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Current changes in mountain permafrost based on observations in the Swiss Alps

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1 Introduction

In the Alps, higher air temperatures, and increasingly intense precipitation and greater extremes in general are being observed (Scherrer et al. 2016). In general, cold regions located at high latitudes and high elevations are showing the highest warming rates (Noetzli et al. 2019). Recently published climate scenarios for Switzerland indicate that air temperatures will continue to rise (CH2018 2018) and that heavy precipitation will intensify in future (Rajczak, Pall and Schär 2013). Climate-driven changes are registered in mountain permafrost substrates and are the focus of long-term permafrost monitoring in the Swiss Alps (PERMOS 2019). They include rising ground temperatures (Biskaborn et al. 2019), varying ice- and water contents (Mollaret et al. 2019) and accelerating slope deformation (PERMOS 2019). Due to their thermal origin and their subsurface nature, changes are often poorly visible, but can be quantified on the basis of borehole temperatures, geophysical investigations and geodetical slope deformation monitoring (PERMOS 2019).

Depending on the site characteristics, ice content and topographical location (Noetzli and Gruber 2009), permafrost reacts to atmospheric changes at varying rates and with different consequences. To discuss changes in mountain permafrost, two main types of mountain permafrost with contrasting characteristics are distinguished here: 1) ice-poor permafrost in rock walls, mountain peaks or talus slopes, constituting a continuous zone of permafrost at high elevations and 2) ice-rich permafrost, which can exist at lower elevations than ice-poor permafrost and represents the lower limit of mountain permafrost. It is typically located at the base of steep slopes where snow avalanches and rock fall deposits can form rock-ice mixtures or at the boundaries of former glaciers, where glacier ice was covered by sediments (Kenner et al. 2019a). These ice-rich features are called rock glaciers and move downslope by a combination of shearing and plastic deformation processes (Arenson, Springman and Sego 2007, Haeberli et al. 2006). The distribution of ice-poor and ice-rich permafrost is shown on a new permafrost and ground ice map of Switzerland ((Kenner et al. 2019a), see https://www.slf.ch/pgim). The most important changes which have been registered in Swiss mountain permafrost over the past two decades are briefly discussed below.

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2 Permafrost temperatures

Overall, permafrost temperatures have increased since the beginning of the measurement series in the late 1980s in the Swiss Alps (PERMOS 2019) (Fig. 1). Due to low ice contents and a thin to absent snow cover, temperature changes in steep permafrost rock closely follow changes in air temperature (Gruber, Hoelzle and Haeberli 2004b, Haberkorn et al. 2015). At such sites, a steady warming of around 1°C is clearly discernable over the past decade (Magnin et al. 2015, PERMOS 2019). In contrast, the temperature of ice-rich permafrost located below the continuous zone of permafrost is today often close to - or already at 0°C, preventing further warming unless the ground ice melts. Temperature variations are damped or even prevented here because energy is released during the freezing of water and consumed during ice melt, leading to prolonged «zero-curtains», during which ground temperatures remain close to 0°C.

Near-surface temperatures in the uppermost decimeters of the ground show the highest amplitudes, whereas ground temperature variations are damped and delayed with increasing depth. The thermal regime of the uppermost part above the permafrost, the so-called active layer, is primarily affected by seasonal weather conditions, ground surface characteristics such as grain size, ground ice content, and by snow distribution. Wherever snow can accumulate, the timing and distribution of the snow cover has a strong regulatory influence on ground temperature due to its insulating properties. Snow-poor winters can cause permafrost temperatures to plummet temporarily, as was observed in many parts of Switzerland in the winters 2015-2016 and 2016-2017 (PERMOS 2019).

3 Active layer properties in sediments

The active layer is the uppermost layer of the ground above the permafrost that thaws every summer and refreezes completely in winter. Active layer thickness (ALT) varies between around 1 and 10 m in Swiss permafrost boreholes (PERMOS 2019), which are located in various types of terrain with diverse ice contents, at different elevations and expositions (see the PERMOS data browser for details: http://newshinypermos.geo.uzh.ch/app/DataBrowser/). Rising temperatures

