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Rock Glaciers and Protalus Forms

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Definition and Distribution

Perennially frozen debris in cold mountains may under the force of gravity form so-called rockglaciers, often showing a shape similar to lava streams (Figs. 1–7). Formerly, rockglaciers were often thought to be a form of debris-covered glaciers, which led to the term 'rock glaciers'. Since then a number of fundamental differences between rockglaciers and glaciers have been established, for example, related to the thermal conditions and the mass balance. This has led to the use of the term 'rockglaciers' in order to stress the individual character of the phenomenon in comparison to glaciers. Therefore, 'rockglacier' is used in this chapter, although the equivalent term 'rock glacier' is also established in the scientific literature.

Rockglaciers can be found in most cold mountains of the Earth, for example, Andes, Rocky Mountains, European Alps (Figs. 1, 2 and 3), Pyrenees, Caucasus, Central Asian mountain ranges (Fig. 7), Siberian mountain ranges, Himalayas, New Zealand Alps, Greenland, Antarctica, Arctic, (Fig. 6) and Antarctic Islands. Often they are found in similar, though slightly colder and dryer climatic settings as glaciers. It is also speculated on the basis of space imagery that rockglacier-like features exist on Mars. Under suitable climatic and topographic conditions rockglaciers may be abundant with their number often exceeding the number of glaciers in the same mountain range, but with significantly smaller areas for individual rockglaciers.

Thermal Conditions

A fundamental characteristic of rockglaciers is their thermal state. They consist of a perennially frozen mixture of debris and ice, i.e., their long-term existence requires permafrost conditions. Permafrost is defined as lithospheric material with year-round negative ground temperatures (*see* Permafrost). A surface layer of several decimeters to meters thaws during summer and is termed 'active layer'. Below the 'permafrost table', i.e., the lower boundary of the active layer, the temperatures in the 'permafrost body' remain negative down to the 'permafrost base'. Thus, the mixture of debris and ice within the permafrost body remains frozen throughout the year,

Figure 1 Active rockglacier in the Muragl valley, Upper Engadine, Swiss Alps. Photograph R. Frauenfelder.

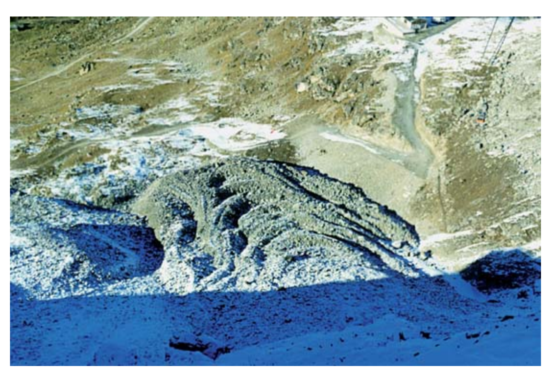

Figure 2 Active rockglacier Murtel, Upper Engadine, Swiss Alps.

Figure 3 Active rockglacier in the Suvretta valley, Upper Engadine, Swiss Alps.

Figure 4 Inactive rockglaciers in the Upper Engadine, Swiss Alps. Note the yellow color from lichen cover, and the vegetated rockglacier fronts.

possibly over centuries and millennia if the thermal conditions do not change substantially over time.

The surface layer of rockglaciers consists of debris with typical diameters ranging from several centimeters, decimeters, to meters, depending on the geological setting, weathering conditions, and processes

Figure 5 Relict rockglacier at the Julier pass, Swiss Alps. Note the complete vegetation cover and the concave forms from ice loss.

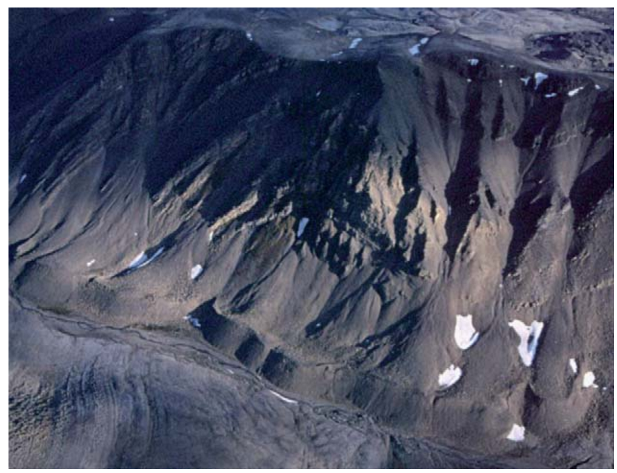

Figure 6 Typical ramp-type rockglaciers on Svalbard.

