Chapter 3
Mountain Permafrost

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3.1 Introduction

This chapter provides an introduction to mountain permafrost and a review of recent scientific progress. In it, we use rather few references to the scientific literature in order to make the text more easily readable. For further reading, we recommend, Haeberli et al. (2006), and Gruber and Haeberli (2007), two recent reviews in which the current state of the art is discussed in depth and in which extensive references can be found.

Permafrost is lithosphere material that permanently remains at or below 0°C. In this context, “permanence” is often defined to be two or more consecutive years, in order to establish a minimum value for avoiding the effect of only one cold and long winter being considered permafrost. By this definition, permafrost can – but does not need to – contain water or ice. Based on this purely thermal definition, every substrate is permafrost when subject to certain temperature conditions. By definition, glaciers are not permafrost. Most permafrost areas experience seasonal thaw, during which surface temperatures rise above the melting point and a certain volume of material directly beneath the surface is thawed. The material that is subject to seasonal temperature changes crossing 0°C is termed the “active layer”, and has a typical thickness of 0.5–8 m.

Mountain permafrost is simply permafrost in mountain areas. It can be situated at low or at high latitudes and in the Arctic or Antarctic – we define mountain permafrost based on the influence that mountain topography has on its properties. Many other terms that are commonly used to classify certain types of permafrost, such as Arctic, Antarctic, polar, or plateau, can be applicable at the same time. These qualifying terms are useful to describe properties, but not to sharply dissect geographic or scientific space. The dominating characteristic of mountain areas and mountain permafrost is their extreme spatial variability with respect to nearly all surface and near-surface characteristics and properties. Examples of this are:

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(a) Elevation itself, as well as other geometric measures such as slope, aspect, curvature, or roughness

(b) Surface micro-climatology, which is dominated by differences in elevation (strongly affecting long-wave radiation and turbulent fluxes) and in short-wave solar irradiance due to shading and variable angles of insolation

(c) Subsurface material thickness and composition, which is dominated by diverse processes of erosion, grain-size fractionation, and deposition

(d) Water availability, which is affected by contributing area, surface shape, and subsurface material

(e) Snow cover, which is influenced by surface micro-climatology, precipitation patterns, wind drift and avalanches.

All these properties affect ground temperature and, as a consequence, permafrost occurrence and characteristics. Water in mountain permafrost areas drains quickly, and the water content of mountain permafrost soils is usually small when compared to the often-waterlogged substrates found in Arctic lowland areas. Data on mountain permafrost are often sparse and biased to areas with existing infrastructure, because access and measurements on most mountain slopes are difficult and expensive. This is especially true for mountain areas outside Europe, where access infrastructure is sparse.

Permafrost is invisible because it is a thermal phenomenon. It is difficult to assess at the ground surface, because it usually lies beneath an active layer. Furthermore, its reliable detection requires temperature measurements spanning at least 2 years in order to understand the seasonal temperature evolution or, alternatively, measurements at greater depths. The depth of zero annual amplitude (ZAA), where the seasonal temperature fluctuation is damped to less than 0.1°C, is usually about 10–15 m below the surface. Below this depth, single measurements can establish the presence or absence of permafrost. However, great care has to be taken to minimize the thermal disturbance caused by drilling or measuring. The difficulty in detecting permafrost, together with expensive access and extreme lateral variability, makes permafrost research in mountain areas a difficult endeavor. Understanding and predicting spatial patterns of permafrost occurrence and characteristics needs to be based on a combination of measurements and models, because the systematic variability caused by topography dominates spatial patterns already over short distances.

