Temperature conditions in two Alpine rock glaciers

D.S. Vonder Mühll
Universities of Basel and Zurich, Switzerland
formerly at: Laboratory for Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Switzerland

L.U. Arenson & S.M. Springman
Institute for Geotechnical Engineering, Swiss Federal Institute of Technology (ETH), Zurich

ABSTRACT: The in-situ thermal regimes at depth within two Alpine rock glaciers, Murtèl-Corvatsch and Muragl, in the upper Engadin, Eastern Swiss Alps, are discussed and compared. Six boreholes were drilled to depths between 51.9m and 72.0m through both rock glaciers in 1999 and 2000. Temperatures were measured within these holes at various depths. The two rock glaciers show quite different stratigraphy and associated thermal characteristics. Intrapermafrost taliks and zones with unfrozen water were encountered during and after the drilling operations at both locations. These are thought to have played a major role in dictating the thermal regime of the rock glaciers.

1 INTRODUCTION

Rock glaciers are particular geomorphic debris-forms in mountain permafrost areas. Only a few scientific boreholes have been drilled through rock glaciers to permit investigation of the thermal characteristics with depth. Besides the complicated logistics, drilling a borehole by combining percussion and coring techniques, at high altitudes with minimal thermal and mechanical disturbances, is very challenging. The material is very heterogeneous, ranging from relatively 'hard' and large rock boulders down to silt size solids or almost 100% 'softer' ice, requiring a range of drill bits. In addition, temperatures are close to the melting point of ice, typically between -2°C and 0°C, and depending on the amount of solid particles, containing substantial amounts of unfrozen water.

One of the longest time series measurements of Alpine permafrost temperatures started when the 58 m deep borehole was drilled through the Murtèl-Corvatsch rock glacier in 1987 (Haeberli et al. 1998). Heat flow was determined in this borehole Murtèl-Corvatsch BH 2/1987 by measuring the thermal conductivity of the frozen cores ($150 mWm^{-2}$). Data from the same site indicates that snow, and in particular the time of the year when the first heavy snow fall arrives, influences the temporal fluctuations markedly. Since 1987, temperatures have ranged from -2.6°C to -1.2°C at 10m depth, and -2.1°C to-1.4°C at 20m, respectively.

Within a joint project of three ETH-Institutes, cored boreholes were drilled in 1999 in the Muragl rock glacier (four boreholes, ca. 70m deep; Musil 2002, Arenson 2002) and again in the Murtèl-Corvatsch rock glacier in 2000 (two boreholes, 52 m and 63 m; Arenson & Springman 2000, Arenson et al. 2002). Until now, very little is known about rock glacier hydrology. During the drilling of the boreholes on Murtèl-Corvatsch, intrapermafrost taliks and zones with unfrozen water were encountered. This paper summarises the main results of the temperature investigations within the boreholes through these rock glaciers.

2 OTHER ROCK GLACIER BOREHOLES

Johnson & Nickling (1979) report details of a 21m borehole drilled in 1969 through the RG II rock glacier in the Kluane Range (Canada), in which temperatures were re-measured ~6 years after drilling. No negative temperatures were registered after 6 years, indicating that the permafrost had melted over a relatively short period (probably supported by water advection).

In Switzerland, a 10m deep drilling with cores at Murtèl-Corvatsch (Barsch 1977) and a 7 m cored drilling at Gruben (Barsch et al. 1979) were performed in the 1970s. Two boreholes were drilled in 1990 (37 m and 65 m deep, at Pontresina-Schafberg) within a snow avalanche structure project (Vonder Mühll & Holub 1992). Temperatures were between 0 and -0.8°C and showed a temporal evolution similar to Murtèl-Corvatsch. Another cored borehole down to 10m depth was drilled in 1995 at Galena Creek, USA (Ackert 1998). No temperature data however has been published for this site.

