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Sub-surface Heterogeneities in the Murtèl – Corvatsch Rock Glacier, Switzerland

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ABSTRACT

Several long-term deep ground temperature data and surface electrical resistivity tomography (ERT) results are available for the Murtèl–Corvatsch rock glacier, located in the Swiss Alps. Even though the boreholes are in close proximity, the temperature profiles show significant differences. One displays expected temperatures and gradients, whereas the second shows isothermal conditions with depth for most of the summer months. Recent ERT surveys indicate significant subsurface heterogeneities in the same area of the rock glacier. These results suggest that taliks with intra-permafrost groundwater flow exist in this lower part of the rock glacier and that these affect rock glacier temperatures.

RÉSUMÉ

Plusieurs températures du sol et résultats tomographie de la résistivité électrique (ERT) existe pour le glacier rocheux Murtèl–Corvatsch, situé dans les Alpes Suisses. Même si les forages sont à proximité, les profils de température exhibent des différences significatives. Une indique des températures et des gradients normaux, alors que le second montre les conditions isothermales en profondeur pour la plupart des mois d'été. Des investigations ERT récentes indiquent hétérogénéités souterraines importantes dans la même région du glacier rocheux. Ces résultats suggèrent que des taliks avec écoulement d'eaux souterraines intra-pergélisol existent dans cette partie du glacier rocheux qui influence les températures de glacier rocheux.

1 INTRODUCTION

Rock glaciers are often located at or below the general lower elevation boundary of permafrost. At these elevations, warm permafrost temperatures are typical, i.e. temperatures warmer than -1^{o}C are often recorded. In addition, ground ice may only be present because of latent heat stored in the ground ice. Permafrost would not naturally form at these lower elevations. Under such warm ground conditions, local thermal and internal material heterogeneities can result in small taliks or allow the formation of unfrozen intra-permafrost channels. Such channels cause additional thermal disturbances due to localised water flow, resulting in more thermal anomalies. The frontal area of a rock glacier that is generally located in area with the warmest air temperature conditions. These sections are most susceptible to thermal anomalies, hence the most affected by these processes. Unfrozen channels and sections will most likely exist in these low elevation zones of active rock glaciers. However, it is challenging to document these processes in the field due to limited resources available for site investigations, in particular creating expensive deep, instrumented boreholes, and the low rates of thermal processes involved. Long-term (> 10 year) monitoring programmes are required to differentiate short-term (seasonal and year to year) changes from general trends.

Several field investigations were carried out on the Murtèl-Corvatsch rock glacier in Switzerland over the last decades. In combination with more recent geophysical surveys, long-term monitoring data provide valuable insights into the internal structure of this rock glacier. This paper presents some of these data and offers a hypothesis on possible heterogeneities within the Murtèl-Corvatsch rock glacier and how internal water flow may be affected by this.

2 THE MURTÈL-CORVATSCH ROCK GLACIER

The Murtèl-Corvatsch rock glacier, which is located in the Engadine, Eastern Switzerland (Figure 1), is probably the most investigated rock glacier within the Alpine permafrost environment. This rock glacier has attracted researchers for many decades due to its easy accessibility and its distinct, classical rock glacier appearance. Long-term velocity measurements, using aerial photographs dating as far back as 1932, have been published by Barsch and Hell (1975). More recently, surface deformation measurements (e.g. Kääb et al., 2003) and ground temperature monitoring have been conducted (e.g. Vonder Mühll et al., 2003; Hoelzle and Gruber, 2008). Extensive geophysical investigations have also been performed on the Murtèl-Corvatsch rock glacier using various technologies as far back as the early 1970’s (e.g.

Barsch, 1973; Fisch et al., 1977; Vonder Mühll, 1993; Lehmann and Green, 2000; Hauck, 2001; Maurer and Hauck, 2007; Hilbich et al., 2009). The geophysical techniques include various seismic, geoelectric/resistivity, EM induction and georadar measurements.

In addition to these different surface investigations and measurements, a total of five boreholes were drilled over the years, with thermistor strings and slope inclinometer installed within them. These monitoring instruments provided unique information on ground temperatures and internal deformations. A 58 m deep borehole was drilled in 1987 through the permafrost base. In addition to the ground temperatures, internal deformations were recorded from 1987 to 1995 (Wagner, 1992; Arenson et al., 2002; Figure 2). Cores were sampled, tested and analyzed from this borehole. Two additional boreholes were drilled in 2000 in close proximity to borehole 2/1987 (19 m and 32 m, respectively) to depths of 51 and 63 metres, respectively (e.g. Vonder Mühll et al., 2003). Cores were sampled and ground temperatures monitored using a thermistor string in borehole 2/2000. Additional details and discussions on the ground temperatures are presented in Section 3.

