil has

Fig. 8 Meteorological data from the first 6 months of monitoring for air temperature and snow depth





(after Holtz & Kovacs, 1981)

Fig. 9 Stress paths in a triaxial apparatus in deviator (axial – radial total stress, $\sigma_a - \sigma_r$) and mean total ($(\sigma_a + 2\sigma_r)/3$) stress space for axial and lateral loading (compression) and unloading (extension)

been used for constant rate of strain stress path tests to failure to conduct parametric studies at a range of strain rates and temperatures just below 0 °C. Granular ice has been mixed with a representative particle size distribution from the test site according to methods developed by Arenson (2002) to represent a range of rock glacier materials. Total stress paths in deviator q and mean total stress p space (see definition in Fig. 9) have been followed in a triaxial stress path apparatus (Arenson 2002) with accurate temperature control within the sample to ±0.03 °C at different strain rates (Yamamoto and Springman 2011). The results (Fig. 10) confirm that the failure state occurs at lower deviatoric stresses, either for higher axial strain rates or greater volumetric ice contents w_i, and give credence to the concerns expressed above.

The results in axial extension are relevant for the zone under the crevasse and seem to indicate the weakest response of all. This test is the most complicated to carry out in the triaxial stress path apparatus and the results will require further investigation in the near future.

Conclusions and Future Work

The background to instabilities in alpine permafrost has been discussed in respect of past mass movements in the European Alps and future predicted climate change. Mechanisms related to degrading rock glaciers that exhibit severe cause for concern about their ongoing stability through deepening crevasses and thermokarst have been identified and discussed in general terms. The impact of the growth of these crevasses, largely attributed to climate change, on typical stress paths experienced by frozen soil has been recognised as adding a potential threat.

One rock glacier is currently being characterised through geophysical and geotechnical methods and instrumented for monitoring temperature and deformations on the surface and at depth in boreholes. Five boreholes have been drilled so far and are delivering data that shows permafrost exists within the body of this rock glacier, mainly between 0 °C and −0.5 °C. A zone of enhanced shear strain has also been detected at about 15 m depth with surface movements up to 3 m.

Two additional boreholes will be drilled to nearly 30 m in late summer 2011 in a zone along the line of F1 to F4 and halfway between F4 and the profile Q2. Surface movements of several metres a year have been measured to date by annual geodetic surveys. The extension of a preferential

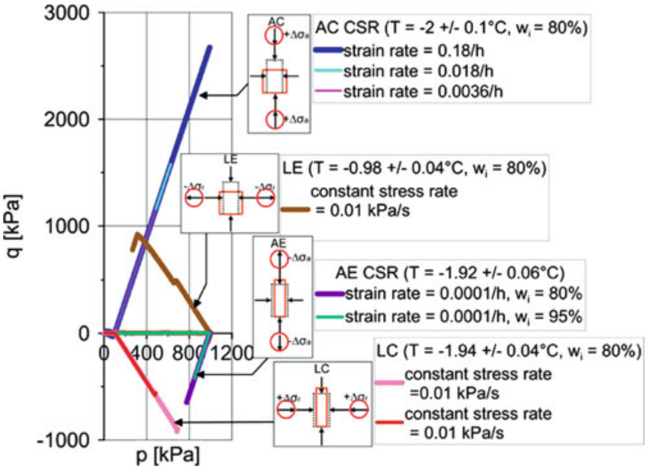


Fig. 10 Total stress paths in deviatoric (q) versus mean (p) stress (After Yamamoto and Springman 2011)

shear zone can then either be confirmed or denied as effort to expose the deformation mechanisms is progressed.

The hydrology is recognised as being significant and studies will be conducted in the active layer as well as for preferential flow on top of the active layer or through unfrozen channels in the rock glacier. Three dimensional Nuclear Magnetic Resonance surveys will be conducted to investigate whether there is any ponding of water near the thermokarst features.

Eventually thermo-hydro-mechanical modelling will be carried out, initially on soil elements loading along stress paths in compression and extension and then on the rock glacier, in order to combine prediction of the pre-failure creep and impending failure.

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