3 THE BOREHOLE SITES

Both rock glaciers presented herein are situated in the Upper Engadin, Switzerland. They are probably the most intensively investigated rock glaciers in the Alpine region (cf. Barsch 1996). Principal goals of the interdisciplinary ETH-project were initially focused on the Muragl rock glacier and included geotechnical, geophysical and glaciological research and monitoring programmes (Maurer et al. 2003).

3.1 *Murtèl-Corvatsch*

A 58 m deep borehole through the active Murtèl-Corvatsch rock glacier (2670m a.s.l.) created the opportunity in 1987 to investigate the thermal regime in a creeping permafrost body (Haeberli et al. 1988, Wagner 1992, Vonder Mühll 1993). The cores, borehole logging, instrumentation for long-term monitoring (borehole deformation, temperature) and a number of geophysical surveys contributed to a better understanding of the internal structure and ongoing processes. Moreover, the probable evolution and development of an active rock glacier could be reconstructed.

Temperatures were measured using thermistors mounted outside a vertical PVC casing lowered into the rock glacier. Sensors were calibrated to obtain an absolute accuracy of better than ±0.1°C and a relative one of at least ±0.05°C (Vonder Mühll 1992). A logger has stored one value each day since 1993 (Vonder Mühll et al. 1998). A special thermal feature was observed (Vonder Mühll 1992), in which seasonal temperature variations occurred, not only to a depth of roughly 20m, but also within a layer between 51-57m depth. Every year, at about the end of June, the temperatures rise within a few days from -0.05°C to about +0.15°C. Temperatures remain positive until late September and drop within a short period of time towards -0.1°C during winter and spring. The values do not vary greatly above 51m and below 57m, and have been negative since 1987.

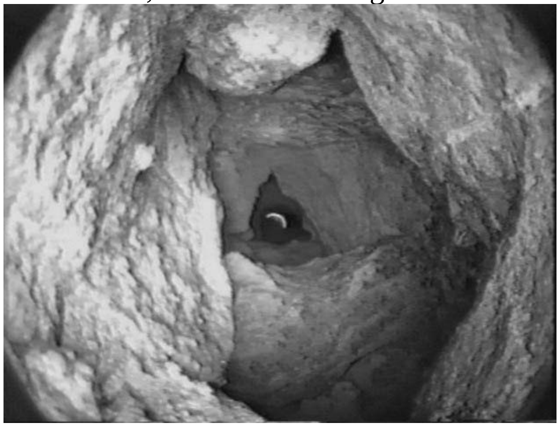

Figure 1. The borehole camera shows large voids in the lower part of the Murtèl-Corvatsch rock glacier, BH 1/2000 (depth: 49 m, nominal diameter 90 mm). Similar structures were observed at corresponding depths in BH 2/1987 & BH 2/2000.

Two additional boreholes were completed in 2000. One of the main aims within this ETH-project was to extract undisturbed cores for geotechnical characterisation. The drill sites were 20m and 35m in flow line direction uphill from BH 2/1987. Having obtained good quality core samples successfully over 30 m, *in-situ* pressuremeter tests were also carried out between 14m and 25m (Arenson et al. 2003). Drilling became technically challenging at depths below about 45 m (Fig. 1, Arenson & Springman 2000, Musil 2002, Maurer et al. 2003).

3.2 *Muragl*

Studies of the Muragl rock glacier in the early 1990’s involved mapping and modelling of permafrost distribution (Haeberli 1992, Hoelzle 1994, Keller 1994), various geophysical soundings (Vonder Mühll 1993) and long-term photogrammetric monitoring (Kääb 1998).

After extensive seismic refraction tomographical and georadar investigations (Musil et al. 1999, Musil 2002), four 70 m deep boreholes were drilled in 1999 between 2500 and 2560m a.s.l.. It was very difficult however to drill undisturbed cores, which could be tested afterwards in a laboratory under triaxial stress conditions. This was due to a combination of effects, including a relatively low ice content, compared to the Murtèl-Corvatsch rock glacier, combined with coarse rock fragments and rock glacier temperatures only a few centigrade below 0°C.