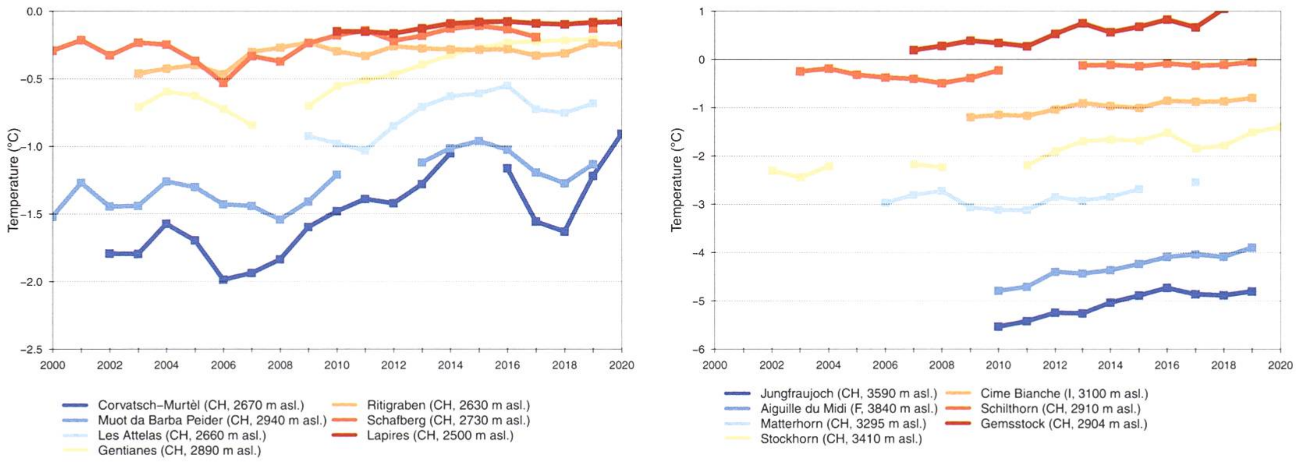

Fig. 1, left: Mean annual ground temperatures (hydrologic years) measured at around 10 m depth in ice-poor rock at sites in Switzerland (Data: PERMOS), France (Data: EDYTEM, Université de Savoie, update from Magnin et al. 2015) and Italy (Data: ARPA Aosta, Italy, update from (Pogliotti et al. 2015) and right: mean annual ground temperatures (hydrologic years) at around 10 m depth in ice-rich permafrost in various rock glaciers in Switzerland (Data: PERMOS). Note the different scales on the y axes.

Fig. 2: Maximum annual active layer thickness (top) in an ice-poor talus slope on the Muot da Barba Peider ridge (Pontresina, Canton Grisons) between 1997 and 2018 and in the ice-rich Schafberg rock glacier nearby (bottom), between 1997 and 2018. Light blue bars indicate thermistor depths used for linear temperature interpolation (Data: SLF/PERMOS).

have induced gradual active layer thickening – particularly in ice-poor permafrost. In contrast, due to latent heat effects, in ice-rich permafrost ALT tends to vary little over long periods, before undergoing deepening due to loss of ice. Active layer properties are of particular interest with regard to slope and infrastructure stability.

As ice and water contents vary seasonally in the active layer, it is particularly subject to deformation in slopes (Rist, Phillips and Springman 2012). The infiltration of water from snow melt or precipitation into active layer sediments can have rapid geotechnical repercussions by reducing effective stress and increasing pore water pressures and may lead to active layer failure (Arenson and Jakob 2015). This process has been observed on the front of steep rock glacier tongues during snow melt or intense precipitation (Fig. 3).

Fig. 3: Front of the Ritigraben rock glacier (Canton Valais) before (left) and after failure (right), causing debris flows on 2 July 2018. Photographs: SLF time-lapse camera.

Active layer thickening and deformation are problematic for the foundations and anchors of infrastructure. Infrastructure located in steep slopes, such as avalanche defence structures, are particularly affected. Thickening active layers affect an increasing proportion of their anchor lengths. Downslope deformation and subsidence cause displacements and damage to these linear structures, compromising their efficiency and shortening their design life (Phillips and Margreth 2010) (Fig. 4). Whereas active layer creep rates can attain 10-30 cm/year in steep permafrost talus slopes, the upper tolerance limit for avalanche defence structures is 5 cm/year (Margreth 2007).

Fig. 4: Misaligned and damaged row of avalanche defense snow nets in a permafrost talus slope at Wisse Schijen (Randa, Canton Valais), resulting from differential downslope deformation and subsidence of the active layer.