The major findings from these various studies between 1987 and 2009 can be summarized as:

- Mean annual air temperature: -1.76°C (1988 – 2006)
- Average snow height: 0.41 m (1988 – 2006)
- Mean annual precipitation: 2000 mm (1988 – 2006)
- Mean temperature at permafrost table: -2.0^{o}C (1988 – 2006)
- Permafrost thickness: 52 m, potential talik below
- Maximum active layer thickness: 3.5 m
- Shear surface at a depth of 28.4 – 31.4 m (1988 – 1995)
- Deformation rate in shear zone: 4.0 cm/year (1988 – 1995)
- ~60% of total deformation in shear zone
- Temperature in shear zone: -1.15^{o}C
- Ice-rich condition above shear zone (volumetric ice content: >80%) and low ice contents (<30%) at greater depths

Water inflows were encountered within the permafrost body during the drilling operations at various depths in the year 2000 (borehole 2/2000): approximately at 5 m, 30 m, and 43 m. As expected, water was found near the permafrost table, indicating that melt-water is flowing on top of the permafrost table, i.e. the bottom of the active layer. The deep sources within the permafrost body are thought to be associated with taliks and internal unfrozen flow channels.

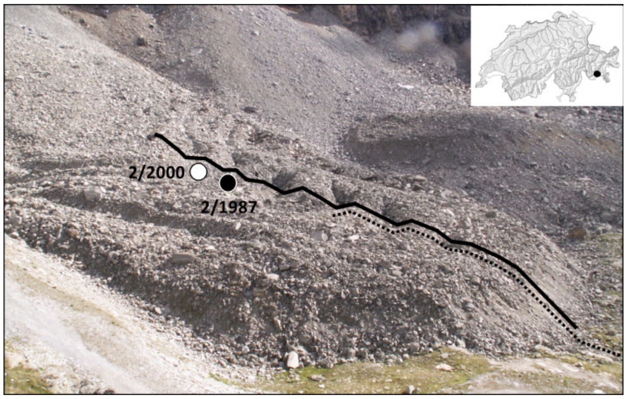

Figure 1. Photograph of Murtèl-Corvatsch rock glacier with position of Borehole 2/1987 (black dot), Borehole 2/2000 (white dot) the electrical resistivity tomography (ERT) monitoring line (bold) and the ERT line of 1998 (dashed) (Hilbich et al., 2009).

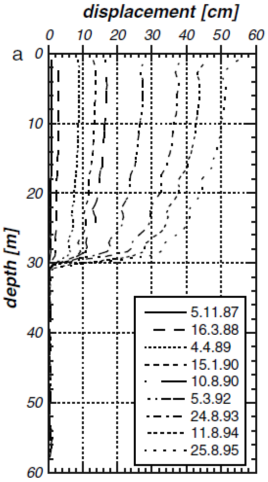

Figure 2. Horizontal down-slope borehole deformation at Murtèl-Corvatsch Borehole 2/1987: 1987–1995 (Wagner 1992; Arenson et al., 2002).

3 GROUND TEMPERATURE REGIMES

3.1 Air temperatures and Snow Cover

Hoelzle and Gruber (2008) report mean monthly air temperature data and snow heights measured at the location of borehole 2/1987 from 1988 to 2006. A summary is presented in Figure 3.

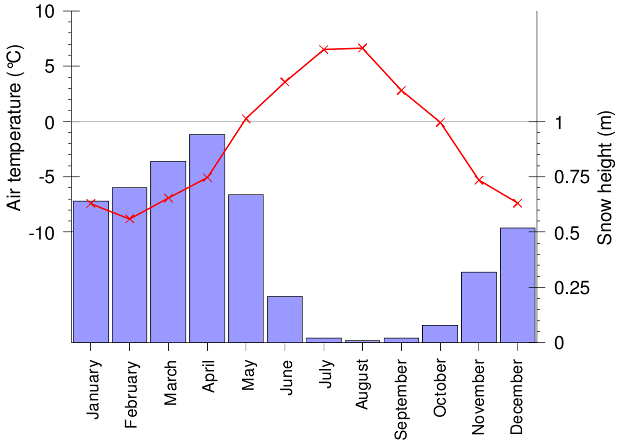

Figure 3. Mean monthly air temperatures and snow height measured on Murtèl-Corvatsch rock glacier borehole 2/1987 (after Hoelzle and Gruber, 2008).