4 THERMAL REGIMES

4.1 *Murtèl-Corvatsch*

Temperature distributions within BH 2/1987 were analysed systematically and are described in Vonder Mühll & Haeberli (1990), Vonder Mühll (1992) and Vonder Mühll et al. (1998). In principle, the thermal regime below the active layer is governed by the two boundary conditions (1) *“temperature at the permafrost table”* (-3°C to -2°C) and (2) *“temperature at 54 m depth”* (which is due to the aquifer at 0°C).

4.1.1 *Borehole BH 1/2000*

A similar temperature field and hydrological state was assumed for BH 1/2000. Difficulty was experienced however when removing the pressuremeter following the test at a depth of about 25m, because water had flowed into the borehole and begun to freeze around the probe. Water flow into the unsupported BH 1/2000 at several levels indicated that the permafrost matrix was highly permeable, most likely with a network of linked channels responding to precipitation and seasonal melting.

A borehole camera was used regularly to inspect progress (Fig. 1). At depths of more than 40m, drilling became more difficult due to blocks and chips of rock rotating with the bit, until the rig stopped.

Initial temperature readings after completion of the drilling, showed very similar results to BH 2/1987 (Fig. 2a). The borehole collapsed at a depth of about 18 m however, and as a TDR cable (Time Domaine Reflectometry) was frozen into BH 1/2000 for deformation monitoring, no additional temperature measurements could be taken.

4.1.2 *Borehole BH 2/2000*

No further *in-situ* testing was carried out in BH 2/2000 during the drilling operation, which took about 10 days. The drilling process became more difficult again at 40m depth, due to loose blocks and lower ice content. A temporary metal casing was installed to avoid borehole instability and the drilling was stopped at 63m depth, without reaching bedrock. Rapid water flow was audible, combined with strong air-flow into the borehole at the surface (Venturi effect). Large voids were also seen below 45m via the borehole camera. The first temperature readings after installation indicated that the permafrost body seemed to be even colder at this site than at the two boreholes further down the slope (Fig. 2a).

A data logger was installed in November 2000 to log temperature data every 6 hours. At that time, temperatures below 25m were almost all isothermal, at 0°C ± 0.2°C and have not changed since (Fig. 2b).

A sudden marked warming took place between 3 and 20m depth on April 25, 2001 (Fig. 3), without affecting the top 3m of the borehole. After about two weeks of rapid warming and exponential cooling, the layer between 3 and 20m depth was isothermal at around 0°C and remained so until the end of October 2001, when cooling processes dominated once more over the same depth range (see temperature versus depth in December 2001 in Fig. 2b). Even though the increase in temperature happened within the reading interval of 6 hours for all depths, the following thermal response indicates that the warming must have happened from the bottom to the top, and cooling from the top to the bottom.

The most likely explanation is that melt-water entered the PVC casing via a leak-hole between 20 and 25m, filling it and then draining away when the hydraulic head of water in the rock glacier at the depth of the leak-hole was lower than that in the casing. As Figure 3 confirms, the warming phenomenon progresses from 20m depth upwards. No warming was encountered in the uppermost 3m, at which depth there is likely to be another leak-hole. These leak-holes are probably caused by differential movement at the shear zone and at the junction of the active layer with the permafrost. A similar, but less pronounced, warming event took place on April 2, after which the temperatures re-equilibrated to previous values. All cases of rapid warming follow a period of drill site air temperatures, which were sustained above zero for longer than a day. It can be seen that the periods of heavy 'rainfall' between March and May arrived in conjunction with subzero