4 Talik formation and permafrost degradation in sediments

If the active layer of permafrost does not refreeze completely in winter, a so-called supra-permafrost talik forms, a layer of unfrozen ground on top of the permafrost. This signals the onset of permafrost warming and ice melt. In sediments supersaturated with ice, loss of ice causes gradual subsidence at the ground surface, which can be detected using remote sensing methods such as laser scanning or photogrammetry (Kenner et al. 2014). Directly visible at the ground surface, thermokarst depressions are the result of ice loss in ice-bearing substrates and can be several meters deep. They can often be observed on ski runs in summer (Fig. 5), where the ground surface has been smoothed artificially and the surface grain sizes reduced, which changes the thermal characteristics of the substrate and propagates ice melt.

Taliks can also form within the permafrost body due to lateral heat fluxes, caused for example by water. Lateral water flows have recently been detected in rock glaciers and the formation of intra-permafrost taliks is currently being observed (Zenklusen Mutter and Phillips 2012), for example in two ice-rich landforms, the Ritigraben (Grächen, Canton Valais) and Schafberg (Pontresina, Canton Grisons) rock glaciers (Fig. 6). Taliks can

Fig. 5 left: thermokarst depressions on a ski run and right: sinkhole at the foot of a pylon in permafrost (both in Canton Valais, Switzerland).