3.2 Borehole 2/1987

The first deep borehole drilled in an Alpine rock glacier was drilled to a depth of 62 m and 46 thermistors were installed at depths between 0.6 and 58.0 m below ground surface. Ground temperature data are available for this borehole since 1987 (Vonder Mühll et al., 1998; PERMOS, 2009). The maximum active layer thicknesses have been fairly constant between 3.4 and 3.5 m. A long term warming of about 2.1°C/100 years is recorded at a depth of 11.5 m. However, there is a significant multi-year variability. From 1987 to 1994, for example, the ground warmed at a rate of about 1.4°C/decade, but the mean ground temperatures dropped in the two following years again by nearly 1°C. A typical temperature profile is shown in Figure 4. The depth of the zero degree amplitude is about 22 m where the temperature is approximately -1.3°C.

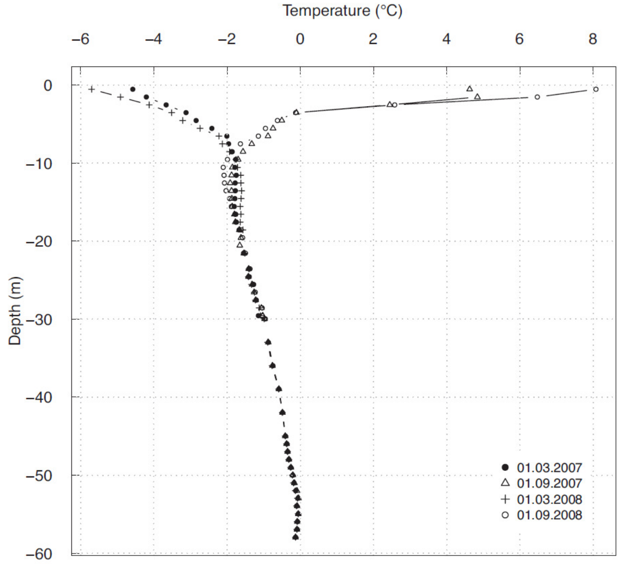

Figure 4. Ground temperatures in borehole 2/1987 for the years 2007 to 2008 (PERMOS, in press).

3.3 Borehole 2/2000

Borehole 2/2000 is located 32 m from borehole 2/1987. Ground temperature data are available since 2000. A contour plot of these ground temperatures is presented in Figure 5 and time series for selected depths are shown in Figure 6. Air temperatures recorded at a climate station near borehole 2/1987 are also presented in both figures. Finally, Figure 7 presents temperature profiles for the year 2009 as well as one year extracts for selected depths. The unexpected ground thermal response reported by Vonder Mühll et al. (2003), which was based on two years of data, continued. They noted the surprisingly rapid increase in temperature from sub-zero values to zero degrees. From the end of April until late October, the temperatures between a depth of 3 m and 25 m stayed constant. This behaviour was thought to be related to advective heat transfer with ground water, but was initially attributed to drilling disturbance when it was expected that these thermal disturbances would cease with time and the ground temperatures would become similar to those recorded in the nearby borehole 2/1987. However, the behaviour continued and does seem to change only marginally with time. Some long-term trends, such as slight cooling (40 m) or warming (57 m), can be observed at most depths, but are not discussed in this paper. The ground stayed below zero degrees at a depth of 5 m during summer for the first time in 2008, however, the temperatures at 15 m depth still reach zero degrees during summer. The winter temperatures show a warming trend over the last 5 years.