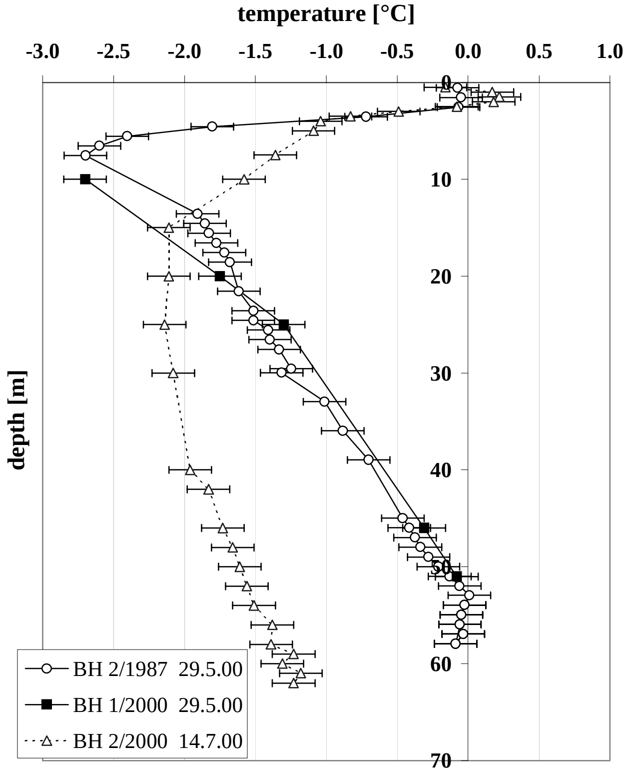

Figure 2a. Temperature versus depth for the three boreholes in the Murtèl-Corvatsch rock glacier in early summer 2000. The horizontal distance between BH 2/1987 and BH 1/2000 is ~20 m, with ~15 m between BH 1/2000 and BH 2/2000.

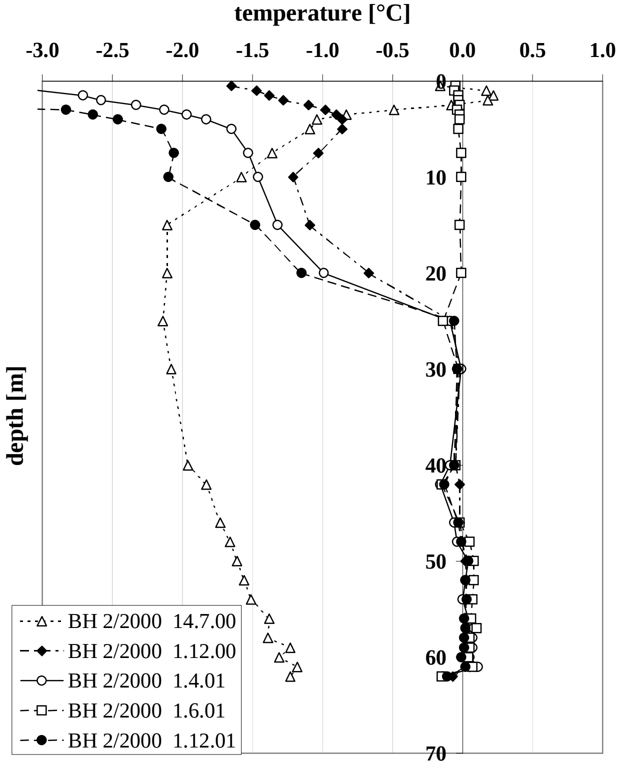

Figure 2b. Temperature versus depth for BH 2/2000 (Murtèl-Corvatsch). N.B., after summer 2000, temperatures below 25 m depth remained at ~0°C. Above, temperatures warmed up to around 0°C for about half a year (April to October 2001)

