A Global View on Permafrost in Steep Bedrock

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Abstract

Mountainous topography covers a considerable proportion of the global permafrost region. There, temperature changes and the degradation of permafrost in steep bedrock can evoke rapid geomorphic change, some of which may result in natural hazards. Due to the strong relief of most rock walls, corresponding events can have a long runout and transform into cascading events, such as impact to lakes or the damming of rivers that propagate far below the periglacial zone. The identification of areas that potentially have permafrost conditions in steep rock is the important first step in the evaluation of corresponding hazards. During the past decade, researchers have given considerable attention to permafrost in steep bedrock, although most investigations have been conducted in the European Alps. This contribution provides a summary of findings related to the delineation of permafrost in rock walls. Based on this, simple considerations and data sources are outlined that may help the application of current knowledge in remote mountain regions.

Keywords: bedrock slopes; mountains; steep terrain; global; hazard zonation; mapping.

Introduction

A significant proportion of the global permafrost region has mountainous topography (Gruber 2011a). Additionally, coastal cliffs may be subject to permafrost conditions, and changes to permafrost there can alter the stability of rock faces perched high above valleys and thus pose a hazard to human life and infrastructure (cf. Carey 2005). This may occur indirectly through, for example, impacts to lakes that may cause long-distance secondary events (cf. Geertsema & Cruden 2008, Geertsema & Clague 2011). However, non-stationarity, incomplete understanding of processes, and lack of information on local surface and subsurface conditions challenge corresponding hazard zonation. Here, the delineation of permafrost rock slopes can serve as a proxy for areas that may require special attention or surveillance, as they are prone to rapid changes in response to climate forcing (Gruber 2011b). Absent or minimal vegetation, a reduced snow cover, and less important active-layer processes make permafrost in steep rock a system that is simple enough for attempting an extrapolation of findings to environments not measured. In this contribution, I summarize findings on the spatial and temporal variability of mean annual ground temperature (MAGT) and permafrost in steep bedrock. These findings, often based on a narrow range of environmental conditions, are extended with hypotheses for generalization to other environments. This is intended to support the estimation of permafrost conditions in steep rock globally, and to provide a framework to test and improve them by means of measurement, experiment, and observation. Unless stated otherwise, the investigations cited have been performed in the European Alps.

Rock Temperature: Factors and Processes

Basic considerations

The energy fluxes at and near the ground surface are shown for the two conceptual end members of steep and homogenous bedrock and a horizontal debris slope in Figure 1. Longwave radiation is mostly affected by air temperature, moisture content, and clouds. Turbulent fluxes mostly depend on air temperature and wind. Solar irradiation, however, is strongly dependent on cloudiness, sun-terrain geometry, and topography, and results in a high degree of spatial differentiation. Figure 2 shows three conceptual scales that determine ground temperatures. When considering global patterns, differing climate conditions affect the strength of the topographic influence. For example, in areas with more abundant clouds and diffuse radiation, topographic differentiation is less pronounced than in areas with few clouds and strong direct solar radiation. The
spatial differentiation of MAGT can be conveniently described relative to mean annual air temperature (MAAT) using

\[ dT = MAGT - MAAT \]

Because MAAT is a commonly available climate variable, \( dT \) helps to estimate local patterns relative to it. MAAT is often subject to strong intra-annual variation, but \( dT \) for near-vertical rock remains rather constant (cf. Noetzli & Vonder Muehll 2010).

**Near-vertical and compact rock**

Near-vertical and compact rock faces exhibit a strong topographic control on subsurface temperatures and a weak thermal influence of snow and active-layer processes typical for debris-covered slopes (Fig. 1). Spatial patterns of \( dT \) are dominated by direct solar radiation (cf. Hoelzle 1994) and modified by rock albedo (cf. Hall 1997). For this reason, they are a simple system to investigate and to then gradually expand by considering additional processes. Gruber et al. (2003) present a review of previous investigations and a strategy for measuring in steep rock faces. Corresponding data are available through PERMOS (cf. Noetzli & Vonder Muehll 2010) and a pan-Alpine inventory of permafrost evidence (Cremonese et al. 2011). In near-vertical and compact rock, MAGT is often measured 5–30 cm below the surface and presumed to be equivalent to that just below the active layer.