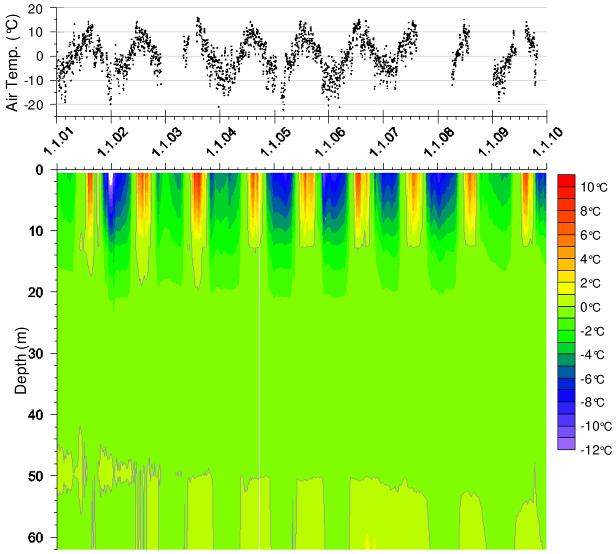

Figure 5. Air temperatures and borehole 2/2000 ground temperatures 2001 – 2009. Note that the zero degree isoline cannot be used to track the active layer depth, because warm conditions near 0°C were observed in the top 15 m for most summers.

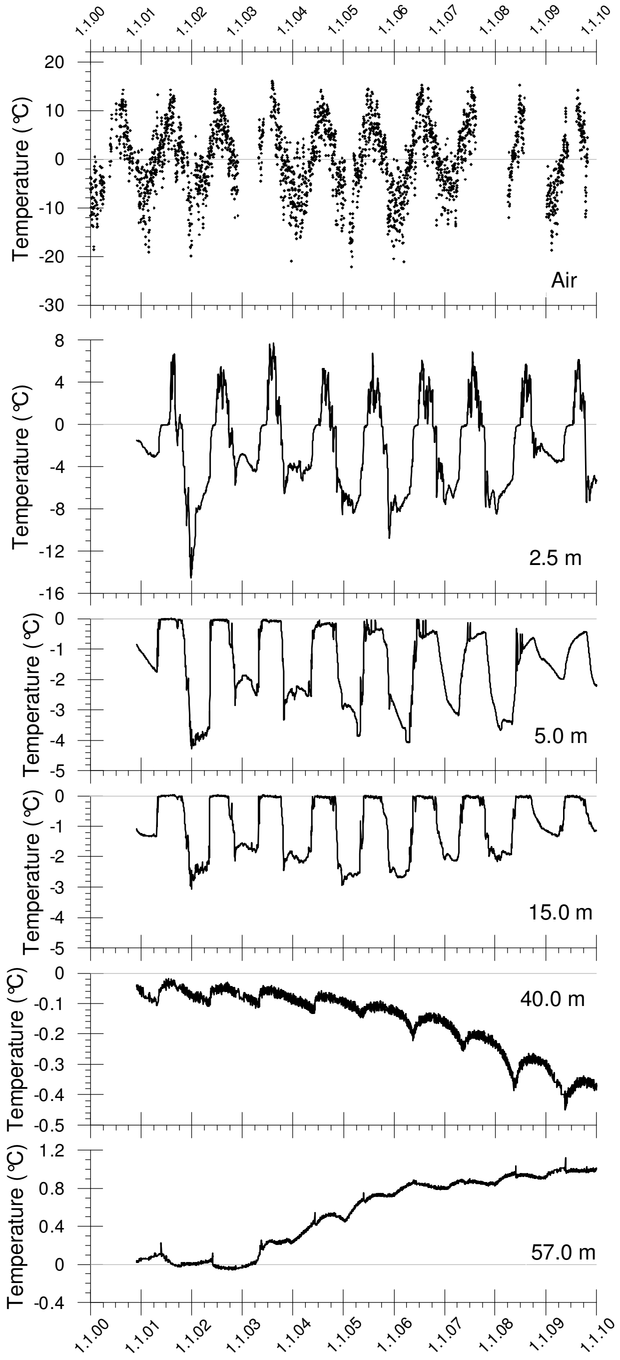

Figure 6. Ground temperature trends for selected depths in borehole 2/2000.