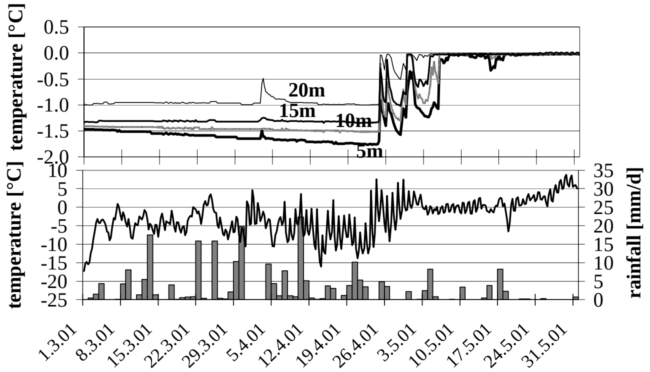

Figure 3. Temperature versus time for various depths in BH 2/2000, together with air temperature and rainfall measured at the weather station on the rock glacier.

temperatures. Perhaps some of this precipitated as snow. In any case, it was adjudged not to have correlated with the temperature response within the casing.

Below 25m depth, the borehole data can be separated into several ranges over April to July 2001, some of which are interconnected (Fig. 4):

1 The temperature remains constant at 30m during 2001, indicating that the casing probably remains full of water below the leak-hole at ~25m.
2 Temperatures between 57 and 60m show a similar pattern to those at 44m: a warmer peak during ~10 days at the end of May, followed by a gentle cooling and again a warming period starting at the end of June (59m and 44m in Fig. 4).
3 In-between, i.e. from 48 to 52m depth (52m in Fig. 4), a slight warming commences when the first peak of the layers above (44m) and below (57 to 60m) ends (end of May).
4 At 42m and 62m, a temperature increase is observed from 10th June, before most of the layers (except at 30m and 62m) warm up rapidly at the end of June.

Otherwise, the temperature at 62m is negative all year, with an increase of ~0.1°C in mid-June.

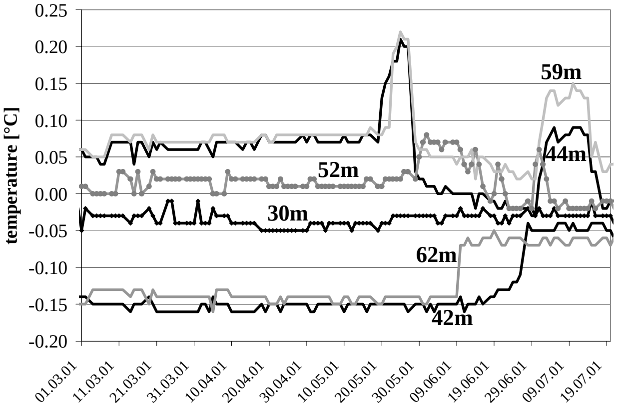

Figure 4. Temperature versus time at various depths below 30 m (Murtèl-Corvatsch BH 2/2000).

4.2 *Muragl*

Three of the four boreholes through the Muragl rock glacier show an almost identical thermal regime. The boreholes BH 2/1999 (2538 m a.s.l.), BH 4/1999 (2549 m a.s.l.) and BH 3/1999 (2558 m a.s.l.) are located more or less in a straight line. Ice particles in the cores were encountered to a depth of roughly 18m. The drilling crew reported a marked escape of air through the formation at about 25m depth. Bedrock was encountered between 30 and 38m.

Borehole BH 1/1999 (2536 m a.s.l.) is located near the edge but inside the geomorphologic boundary of the rock glacier. According to the results of the pre-investigation, low seismic velocities indicated that no permafrost could be expected to be present at this site. The borehole-to-borehole geophysics was aimed however at investigating the transition across the permafrost boundary. Bedrock was reached at only 50m depth. Stable post-drilling borehole temperatures were measured above 0°C at all depths. A water table was established later at about 16m depth. Negative temperatures were only measured near the surface in winter, due to seasonal temperature variations.

Below the active layer, which is about 3m thick, the permafrost body, i.e. the layer of perennially negative temperatures, extended to 18-20m in BH 2/1999 to 4/1999 (Fig. 5). Temperatures are only slightly below 0°C (coldest at 10m depth, BH 4/1999: 0.5°C). Extrapolation of the temperature gradient between 30m and 60m depth to the surface shows a slightly negative mean surface temperature (-0.3°C to 0.0°C).