The scientific and practical relevance of mountain permafrost has many facets. Permafrost is an important element of landscape evolution because of the characteristic landforms such as rock glaciers, push-moraines, ice faces and hanging glaciers, which are connected to its existence, and because it affects long-term sediment transfer mechanisms. This alteration of sediment transfer systems (Fig. 3.1) leads to changing regimes of natural hazards, such as rock avalanches and debris flows. Here, permafrost warming and thaw has the potential to alter frequency and magnitude of events, and to affect geographic areas that have previously been considered safe based on historical evidence. The safe construction and maintenance of infrastructure in mountain permafrost requires special techniques for the handling of thermal perturbations and ground movement. Furthermore, in some areas, land cover and land use are connected to the presence of water tables perched on permafrost.
3.2 Spatial Distribution

The processes that govern the existence and evolution of mountain permafrost can be categorized into the scales and process domains of climate, topography and ground conditions (Fig. 3.2). The climate scale governs the global distribution of cold climates in mountains. It refers to the influence that latitude and global circulation have on the general climatic characteristics of an area. These climatic conditions are then further modified by topography, which affects ground temperatures because of its strong influence on surface micro-climatology. This influence is due to differences in ambient air temperature caused by elevation, differences in solar radiation caused by terrain shape, or snow transport by wind and avalanches. Locally, the influence of topographically altered climate conditions on ground temperatures are modified further by ground properties and their influence on heat transfer. Here, coarse block layers result in relative ground cooling when compared to bedrock or fine-grained substrate, and a high ice content can significantly retard warming and permafrost degradation at depth.

The distinction between these three scales and process domains is not sharply defined. The effect that topography has on regional precipitation patterns, for instance, spans the scales of climate and topography, and the effect of snow redistribution on ground temperatures spans the scales of topography and ground conditions.
Nevertheless, this concept of scales is useful for understanding the diverse influences on mountain permafrost characteristics. The overall magnitude of the effect of topography and ground conditions can be as high as 15°C within a horizontal distance of 1 km — a similar difference in ground temperature in polar lowland areas would normally occur over a latitudinal distance of roughly 1,000 km.

In the European Alps, a mean annual air temperature below −3°C can be used for first-order classification of altitudinal belts that have significant amounts of permafrost. However, this rule is subject to many exceptions, and may not hold for other mountain areas. Figure 3.3 illustrates the influence that continentality has on mountain permafrost distribution. We speak of continental climates where total precipitation and cloudiness are low and total solar radiation as well as annual and diurnal temperature amplitudes are high. Maritime areas have high precipitation, often overcast skies, and rather small temperature amplitudes and solar radiation sums. The upper limit of closed forests rises along with summer air temperatures,
which are higher in continental climates. The glaciation limit rises with decreasing precipitation towards continental areas, whereas the permafrost limit rises towards maritime areas because thick snow cover provides insulation during winter and results in warmer ground temperatures. However, this only holds true for gently inclined slopes that accumulate a thick snow cover. The regional boundary for permafrost in steep bedrock is probably much less affected by continentality. The relative difference between sun exposed and shaded slopes is usually greater in steep than in moderately inclined terrain, because of the dampening effect of snow cover, and it is higher in continental areas because of the increased solar radiation. As a consequence of these patterns, permafrost can exist in forested mountain areas in continental climate, whereas in the European Alps even alpine meadows usually are a reliable sign of the absence of permafrost. In maritime climates, the glaciation limit is lower than the regional limit of permafrost. As a consequence, perennially frozen talus and rock glaciers are often absent, because their potential locations are covered by glaciers, and permafrost only exists in steep bedrock.

Permafrost in mountain areas occurs in a wide range of materials and surface cover types, which decisively influence ground temperatures. One of the most prominent surface covers are coarse block layers. They exert a cooling influence on ground temperatures and thus affect permafrost distribution patterns. For this reason, coarse rock has also received considerable attention from the engineering community as a construction material (Goering and Kumar 1996). The cooling influence of blocky layers is mainly based on three processes:

(a) Temperature-driven convection of air
(b) A reduced warming effect of the winter snow
(c) The advection of latent heat by snow that enters deep into the voids of the active layer.