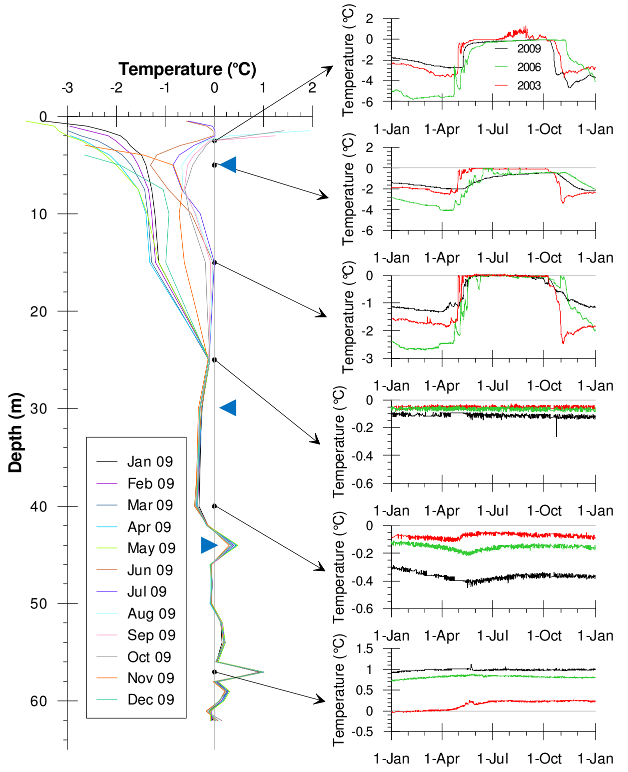

Figure 7. Selected ground temperature profiles for 2009 and one year trends. ◄ mark depths of observed water inflow during drilling.

Analysis of these temperature data presented herein are reduced to the minimum required within the context of this paper, which is the cross comparison with ERT data. Detailed analysis of the ten year ground temperature data will be presented in a special publication.

4 ELECTRICAL RESISTIVITY

Monitoring of the 2-dimensional electrical resistivity distribution along so-called electrical resistivity tomography (ERT) profiles can be considered to be a standard method in permafrost research, since the method is especially sensitive to the phase change between the frozen and unfrozen phase of the pore water (Hauck and Kneisel, 2008). Regular ERT monitoring at the Murtèl Corvatsch rock glacier started officially in 2005 (Hilbich et al., 2008) even though first measurements were conducted in 1998 (Hauck and Vonder Mühll, 2003). At least one measurement is made each August/September for long-term inter-annual comparisons within the Swiss permafrost network PERMOS (PERMOS, 2009).