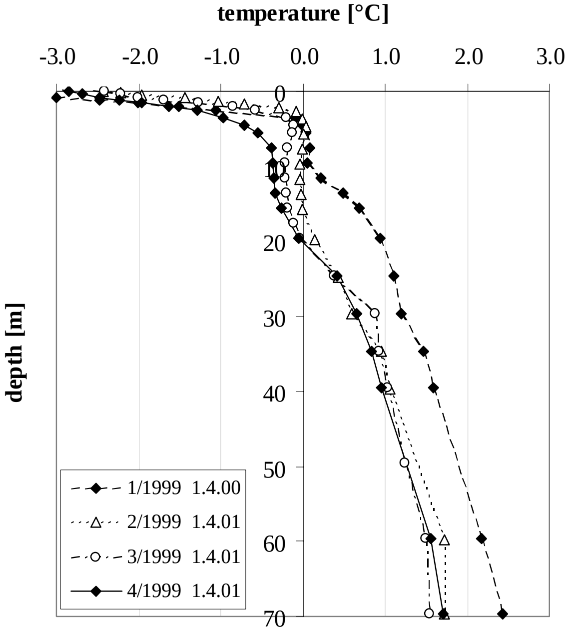

Figure 5. Temperature versus depth of the four boreholes through the Muragl rock glacier in April 2001 (BH 1/1999: April 2000). N.B. BH1/1999 shows only seasonally negative temperatures. Permafrost thickness is less than 20 m at the other three boreholes.

Within the permafrost body, the thermal regime is likely to be controlled by diffusive (conduction) processes and is characterised by logarithmic amplitude decrease, linear phase lag and a reduction of high-frequency components with increasing depth. A special feature is observed in all three permafrost boreholes of the Muragl rock glacier below the permafrost base (Fig. 6). While the temperature remained stable at 20m (-0.03°C) and at 30m (+0.80°C), a considerable variation with an amplitude of about 0.2°C occurs at 25m during the summer season, which was also observed for the temperatures at 2m depth and within the logger station at about 2m above the surface.

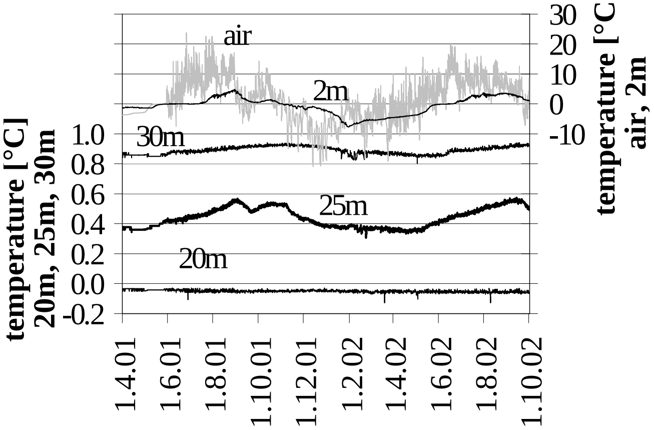

Figure 6. Temperature versus time at various depths for the Muragl rock glacier BH 3/1999. Similarly to BH 2/1999 and BH 4/1999, the sensor at 25 m depth is obviously connected to the atmosphere, while the others at 20 and 30 m are not.

5 DISCUSSION

The thermal regime of the two rock glaciers described is, in general, typical permafrost with a negative mean surface temperature, an active layer thawing in summer, a permafrost body within which thermal diffusion is dominant and an unfrozen layer below, with temperatures close to 0°C. Marked temperature irregularities are observed for both sites however, which can only be explained by advection processes. Water and circulating air both seem to play important roles as transport media.