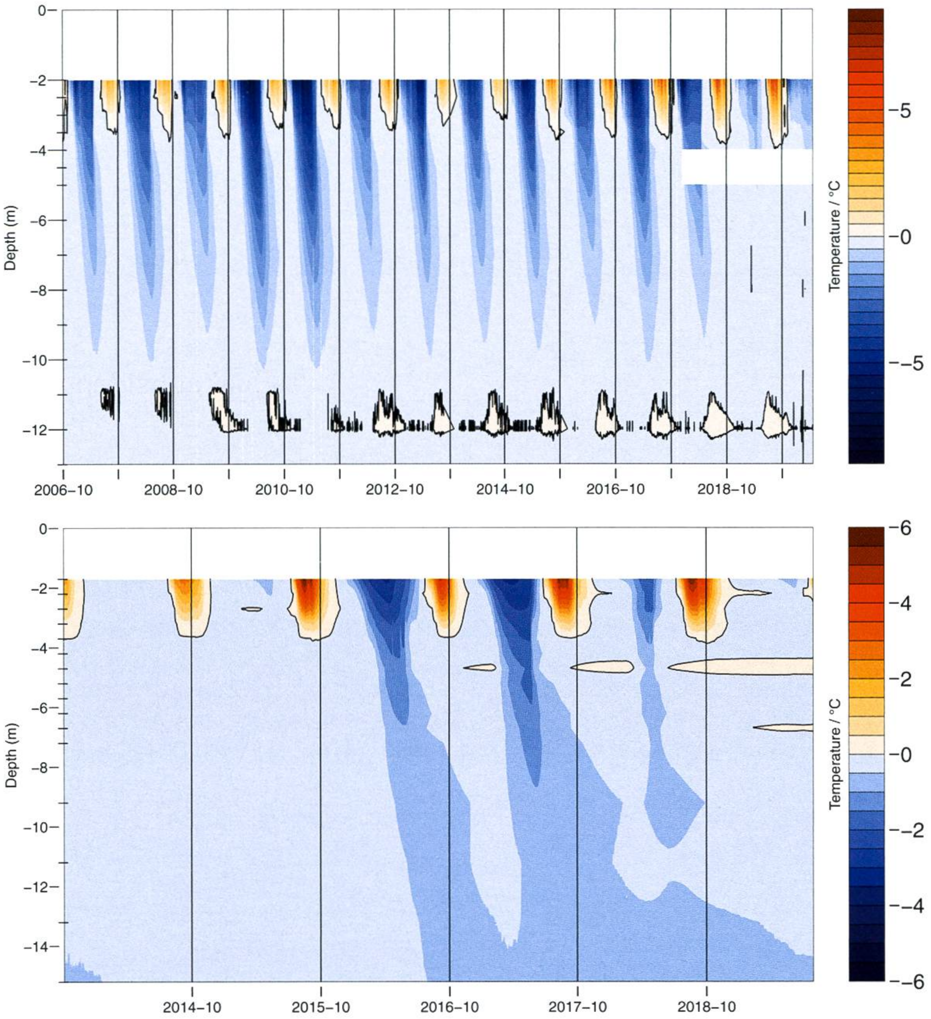

Fig. 6: Contour plots showing in Figure above ground temperatures measured in a borehole in the Ritigraben rock glacier (Grächen, Canton Valais) between 2007 and 2019. A seasonal talik started to form at 11-12 m depth in 2006. Below: Groundwater temperatures measured in a borehole (B1) in the Schafberg rock glacier (Pontresina, Canton Grisons). A talik formed at 4.7 m depth in 2016 and a second one formed at 6.7 m depth in 2019 (Data: SLF/PERMOS). The ticks on the y axes indicate thermistor depths.

be detected on the basis of positive ground temperature data in boreholes. However, as ice and water cannot be distinguished from each other at 0°C, geophysical measurements (e.g. electrical resistivity tomography or electromagnetometry) are used to track ongoing changes in the ice-/water content ratios (Mewes et al. 2017, Hilbich et al. 2008, Hauck, Böttcher and Mauer 2011).

5 Rock glacier dynamics

The deformation rates of rock glaciers have increased considerably over the past two decades, in various regions of the Swiss Alps (Fig. 7) (PERMOS 2019) as well as in the entire European Alps (Delaloye et al. 2008) – with short interruptions induced by snow-poor winters (e.g. winters 2015-2016 and 2016-2017), which caused efficient ground cooling (PERMOS 2019) and presumably, lower liquid water contents in the ground. Although rock glacier runoff is currently a subject of great interest (Colombo et al. 2018, Jones et al. 2018), their hydraulic conductivity is still poorly understood, and few direct measurements have been carried out (Krainer and Mostler 2002). Nevertheless, it is known that with rising ice temperatures, the hydraulic conductivity of ice increases (Burt and Williams 1976, Fountain and Walder 1998), allowing more efficient water transport to shear horizons, and thus increasing deformation rates (Cicoira et al. 2019). Water influences the dynamics of ice-rich permafrost features at various time scales (Kenner et al. 2017, Wirz et al. 2014). Due to the insulating properties of snow, the timing and depth of the autumn snow cover determine the volumetric content of unfrozen water within the ground – the thicker the snow cover, the