Figure 7 Rockglacier in the Tien Shan. Photograph S. Titkov.

of debris reworking. If this layer is at least as thick as the local active layer, i.e., the seasonal thaw depth under the specific local conditions, positive ground temperatures during summer cannot reach down to the ground-ice-containing permafrost body. Thus, ground-ice can persist over very long time periods.

From the above principle it becomes clear that the long-lasting persistence of the frozen core within a rockglacier requires permafrost conditions. The difference between rockglaciers, dead ice, or debris-covered glaciers can thus be described by the thermal state of the material.

Transformations between these conditions are possible. For instance, glacier ice under an insulating debris cover and lying within a permafrost environment is subject to seasonal ice melt, though substantially damped, wherever the debris cover is thinner than the local seasonal thaw depth. The ice body will continuously lose mass if not compensated by the advection of glacier ice. The resulting meltwater, and with it the contained energy, can percolate into and warm the underlying ice body. If the ice body contains sufficient debris, this material will accumulate at the top of the ice core, leading to a thickening of the debris cover. When the thickness of this debris cover equals local seasonal thaw depth, the underlying ice is protected against surface melt unless lateral processes such as ice flow or erosion occur. Thus, the debris within rockglaciers might stem from periglacial and glacial processes, and the rockglacier ice content might originate from refreezing rain and meltwater, glaciers, buried ice- and snow patches, etc., or combinations thereof. Temporal transformations and spatial transitions between rockglaciers, debris-covered glaciers, or dead ice, ice-cored moraines, etc., are certainly possible, and indeed often found in nature.

Being closely related to permafrost conditions rockglaciers indicate the existence of discontinuous or continuous mountain permafrost on a regional scale. The lower boundary of regional rockglacier distribution does, however, not generally coincide exactly with the lower boundary of permafrost distribution. Rockglaciers may end above the regional permafrost limit due to topographic conditions, the lack of sufficient material supply, or insufficient time to fully develop. Alternatively, the coarse debris cover on top of a rockglacier favors ground cooling due to enhanced heat transfer to the atmosphere. Rockglaciers may therefore extent below the regional permafrost limit when the surrounding terrain cover causes comparably higher ground temperatures.

Composition

The composition of rockglaciers is investigated by boreholes and geophysical surveys, in particular geoseismics, direct current resistivity soundings, or georadar. So far, only a few boreholes have been drilled through rockglaciers. It is, therefore, not absolutely certain to what extent the related findings can be generalized. All drillings revealed a surface layer of ice-free debris with a thickness on the order of meters (active layer). The underlying layer of a few tens of meters of thickness consists of a frozen mixture of ice and debris with an ice content ranging from close to 100% to a few tens of per cent. In rockglaciers where deep core-drilling has been conducted, a third layer of frozen coarse debris with little ice content was encountered. This layer is believed to originate from surface blocks fallen over the rockglacier front and overridden by the advancing rockglacier (*see* Kinematics and advance below).

In the rockglaciers with deep core-drillings, a meter-thick layer of sand-rich ice was found within the second ice-rich layer, at depths between 15 to 30 m. The majority of the horizontal deformation within the rockglacier was found to be concentrated in these sandy ice layers (see Kinematics and advance below).

A large number of geophysical soundings have confirmed the general layering and composition described above for other rockglaciers. In addition, some high-resolution soundings revealed fine layers within the above-described ice-rich subsurface layer. These microlayers were attributed to seasonal sequences of snow/ice and debris deposition at the rockglacier surface, and their continuous incorporation and deformation within the creeping body.

Kinematics and Advance

Beside their special thermal conditions, the second fundamental characteristic of rockglaciers is their mode of displacement. Provided there is sufficient terrain slope, the ice-debris mixture within a rockglacier deforms under the force of gravity and the stress of the vertical column. The resulting surface speeds on rockglaciers amount to up to several meters per year. Rockglacier surface speed depends among other things on surface slope, composition and internal structure, thickness of the ice-rich body, and ground temperature. The observed minimum surface speeds of a few millimeters per year are not limited by the deformation process itself, but rather by the available measurement technique (e.g., digital photogrammetry, global navigation satellite system, radar interferometry).