5.1 *Murtèl-Corvatsch*

The temporally isothermal regime between 3m and 25m depth from end of April until late October is unexpected. The fast impact (within less than the sampling interval of 6 hours) and the large amplitude of the temperature change imply that this event is caused by heat advection via a liquid. The degree of cooling in the autumn does not point to significant unfrozen water content (indicated by a long lasting zero curtain at each depth) however.

Ground penetrating radar investigations (GPR; Lehmann et al. 1998, Vonder Mühll et al. 2000) predict the shear horizon at 22m within BH 2/2000. Below this depth boulders with interstitial ice prevail, above the shear horizon, the rock glacier consists of almost pure ice besides the surface boulder layer. This layer has obviously been warmed by water and has not frozen since. It must also be assumed that the shear zone marks a preferential water flow channel within the rock glacier, since the depth corresponds perfectly with the water inflow observed in BH 2/2000 in April 2000. Hence, the reflectors determined by GPR investigations as the shear horizon and “bedrock”, are also layers containing a considerable amount of free water. Indeed, based on data from BH 1 and 2/2000 and the tendency of GPR investigations to locate hydraulic channels, it is questionable whether bedrock really was found at ca. 60 m in BH1/1987. The temperature sensors installed were more effective at monitoring hydrological conditions and locating the shear zones.

The presence of an active talik, which was encountered previously in BH 2/1987, is confirmed by data from BH 1 and 2/2000. Despite similar behaviour at particular depths, the activity varies fundamentally. In May, the layers at 44m and roughly 58m depth are thermally connected, but de-coupled from the layer in-between. There is currently no appropriate explanation for this. Amplitude and phase lag of the changes hint at a mixture of air and water as the transport medium.

5.2 *Muragl*

Temperatures in Muragl rock glacier are much warmer than at the Murtèl-Corvatsch site. The thermal regime at Muragl is mainly governed by heat conduction within the permafrost. Similar to the second site however, there is an unsaturated layer below the permafrost body, where temperature measurements hint at advection heat transfer processes, which will accelerate basal melting of the frozen body.

There seems to be a ventricular link between about 25m depth and the atmosphere. The drilling crew observed a significant loss of air pressure in that layer. The water table in the borehole was well below this horizon (at about 35 m depth). As a result, and because the amplitude of the temperature change varies only gradually with time, the transport medium must be air rather than water.

6 CONCLUSIONS

Temperatures inside a rock glacier may be governed by the two boundary conditions “*mean annual surface temperature*” and “*permafrost base*” and mainly by heat conduction processes (e.g. Murtèl-Corvatsch BH 2/1987). There are large lateral variations of the ground thermal regime however. This is partly because the surface often consists of boulders, cobbles and gravel of various sizes. The energy balance is quite different under these rough surface conditions to what is expected on a smooth, bedrock or alpine vegetated surface. A rock glacier generates cool surface conditions by creeping down-valley.

In some cases, the definition of "permafrost base" is not easy. The lower part of the Murtèl-Corvatsch rock glacier consists of an aquifer, which shows extensive seasonal temperature variations. Below about 20m depth on the Muragl rock glacier, temperatures are now above 0°C throughout the year. The stratigraphy at this depth is very porous and air was lost during drilling, allowing water to drain easily within this layer. Both cases indicate that strong lateral energy fluxes are present at the "permafrost depth", influencing the future development (i.e. melting) of the frozen body.

Until recently, rock glaciers were assumed to be hydraulically impermeable, constant volume, creeping permafrost bodies. Although there are only a very limited number of rock glacier boreholes with time series of temperature data, these results convincingly demonstrate that heat transfer through advection plays an important role. Even if rock glacier hydrology is far from being fully understood and many questions remain to be addressed, it is known that significant permafrost bodies can melt within a few years (RG II Kluane Range: Johnson & Nickling 1979, Muragl and Murtèl-Corvatsch: this paper). This cannot be explained by heat conduction alone.

Rock glacier hydrology therefore will continue to be an area for fruitful research in the future, particularly in relation to the influence of free ground water on their stability.

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