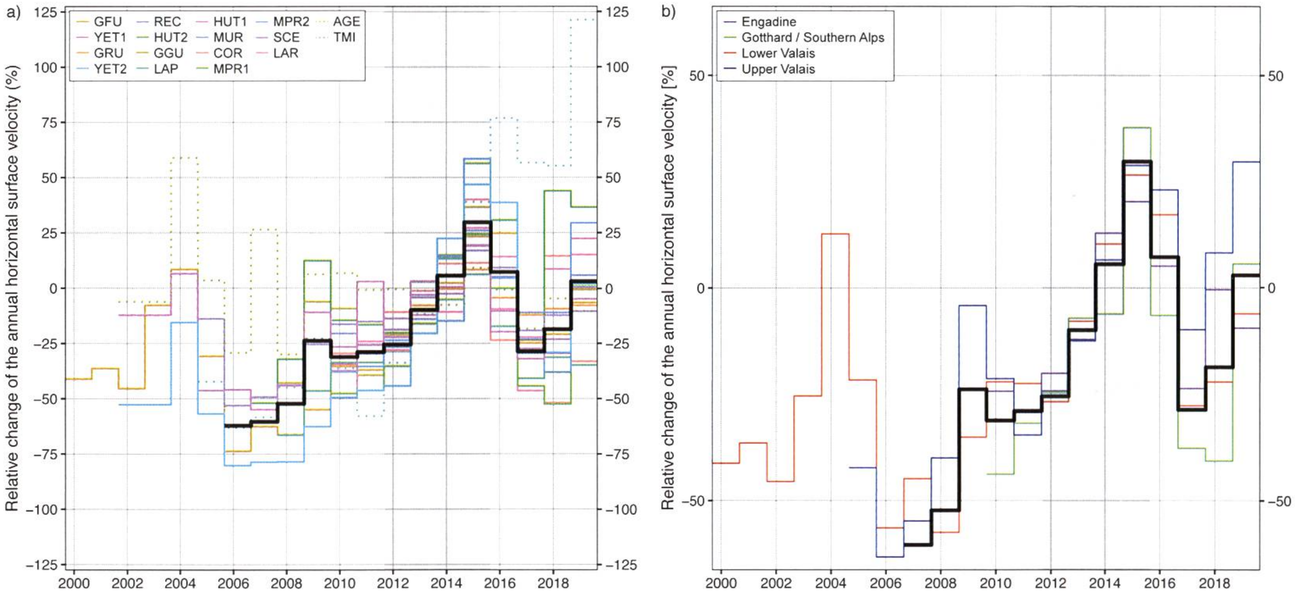

Fig. 7, left: Mean annual horizontal surface velocity (in %) relative to the reference period 2012–2015 (grey area) at 17 Swiss rock glacier lobes from 2000 to 2018 derived from terrestrial geodetic surveys. Rock glaciers showing an atypical evolution are shown in dotted lines and the black line corresponds to the mean of the Swiss Alps (excluding the two atypical rock glaciers). Right: Relative change of annual horizontal surface velocity of rock glaciers in four regions of the Swiss Alps (Data and figures: ©PERMOS). For details on the rock glaciers, see PERMOS (2019).

longer it takes for ground water to freeze. Water availability during winter in turn influences the degree of seasonal rock glacier deceleration. The start of snow melt controls the beginning of the seasonal rock glacier acceleration and is another climate-dependent influencing factor for the deformation velocity of rock glaciers (Kenner et al. 2019b). As rock glaciers transport rock sediments from headwalls, their acceleration and loss of ice implies increased sediment availability downslope - and if they creep towards steep terrain, rock fall or debris flows can be triggered on their steep fronts (Kummert and Delaloye 2018), as shown in Figure 3.

6 Rock slope dynamics

An interesting and controversial subject in the literature at present is whether or not the occurrence of rock avalanches is increasing in mountain permafrost areas, whether climate change is relevant (Loew, Buehler and Aaron 2020) and whether permafrost has any role at all in rock slope failures (Krähenbühl, Nänni and Donau 2018). Processes occurring at different temporal and spatial scales need to be considered here (Gallach et al. 2018).

On the very long term, at the scales of tens to hundreds of millennia, the geological structure in combination with the erosional effects of glaciation are the controlling factors for the occurrence of rock slope failures (Krautblatter and Leith 2015). At shorter time scales, the frequency of such failures is temporally modulated by climate sensitive processes and the occurrence of surface ice (i.e. glaciers), as well as subsurface ice (i.e. permafrost).

The destabilizing effect of permafrost ice, which acts on time scales of several millennia is often neglected in the literature. Moisture freezing in rock joints can contribute to ice-wedging and rock bridge failure, as was observed at Piz Kesch (Canton Grisons), where a 150'000 m^3 rock avalanche occurred in February 2014, revealing permafrost ice in the detachment zone; this ice was C^{14} dated at over 6000 years BC (Phillips et al. 2017). Recent dating of ice in rock fall scars in the

Mont Blanc massif has also shown the ice to be several thousand years old (personal communication, Ludovic Ravanel (Université Savoie Mont Blanc), 2019). Whilst geological structure played the key role in the Piz Kesch rock slope failure, the preparatory role of ice-wedging under permafrost conditions should be considered.

Permafrost ice also influences the hydrology of rock masses. Generally, near-surface permafrost ice effectively prevents the infiltration of water into the rock mass, thus having a stabilizing effect in this respect (Hasler et al. 2011). This implies that the melting of ice in fractures at short time scales of decades to weeks can strongly increase the water permeability of a rock mass and can thus substantially weaken the rock structure. During the process of ice melt in the cleft system, ice-plugged fractures at greater depths can cause elevated hydrostatic pressure (Hasler, Gruber and Beutel 2012). Following the 2017 Pizzo Cengalo rock avalanche, a ca. 70 m high water table was visible in the detachment zone (Walter et al. 2020), suggesting that hydrostatic pressure may have contributed to the final triggering of this event. Furthermore, the rock microstructure is weakened by the infiltration of water (Voigtländer, Leith and Krautblatter 2018). Water fluxes into open, newly ice-free rock joints can moreover cause rapid, short-term temperature increases (Phillips et al. 2016).