Based on the work of Allen et al. (2009) summarizing 14 one-year time series from the Southern Alps of New Zealand (44°S), \( dT \) in sun-exposed slopes can be estimated to 4.5–6.5°C. In the European Alps (46°N), Boeckli et al. (2012) estimated this to be 5.5–6°C based on 57 locations and a statistical model. A process-based modeling study (Gruber et al. 2004) in the European Alps resulted in \( dT \) ranging from 6.5 to 9°C. The model is driven by daily data that do not resolve temperature differences between east and west exposure. This may result from convective clouding in the afternoon lowering the temperature on west-exposed faces by reducing direct solar radiation. Generally, \( dT \) increases with elevation due to more shortwave and less longwave radiation, and with decreasing precipitation due to a higher amount of direct radiation. Reflection from surrounding snow-covered slopes can locally increase shortwave irradiation and thus \( dT \). This effect is assumed to have affected \( dT \) at two measured locations by 2–3°C (cf. Allen et al. 2009). Without any solar radiation, \( dT \) would become slightly negative due to longwave loss.

Summarizing this paragraph, \( dT \) likely ranges from 0 to 9°C in steep and compact rock at latitudes near 45°, and varies mostly as a function of solar radiation.

**Surface heterogeneity and clefts**

Most rock slopes differ from the near-vertical case because micro-topography and fracturing promote patchy covers of debris, snow, and ice (Gruber & Haeberli 2007). The thermal influence of snow, fractures, and active-layer processes can thus contribute to the heterogeneity of \( dT \). Safety issues and the dominance of lateral heterogeneity in near-surface measurements of MAGT, however, complicate corresponding research. Gubler et al. (2011) found that MAGT on more gentle slopes can already vary by up to 2.5°C within an area of 10 m x 10 m. For heterogeneous bedrock slopes, this value is likely often exceeded.

Using measurements at four depths down to 85 cm in borings and deeper on thermistor strings lowered into clefts, Hasler et al. (2011) estimated a local cooling effect of fractures on the order of 1.5°C. This cooling resulting from ventilation likely depends on cleft aperture and abundance, and its functioning may resemble ventilation effects in coarse blocks (cf. Harris & Pedersen 1998) or, in extreme cases, those in ice caves (Obleitner & Spötl 2011, Schöner et al. 2011). A local lowering of \( dT \) by several °C, even in shaded slopes, thus appears possible in rare cases. For practical use, however, an assumption of 1–2°C cooling, increasing from shaded to sun-exposed slopes, appears plausible for heterogeneous conditions. Snow deposited in clefts may have an additional cooling effect by consuming latent heat during melting. At the same time, however, snow cover or infill can inhibit air circulation and thus reduce the associated cooling (Hasler et al. 2011). A thermal diode effect caused by seasonally varying proportions of ice/water/air in pores and fractures can cause a lowering of temperatures at depth (Gruber & Haeberli 2007) similar to the thermal offset described for lowland permafrost (cf. Smith & Riseborough 2002), but this has not been detected in measurements (Hasler et al. 2011).

**Snow and perennial ice**

Snow on rock faces alters the coupling between the atmosphere and subsurface and thus affects \( dT \). It is usually thinner and spatially and temporally more variable than in gentle terrain. Due to difficult access, corresponding studies are rare (cf. Wirz et al. 2011). Rock faces often extend far above the equilibrium line of glaciers and receive much of their precipitation in solid form. In those conditions, temperature moderates the retention of snow because cohesive snow near melting conditions is more likely to accumulate than cold snow that is prone to be removed by wind and sliding. For cold and shaded faces, this can cause a pronounced snow cover during summer, whereas precipitation in winter barely affects the bare and dark surfaces of ice and rock (cf. Gruber & Haeberli 2007). Depending on the seasonality of precipitation, snow during summer can be common in high-elevation rock faces. For thin snow, the net warming through thermal insulation during winter is reduced and the relative importance of cooling through albedo and latent heat uptake during melt becomes greater. Higher albedo decreases \( dT \) more strongly on sun-exposed slopes, whereas the effect of latent heat can cause a lowering of \( dT \) in all slope aspects.