During winter, ground temperature is higher than near-surface air temperature and, in deposits with sufficient permeability, free convection of air can thermally couple the atmosphere and the sub-surface effectively. Because a closed snow cover reduces or inhibits convection, the effectiveness of this cooling mechanism is greatest in areas or during times with little snow. The warming effect of the winter snow cover is based on a contrast in thermal resistance between cold and warm periods. This contrast reduces the influence that cold winter temperatures have on ground temperatures at depth. Because block layers have a very low thermal conductivity, they reduce the contrast between summer and winter by increasing the overall thermal resistance. In this way, block covers can result in significant ground cooling by reducing the warming effect of the winter snow (Gruber and Hoelzl 2008). The magnitude of this relative cooling is greatest in areas with thick snow cover. In very coarse deposits, snow can penetrate deeply into the voids of the active layer. Especially in areas with high wind speed, this process can advect significant latent heat into the ground, which is only slowly removed by heat conduction from the warming surface during summer.

Permafrost and ground temperatures in steep bedrock are discussed in depth by Gruber and Haeberli (2007). Unfortunately, little quantitative understanding exists with respect to the many intermediate conditions in the spectrum between steep
bedrock and moderately inclined coarse blocks that make up a large proportion of mountain permafrost areas. For example, the influence of water flow and summer–winter contrasts of thermal conductivity in fine-grained soil, or the influence of snow on temperatures in moderately steep rock walls, are hardly known at present.

Active talus slopes as well as active volcanic areas (Kellerer-Pirklbauer et al. 2007) often accumulate permafrost deposits consisting of debris or scoria mixed and inter-layered with snow deposits. Very ice-rich talus often begins to creep and ultimately forms rock glaciers. Figure 3.4 shows a buried perennial snow patch in aggrading permafrost, and illustrates the influence of topography and strong winds on the spatial pattern of such mixed deposits.

Unusual forms of permafrost can sometimes be found in areas that have a mean annual air temperature several degrees above freezing. Ice caves, for instance, preserve ice (and thus permafrost conditions) over several years (see Luetscher et al. 2005). The main process responsible for this effect is strong density-driven exchange of air through the cave system during winter, which terminates during summer when the cold air is stratified stably in the cave. Additionally, winter snow sometimes falls through the cave opening (bringing with it significant latent heat) and does not melt during summer because almost no solar radiation arrives inside the cave, and air exchange with the warm surface is minimal. Steeply inclined slopes of coarse blocks often have permafrost conditions at the foot of the slope, which are caused by a seasonal sub-surface ventilation pattern (“chimney effect”) which can reduce the mean temperature in the lower parts of steep and blocky slopes locally by several degrees (Delaloye and Lambiel 2005).

![Fig. 3.4](image)

**Fig. 3.4** The interplay of strong winds and topography governs the spatial distribution of permafrost characteristics and small glaciers on Deception Island, Maritime Antarctic. The contrast of light-colored substrate on the ridge in the foreground of the *left panel* and the darker lower slopes is due to wind transport of fine scoria from convex to concave areas. Similarly, snow is transported and deposited. On the *right panel*, a cross section through aggrading permafrost is shown. The sequence from top to bottom is: active layer in fine scoria; permafrost in fine scoria (above buried snow patch); buried snow patch consisting of dense ice in the lower and compact snow in the upper part; permafrost in fine sediments; and unfrozen sediments where the permafrost has been undercut by a stream.
Two types of phenomena often visually indicate the presence of permafrost in mountain areas (Fig. 3.5). Rock glaciers and other creep phenomena form distinct landforms caused by the slow deformation of cohesive, ice-rich sediments (Haeberli et al. 2006). When thawed, relict forms can be used to infer past permafrost conditions. Ice faces and hanging glaciers, on the other hand, only indicate current permafrost conditions, because they leave no long-lived remnants after degradation. Ice faces, hanging glaciers and active rock glaciers are reliable indicators of permafrost. Their absence, however, does not indicate the absence of permafrost.

3.3 Temperature, Ice Content, and Age

A number of borehole temperature measurements exist in mountain permafrost. Some are part of monitoring networks or research projects, others have been drilled and measured during construction or mineral prospecting, and data are seldom available for the scientific community. The most prominent scientific monitoring networks include the PACE transect of boreholes from the European Alps to the Arctic island of Spitzbergen and the PERMOS permafrost monitoring network in Switzerland (Vonder Mühll et al. 2007), which have contributed significantly to the understanding of mountain permafrost temperatures. Both networks contribute data to global monitoring organizations. The thermal response of permafrost to climate change is presented in more detail in Chap. 14.