Correspondingly, summer heat waves (e.g. 2003, 2015 and 2018) and water infiltration lead to active layer thickening and this coincides with near-surface rock slope failures with volumes ranging between a few hundred to several thousand cubic metres (Luethi, Gruber and Ravanel 2015, PERMOS 2019, Gruber, Hoelzle and Haeberli 2004a). These small-medium sized events mainly occur in summer and autumn (Fig. 8). Note that the frequency of occurrence and volumes of these events are hard to quantify, as there is no official permafrost rock fall observer network. Rock fall observations are acquired from the public, so there is considerable observer-bias, depending on the number of people in the mountains and whether they report their observations. Aerial images will reveal rock fall events subsequently, but their timing often remains vague. Events exceeding ca. 50'000-70'000 m³ are often registered by the Swiss Seismological Service SED, allowing better estimations of volume and precise information on their timing and dynamics (Dammeier et al. 2011, Walter et al. 2020).

Large, deep-seated rock avalanches occur year-round in mountain permafrost, regardless of current air temperatures and weather conditions (Phillips et al. 2017). Temperature variations at depth are considerably delayed and processes acting on time scales of centuries to millennia might be most relevant here. It is unsure whether permafrost

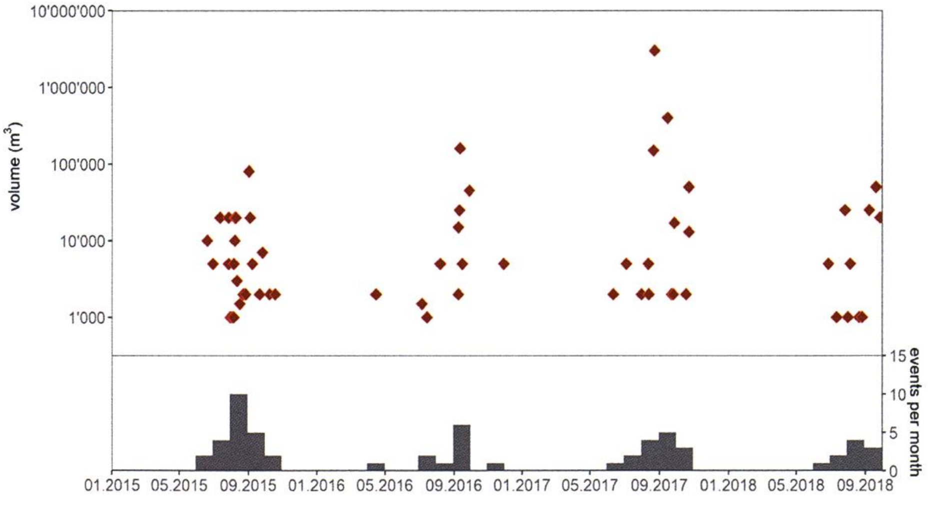

Fig. 8: Rock slope failures registered in the PERMOS permafrost rock fall database from 2015 to 2018. Events with a volume exceeding 1000 m³ and with a detachment zone above 2200 m asl. are shown. Top: volumes of the rock avalanches. Bottom: number of events per month (PERMOS 2019). See Phillips et al. (2017) for the seasonal/elevational distribution of rock avalanches in permafrost since 1714.

warming over several decades influences the frequency of large-scale rock slope failures, for example due to water infiltration. Rock slope failures exceeding 1 million m^3 (Bergsturz events) are well-documented in the Swiss Alps but rare (a few events per century), (Gruner 2012, Fischer et al. 2012) so it is statistically not significant to distinguish changes in their frequency of occurrence in mountain permafrost areas. When sediments from catastrophic rock slope failures in periglacial environments hit snow, ice or water, process chains with long runout distances can be triggered (Crosta, Chen and Lee 2004, Dufresne et al. 2019, Mergili et al. 2020), and have a high damage potential in inhabited areas. Rock-ice and rock-snow mixtures have a particularly high mobility, with increased runout distances (Noetzli et al. 2006, Schneider et al. 2011).