Based on numerical experiments under the assumption of laterally homogeneous snow cover, Pogliotti (2011) estimated this cooling to have magnitudes of up to 2°C with respect to snow-free rock. In reality, this is further modified in laterally heterogeneous and discontinuous snow cover because a lateral interaction between snow-covered and snow-free rock facets
exists by heat conduction in rock as well as by radiative and sensible exchange at the surface (cf. Neumann & Marsh 1998). Based on distributed measurements of rock temperature, Hasler et al. (2011) estimated the cooling effect of snow in radiation-exposed faces to be up to 2–3°C.

Ice faces, hanging glaciers, or surface lowering of glaciers can influence the temperature regime in steep rock and can exhibit strong spatio-temporal variations (Fischer et al. 2011). While ice faces and hanging glaciers are diagnostic of permafrost conditions at their rock-ice interface, their absence does not indicate the absence of permafrost. The occurrence of cold firm (Suter et al. 2001, Suter & Hoelzle 2002, Hoelzle et al. 2011), and thus hanging glaciers, follows differing patterns than rock temperature because they are subject to higher albedo and are affected by wind through snow transport. In gently inclined parts of hanging glaciers, the percolation of water into the firn and heat release at depth during refreezing can cause zones of temperate firn and ice (Haeberli & Alean 1985). As a consequence, an inference of temperature below ice cover is difficult. For ice faces that are subject to minimal flow and balance change, a cooling with respect to rock is likely for sun-exposed slopes due to the influence of albedo. For a north-exposed ice face, Hasler et al. (2011) report approximately the same mean annual temperature as in nearby rock.

Three-dimensional and transient effects
Spatial variation of surface conditions and their temporal changes influence permafrost bodies at depth (cf. Gold & Lachenbruch 1973), and in mountain areas this is further complicated by geometric effects (Kohl 1999, Gruber et al. 2004). The combination of a distributed MAGT model and three-dimensional heat-transfer modeling of steep topography (Noetzli et al. 2007) showed complicated permafrost bodies with steeply inclined isotherms near peaks and ridges. Even in steady-state, permafrost can be induced below non-permafrost terrain facets due to nearby cold slopes. Transient simulations were performed with a similar setup (Noetzli & Gruber 2009) and accounted for temperature changes during the past. This revealed the importance of past climate and latent heat that can lead to permafrost bodies persisting at depth below slopes that today would be interpreted as permafrost-free. Because of multi-lateral warming, the reaction of convex topography, such as ridges or rock spurs, can be much faster than that of flat terrain (Noetzli & Gruber 2009). Several new boreholes in steep rock and in ridges (Noetzli et al. 2010, Noetzli et al. 2008, Noetzli & Vonder Muehll 2010) support many of the general findings from the modeling studies.

The Global View: Estimating Spatial Patterns of Rock Temperatures for Diverse Mountain Ranges

In this section, simple approaches for estimating permafrost occurrence in rock faces worldwide are proposed. It is important to keep in mind that this is based on limited point data from a restricted range of environmental conditions.