A coherent ice content within rockglaciers leads to the lateral transfer of stresses, and thus to a coherent velocity field (Fig. 8). Due to effects such as lateral friction and variations in viscosity, the highest horizontal speeds on a rockglacier are usually found along its centerline. In the few boreholes available so far through rockglaciers, the horizontal deformation was concentrated in horizontal layers of some decimeters to meters thickness, rather than distributed through the body of the rockglacier with a clear

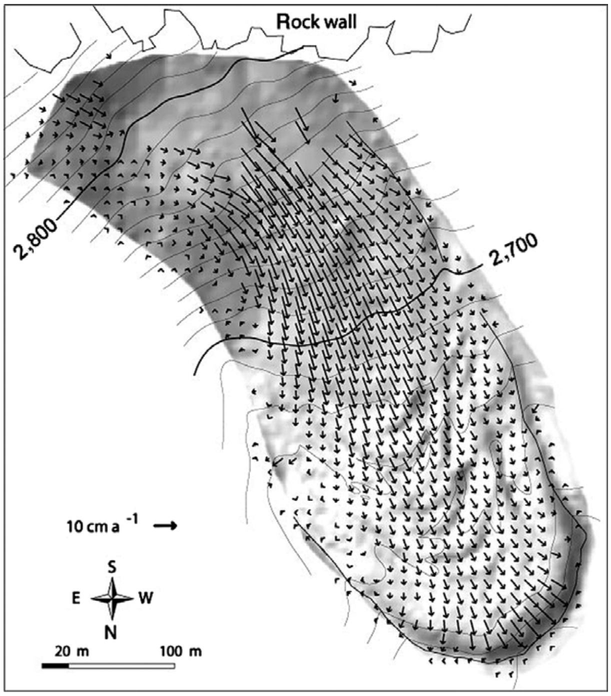

Figure 8 Surface displacement vectors on Murtel rockglacier, Swiss Alps, measured from air photos of 1987 and 1996.

parabolic variation of horizontal speeds with depth such as found for glacier ice.

The basic concept of mass transport within a rockglacier can be derived from the characteristic thermal and kinematic conditions: debris is deposited at the rockglacier surface, either directly from weathering processes at the headwall or from other secondary sources, in most cases glaciers. Together with ice from different sources (see Thermal conditions above) this mass represents the mass input to the rockglacier system. Following a basic law of fluid dynamics, the surface debris is transported downslope with the highest creep speeds at the surface of the rockglacier. The advected surface material then falls over the steep rockglacier front. The grain-size sorting along the frontal slope occurring during this process leads to the typical appearance of rockglacier fronts. The surface debris that accumulates at the front is then overridden by the advancing rockglacier and again incorporated into its base ('caterpillar' or 'conveyor belt' effect). Due to their debris content and thermal conditions, rockglaciers, in contrast to glaciers, cannot retreat. In the case of a total cessation of mass supply, a rockglacier will remain stagnant in its horizontal extent but not retreat. The main process of mass loss is the melt-out of ice at the rockglacier front where the thermally protecting debris cover becomes thinner than the thaw depth due to frontal erosion. In addition, the frontal grain-size sorting leads to smaller grain sizes in the upper part of the front, which reduces the insulation effect in comparison to the coarser debris at the rockglacier surface. Further processes of mass loss of rockglaciers include evacuation of debris, erosion and rockfall over steep terrain, debris flows, or fluvial and coastal erosion. Due to the melt-out of ice, the potential loss of debris, and the decrease of horizontal speeds with depth, the advance rate of rockglaciers is significantly smaller than their surface speed. Advance rates measured so far range from a few centimeters to decimeters per year.

Shape and Surface Morphology

Rockglaciers can be up to several hundred meters in width and up to a few kilometers in length. Their altitudinal extent amounts up to several hundred meters, their thickness up to several tens of meters. The overall shape and extent reflects the creep of the mass, usually along the steepest descent of the terrain. The ratios between rockglacier length and width vary significantly, with values both above and below one. The latter ratio reflects a number of internal conditions such as viscosity, and external factors such as topography or mass supply.

Many rockglaciers show a characteristic surface morphology consisting of a sequence of transverse and/or longitudinal ridges and furrows. This morphology in addition to the overall shape makes rockglaciers resemble lava streams. So far, little is known about the origin of the rockglacier surface morphology.

According to the main hypotheses on transverse ridges and furrows on rockglaciers, their formation might be attributed to: external factors, such as variations in debris input or climate conditions, or internal factors, such as the dynamic evolution of ridges under compression flow, or disturbance propagation from differential movement of discrete layers. In addition, it is as yet unknown whether transverse ridges and furrows represent dynamic structures, for example, forming from emergence under compression flow regime (i.e., active formation), or if these forms are thermally derived due to, for instance, differential melt (thermokarst) or frost heave processes (i.e., passive formation). It is important to note that these four elements of hypotheses do not necessarily contradict each other. One possible process might enhance the other, or a combination might be necessary for the formation of microtopographic structures. A number of studies suggest that compressive flow is a major process involved in the formation of transverse ridges.