In mountain areas, temperature does not simply increase with depth (Fig. 3.6). The subsurface temperature field is usually rather complex and governed by lateral heat fluxes, which are caused by topography and variable surface conditions (Fig. 3.7). These complex patterns can result in permafrost being induced, for instance, under a
seemingly warm sun-exposed slope from the nearby cold and shaded slope (Noetzli et al. 2007). Furthermore, recent warming has already penetrated tens of meters into the ground and can thus lead to inverted temperature profiles. As a consequence, great care must be taken in the interpretation of temperature profiles, and heat fluxes at a depth of several decameters can be positive or negative, depending on location and time (Gruber et al. 2004). The thermal profiles observed in mountain permafrost are usually either cold (i.e., colder than about 0.5°C with insignificant amounts of liquid water) or temperate. Temperature profiles in temperate permafrost have large sections (sometimes tens of meters thick) of near-isothermal conditions due to phase transition of ice contained in unconsolidated material or highly fractured rock. Areas of temperate mountain permafrost will likely increase under current atmospheric warming trends.

Glaciers and permafrost interact in many ways. Permafrost exists below the interface of cold ice and rock or sediments, and the melt of parts of a temperate glacier tongue can be followed by permafrost formation in the newly exposed material. Cold glacier tongues advancing into perennially frozen sediments can deform them into so-called push-moraines, which are landforms indicative of permafrost. Many intermediate forms of creep phenomena exist between very small debris-covered glaciers, ice-cored moraines and rock glaciers (Fig. 3.8). Ice in rock glaciers (Haeberli et al. 2006) exists in many forms, ranging from massive ice with dispersed debris to relatively homogeneous ice/rock mixtures. The origin of ice in rock glaciers is difficult to trace to either glacial or non-glacial formation, because of many shared characteristics between both ice types. Especially in the rooting zone of rock glaciers, a complex and temporally variable combination of processes such as

**Fig. 3.6** Schematic cross-section through the steady-state thermal field of a ridge or summit. Isotherms are shown by *black lines; darker shading* refers to colder temperatures. In the upper part of the section, heat flow and thermal gradient are predominantly lateral.
metamorphosis of debris-laden avalanche snow, ice segregation, and freezing of shallow ground water occurs. Talus slopes in permafrost areas can be cemented by interstitial ice (Fig. 3.9, left) and, as a consequence, aggrade significant amounts of material protected from erosion – but possibly released in enhanced debris flow activity if thawed during climate change.

Ice in fissures and fractures is common in bedrock permafrost (Fig. 3.9, right) and has been observed both at construction sites and in the fresh detachment scars of rock fall. The percolation of water in previously ice-filled joints can lead to fast and linear thaw of permafrost and, possibly the fast destabilization of large masses of rock. The origin of ice in fractures is unclear. Both the percolation and freezing of meteoric water and ice segregation are possible, and, at present no clear evidence pointing at one or the other process exists.

Permafrost in debris slopes and the landforms associated with it are usually of Holocene age, because their locations are subject to glacier cover and removal of unconsolidated sediments during glacial cycles. By contrast, permafrost in steep
and high bedrock peaks is likely to be very old. Rock temperatures of $-10^\circ$C or lower are not uncommon and, therefore, permafrost and ice in cracks and crevices of high peaks may have endured over several glacial and interglacial cycles. The age of this cold bedrock permafrost is more probably controlled by uplift and erosion than by past climate fluctuations.
3.4 Conclusion

Mountain permafrost is a fascinating phenomenon: It is invisible, extremely variable and heterogeneous, difficult to measure, difficult to model, and it currently undergoes rapid changes. These changes can affect landscape dynamics as well as human infrastructure and safety. Despite this importance, most systematic investigations of mountain permafrost at present are local in nature, because the strong heterogeneity of the system and the limited amount of available data often preclude continental-scale evaluation and modeling. In the future, however, an increased resolution of global and regional climate (or earth system) models, or the improved representation of mountain topography at the sub-grid scale, will likely allow the explicit consideration of mountain permafrost in continental-scale assessments.

References