Global distribution
For strongly shaded rock faces, the 0°C long-term isotherm of the MAAT is a good pointer to determine the elevation above which permafrost must be expected, even though permafrost may sometimes be found at lower elevation. Due to the absence of better data, the zonation shown in Gruber (2011a) can provide an approximation globally at about 1 km resolution. While few rock faces are dominated by inversion effects, inversions are important to consider in the choice of local meteorological stations as possible alternatives. As the extrapolation of MAAT in rugged terrain involves considerable vertical distances, the choice of appropriate lapse rates is important. If suitable ground measurements do not exist, the lapse rate can be approximated based on model data (Gruber 2011a) or regional radiosonde measurements. MAAT data covering a period of several decades helps to minimize the influence of short-term fluctuations. It is sometimes necessary to account for longer-term transient effects that have occurred during the past decades or centuries with respect to the measurement period chosen (cf. Noetzli & Gruber 2009).

Topography and solar radiation
Topography influences ΔT for individual slopes, mainly through its geometric effect on incoming solar radiation. Generally, steeper and more rugged terrain causes a wider range of ΔT than more gentle terrain. This effect, however, is modified by latitude and the proportion of direct radiation. As a first approximation, a ruggedness index (e.g., Gruber 2011a) can be used to identify terrain tending to have a higher proportion of steep and strongly shaded rock slopes. Locally, the differentiation of slopes with respect to solar radiation can be estimated based on the calculation of mean annual potential solar irradiation and a decameter-resolution DEM (e.g., Farr et al. 2007). This operation is routinely available in GIS software.
Latitude
Besides its effect on MAAT, latitude influences the maximum amount of total annual solar irradiation received by the most suitably exposed slope. For this reason, the range of dT is also likely to be affected by latitude (Fig. 3). Further, the partitioning of radiation with topography changes with latitude. Toward the poles, increasingly steep slopes receive the highest amounts of radiation; near the tropics, rather gentle slopes receive the highest radiation input. Furthermore, the sensitivity to cast shadowing by obstructed horizons increases toward the poles with the prevalence of low solar elevation angles.

Continentality
Continental (as opposed to maritime) climate is characterized by comparably large seasonal thermal variations and dryness, both generally caused by large distances from major water bodies and altered by atmospheric circulation patterns and rain-shadow effects. The dryness in continental areas is usually accompanied by very high amounts of direct solar radiation afforded by often cloud-free skies. Besides MAAT, continentality is often used to describe spatial patterns of cryosphere phenomena (e.g. Holmlund & Schneider 1997, King 1986, Haeberli & Burn 2002, Shumskii 1964) and is frequently characterized by a continentality index defined as the average difference between the coldest and warmest month at a location.

The continentality index shown in Figure 4 provides an appreciation of its global patterns that may help to inform the extrapolation of findings from one mountain range to another. The patterns of temperature range, the proportion of direct sunlight, and precipitation are jointly described by the concept of continentality. However, these affect rock temperature in differing ways and often correlate much less than expected when plotted based on gridded climate data. Until further analyses help to disentangle these effects, the assumption of subdued spatial differentiation of dT toward maritime areas likely provides a good assumption. This effect of continentally or precipitation on the degree of spatial differentiation due to solar radiation is, however, not clearly detectable in current measurements (cf. Allen et al. 2009, Boeckli et al. 2012) that span only small gradients.

Surface characteristics
As a general rule, rough surfaces can be assumed to be colder than smooth ones. Cooling is caused by a thin, intermittent, and frequent snow cover and by air circulation in fractures or debris.

At least qualitatively, the roughness of rock walls can be assessed based on field visits, photographs, aerial photographs, or high-resolution satellite imagery. Increasingly, the imagery freely available on GoogleEarth, for example, has sufficient resolution to provide valuable first impressions.

Conclusion
Based on research from a narrow range of environmental conditions and the consideration of what appear to be the processes that govern permafrost distribution in steep bedrock, I have proposed simple considerations to estimate permafrost in rock walls worldwide. Besides the potential for practical application, this contribution points to the wide range of
environmental conditions that drive permafrost in steep terrain. More systematic research in integrating local and regional research to achieve a coherent understanding would be a good avenue to progress beyond the heuristics presented here. Such research would consolidate understanding by basing it on a wider range of environmental conditions.

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