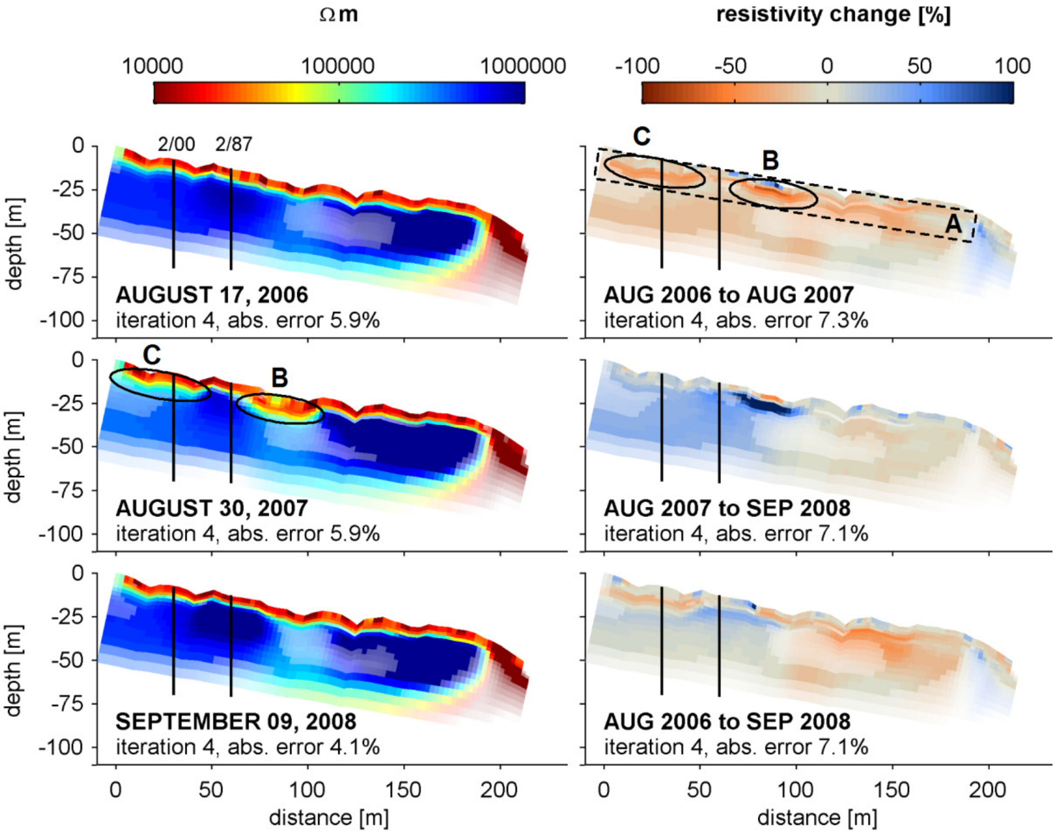

Figure 8. (left) ERT inversion models with intensity of colours scaled by the DOI index and (right) time-lapse tomograms scaled by $DOI_{max} > 0.2$ for the Murtèl-Corvatsch rock glacier data sets (modified after Hilbich et al., 2009). The pale colours are associated with unreliable inversion results. Highlighted zones A, B and C are described in the text. The locations of boreholes 2/1987 and 2/2000 are shown as vertical lines on the right and left respectively.

Figure 8 (left panels) shows resistivity tomograms for measurements at roughly the same time at the end of summer in 2006, 2007 and 2008 (taken from Hilbich et al. 2009). The overall resistivity distribution is similar in all cases: resistivity values of around 20 kΩm in the uppermost 3-5 m delineate the unfrozen and blocky active layer, values above 200 kΩm indicate the massive ice core of the rock glacier and values below 10 kΩm hint at the unfrozen area at the rock glacier front.

Hilbich et al. (2009) emphasised the need for analysing the reliability of ERT inversion data from coarse blocky and ice-rich permafrost sites due to the strong resistivity contrasts and high contact resistances. Potential inversion artefacts have to be separated from true subsurface changes to assess temporal resistivity changes, e.g. by using the so-called depth-of-investigation (DOI) method. Unreliable model regions are marked in Figure 8 with pale colours.

Since air and ice are both electrical isolators, the presence of unfrozen and electrically conductive water causes decreasing resistivities and should be visible, both, as spatial anomalies and as temporal changes between different measurements. Regions with decreased resistivity values can be found at the upper boundary of the tomogram (active layer), as well as near horizontal distance 100 (region B). Borehole 2/1987 is located in a region with especially high resistivity values (Figure 8). Note, however, that the less resistive anomalies within the ice core are within the less reliable model regions, making a careful interpretation necessary.

The right panels of Figure 8 show the inter-annual changes in electric resistivity for the three years. Now, regions with potential thawing processes are more easily visible through decreasing resistivity values (red colours). Hereby, changes are most pronounced in the uppermost part of the ice core, between 5-15 m (labelled A in Figure 8), indicating an increased unfrozen water content at the end of summer 2007 and 2008 compared to 2006, as well as a locally increased active layer depth in 2007 near horizontal distance 100 (labelled B). Similarly, in the upslope part of the profile, a zone with decreased resistivity is observed (labelled C), which also indicates a locally increased unfrozen water content and which is probably related to the warm and isothermal part of borehole 2/2000 during the summer months, as shown in Figure 7. Note again, that borehole 2/1987 is located within a stable area with almost no resistivity decrease and comparatively low temperatures.

The anomaly in region B was in interpreted in Hilbich et al. (2009) as a zone with locally increased active layer depth, whereas region A was attributed to an increased water content in the still frozen ice core, both as a consequence of the warm winter 2006/2007. Accordingly, also in zone C the resistivity increase indicates higher unfrozen water contents in the ice compared to the location of borehole 2/1987. Thus, ERT data confirm the presence of an anomalous zone within the Murtèl-Corvatsch rock glacier, which is in accordance with borehole temperatures.

5 DISCUSSION

Long-term ground temperature data and ERT surveys carried out during three years indicated ground surface heterogeneities in the lower part of the Murtèl-Corvatsch rock glacier in Switzerland. The location of the resistivity anomalies corresponds well with the observed ground temperatures, i.e. with the stable conditions at borehole 2/1987 compared to the irregularities in borehole 2/2000, which are most likely to be related to intra-permafrost flow channels. In combination with borehole temperature results the lower resistivity values may be an indicator of well drained zones of higher permeability. During the summer months, water can flow through these channels. Three channels may have been reached in borehole 2/2000 at depths of approximately 25 m, 45 m and 57 m. It is believed that these channels are not connected and also show different flow response. However it has to be noted that according to Hilbich et al. (2009), the reliability of ERT data is very limited at depths > 10-15m. Information from deeper parts of the ERT tomograms should therefore be treated with great care.