7 Practical challenges related to permafrost degradation

Rising ground temperatures, accelerating deformation rates and the occurrence of subsidence due to ground ice loss are a challenge for the construction and maintenance of mountain infrastructure. Specially adapted construction material and flexible structures are required (Bommer, Phillips and Arenson 2010) and in high mountain areas damages to infrastructure can incur high costs and require complex repairs (Duvillard et al. 2019). Negative ground temperatures are the main challenge in ice-poor bedrock, requiring the use of specially adapted anchor grout which can set before freezing (Baumann 2019). Ice-rich permafrost ground should be avoided for construction purposes. As this is not always possible, flexible structures such as pylons on rails (Fig. 9) or buildings with adaptable geometries are necessary to counter slope deformation and subsidence (Phillips et al. 2007). For infrastructure located in Alpine valleys below dynamic permafrost features, protection measures against mass movements are necessary. These can be structural ones, such as retention dams (Keller et al. 2002), and/or early warning systems (Wilhelm et al. 2019). Construction activity and the active use of mountain infrastructure can modify the thermal regime of permafrost substrates through mechanical disturbance (e.g. open foundation pits in summer) or heat input (e.g. from hydration heat of concrete, from heated buildings or heat-inducing machines and waste water) (Bommer et al. 2010). These disturbances

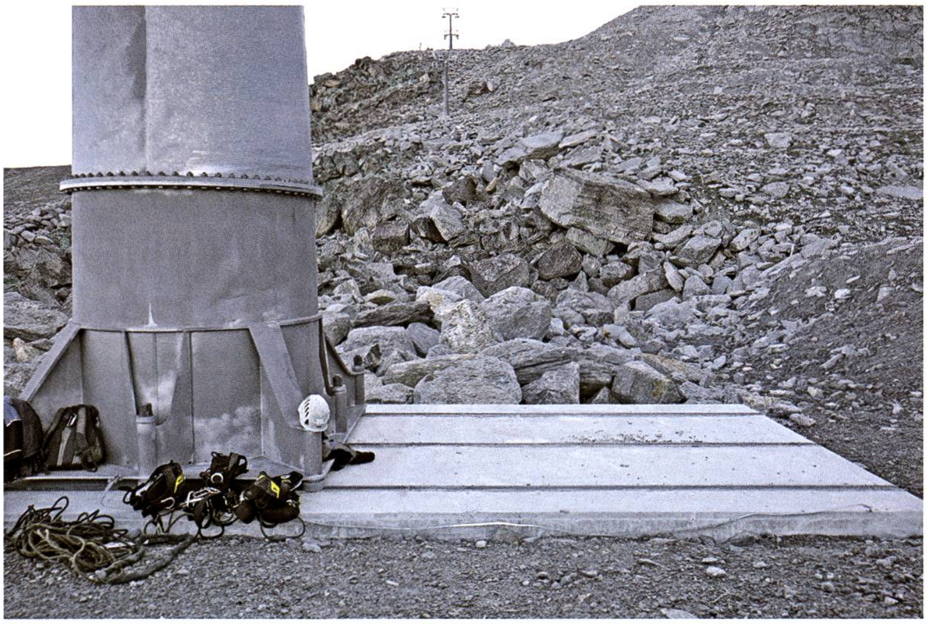

Fig. 9: Chairlift pylon on rails on ice-rich permafrost in a ski resort, Canton Valais.

can be significantly faster and have stronger effects than those induced by climate change in undisturbed terrain (Duvillard et al. 2019).

8 Conclusions and outlook

Over the past two decades, monitoring data reveal that ground temperatures have increased in all types of mountain permafrost terrain in the Swiss Alps. In parallel, active layers are thickening and deformation rates of ice-rich terrain are rising. Temperature ranges, together with ground ice and water content predominantly determine the rates of change occurring. The distribution ratios of frozen and unfrozen water content are currently changing, i.e. volumetric water contents are increasing. As permafrost is a thermal phenomenon, the effects of change in permafrost substrates are often poorly discernable and require in-situ monitoring systems, which can be complemented with remote sensing techniques. A greater focus on ground water distribution in permafrost is required, with widespread ground water monitoring instrumentation. In a warming climate, future snow cover distribution will be an important driver of ground temperatures and of the deformation rates of ice-rich permafrost.

Mass movements triggered in permafrost areas as well as potentially changing frequency and magnitudes are the focus of much interest. To improve our understanding of the role of permafrost in slope failures, measurement networks need to include more data from high elevation permafrost rock masses, including thermal data and deformation measurements. Cascading processes such as the 2017 rock avalanche and debris flows at Pizzo Cengalo are challenging to predict and understand. Rock avalanches onto snow and ice or into lakes can have far-reaching effects, so the processes involved in slope failures in mountain permafrost must be further investigated in an interdisciplinary effort including geologists and permafrost scientists.

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