Pressurized conditions may exist in the 25 m channel, which is thought to be fed by melt water. The water seems to remain at a constant temperature of zero degrees. During spring, it enters the borehole through this channel and rises. In 2009, for example, the pressure was lower than during previous years and it did not reach the 5 m level. Further, field observation showed significant water flow on top of the permafrost table about 10 – 20 m above borehole 2/2000 in summer 2009. However, at the location of the borehole, the water was no longer observed. This may be an indicator for such channels where surface runoff suddenly flows into the rock glacier. On the other hand, it may be possible that the ground starts to refreeze from the top, i.e. the cavity caused by the drilling slowly closes with time. The channel starts to empty as no more melt-water is available and the empty space cools down to sub-zero temperatures. The cooling rates (Figure 7) indicate that not only thermal conduction but natural convection must occur. Cold air can penetrate through the porous layer and cause the ground to cool during winter.

The channel observed at 45 m depth is likely to be a talik with evidence of constant ground water flow. In contrast to the shallow heterogeneity, the ERT survey cannot identify this layer because of insufficient sensitivity at that depth. These temperatures do not show seasonal variations and have stayed constant over the years. This indicates that the source of this water is different from the previous channel and is most likely to be connected to a deeper aquifer.

The third thermal anomaly observed forms the permafrost base. Similar to the data from 45 m, seasonal variations are small, but a long-term trend can be observed. Until 2003, the temperatures stayed constant at zero degrees, but have since increased to 1°C. This is an indicator for permafrost degradation at the rock glacier base due to constant ground water flow. This base talik was also observed in borehole 2/1987 and is described in more detail in Vonder Mühll et al. (1998).

These findings suggest that intra-permafrost channels and taliks exist in frontal parts of active rock glaciers. Such channels can accommodate seasonal flow of melt-water or continuous ground water flow. The channels may further allow for cold air to penetrate deeper into the rock glacier due to natural convection. However, such flow channels form thermal disturbances and alter the one-dimensional theoretical thermal profile that would form if the ground is only affected by air temperature and a deep geothermal gradient. Such locally confined melting processes can lead to enhanced permafrost degradation from within the rock glacier, which may be more susceptible to changing incoming radiation and air temperatures than previously assumed. Ultimately this may result in sinkholes and Sackungen that could be misinterpreted as tension cracks at the surface (e.g. Roer et al., 2008). However, the authors are not aware of any direct observations in connection with the Murtèl-Corvatsch rock glacier.

6 CONCLUSIONS

Several ground surface anomalies could be identified in the frontal region of the Murtèl-Corvatsch rock glacier in Switzerland, based on long-term ground temperature monitoring and electrical resistivity surveys. Two different channel types may exist in the permafrost body that affect the ground thermal regime: i) melt water run-off channels, and ii) constant ground water flow channels.

The first type is characterised by seasonal flow variations. The temperatures stay constant at 0°C during summer, whereas natural convection may occur in winter, cooling the ground. These channels therefore do not form taliks, because they are colder than zero degrees during winter. On the other hand, non-cryotic ground may exist at greater depths, where a constant ground water flow is assumed. These channels may be relatively thin, but have potential to cause a significant thermal disturbance. Some channels may refreeze and the water flow can change from year to year. It is further believed that the base of the Murtèl-Corvatsch rock glacier is controlled by a talik that slowly degrades the permafrost at the base, thinning the permafrost body from below.

The geophysical surveys identified these anomalies, in particular the shallow ones, and also expose some aspects of the dynamics. The thermal and structural anomalies discovered in the lower part of Murtèl-Corvatsch rock glacier may be typical for active rock glaciers that are located at the lower elevation boundary of permafrost. However, no data are currently available that would support these findings. Nevertheless, it is an indicator that three dimensional effects play a significant role in ongoing degradation of rock glaciers. Ground temperatures are not only influenced by surface climate conditions, but also by intra-permafrost water flow that may cause internal permafrost degradation. This may be responsible for sudden rock glacier deformations and potential Sackungen. However, such processes need further evidence, in particular of the role of potential groundwater flow through these intra-permafrost channels. This study further confirmed the importance of long-term monitoring stations. Without these, such observations would not be possible.

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