The high thermal inertia of rockglaciers allows these frozen bodies to continuously deform and preserves their topography over centuries and millennia. In addition, the content of debris and the ice-free, blocky active layer of rockglaciers contribute to the conservation of surface features even over periods of ice-melt. The surface topography of rockglaciers cumulatively reflects the dynamic history and thus in a complex way, their present and past internal conditions and environment.

Activity and Age

The degree of activity of rockglaciers is usually classified in three different types: (i) active, (ii) inactive, and (iii) relictic. It should, however, be noted that this classification is a theoretical concept. The transition between the three stages is actually continuous.

Active rockglaciers (Figs. 1–3) have a coherent core of ice-rich frozen debris, the deformation of which leads to the creep of the feature with rates of several centimeters to meters per year. The permafrost conditions of the body are intact, with perennially negative ground temperatures throughout the entire column except for the active layer where seasonal thaw is found. The continuous creep and related debris transport along the surface leads to the characteristic steep front with freshly exposed fines in the upper part and coarser debris in the lower part, vertically sorted by grain size due to debris fall along the front (see Kinematics and advance above). The continuous deformation of the rockglacier surface, rotation, and possibly related uplift of individual blocks, and the out-wash of fines towards the permafrost table allows only few specialized plant species to grow, if at all, and prevents lichens reaching great age and size.

Inactive rockglaciers (Fig. 4) have no coherent ice-core, and thus no coherent velocity field due to the lack of stress transfer. They show no significant horizontal speed, except perhaps local movement, for example, due to thermokarst processes, patches of ice-rich ground, or erosion processes. Inactive rockglaciers contain a permafrost body, though thinner with a thick active layer (see Environmental change and climatic significance below). They can be transitional forms between active and relict rockglaciers. However, indications have also been found that active rockglaciers might become inactive for certain periods, for example, due to climatic changes, but reactivate after environmental conditions became suitable again. Due to their kinematic inactivity, inactive rockglaciers or inactive parts of rockglacier complexes usually show more vegetation cover, and more and larger lichens compared to active rockglaciers under a similar environmental setting. In particular the frontal parts with fines exposed are preferred locations for vegetation invasion. Due to the lack of material supply towards and over the front, erosion is able to reduce the frontal slope.

No permafrost is present in the bodies of relict rockglaciers (Fig. 5), and the ice content has completely melted out. Due to this mass loss, the surface of relict rockglaciers is concave, but with the original debris concentration of the active phase still reflected in the surface topography. The characteristic ridges on rockglaciers can often also be recognized on relict rockglaciers. Similarly, the frontal zones, which in active rockglaciers contain less ice, become visible as terminal ridges. Relict rockglaciers might be covered by dense vegetation, even trees. For some rockglaciers with clear relict characteristics patchy permafrost and ground ice occurrences, and even movements on the order of millimeters per year have been found, pointing to continuous transitions between the stages of rockglacier activity.

A number of studies have shown that the age of active rockglaciers is in the order of some to many millennia. The dating methods used range from surface-dating techniques, ^{14}C dating of organic material recovered from boreholes, flowline calculations, and lichen measurements to paleoclimatic considerations and numerical models. In the European Alps, today's relict rockglaciers are believed to have formed during the last Late Glacial period, though much older forms might exist in places where the climate conditions permitted continuous evolution and glaciations did not interrupt it.

Environmental Change and Climatic Significance

Rockglaciers are intimately dependent on their geoecological environment. Thus, changes in these conditions have a potentially strong effect on the rockglacier system. Millennia-scale climatic changes, for example, temperature shifts such as between the last glacial maximum, the Late Glacial period, and the Holocene, affect among others the thermal conditions, and the production and availability of debris. An increase in ground temperatures, possibly above the 0° C threshold, and/or a reduction of headwall weathering and rockfall onto underlying rockglaciers is, for instance, most likely responsible for the decline in activity of rockglaciers at the beginning of the Holocene. Similarly, the atmospheric warming trends since the end of the Little Ice Age observed in most cold mountain regions may be responsible for the recent decay of rockglaciers. Indeed, the altitudinal belts where active, inactive, and relict rockglaciers are found suggest that temperature changes are an important driver of changes in rockglacier activity.

Significantly less well investigated, but potentially of similar importance to temperature, is the influence of long-term changes in precipitation regime. Related changes in mass supply or ground temperature may also be due to spatiotemporal changes in snow cover. Changes in the climatic regime may also indirectly favor or hinder rockglacier development. Thus, rockglaciers may be overridden by glaciers in times of climate change, or rockglaciers may develop or recover at locations previously occupied by glaciers (see Thermal conditions above).

As yet, still too little is known about the exact climatic significance of rockglaciers in order to use them safely for the reconstruction of paleoclimate. The typical climate of modern active rockglaciers seems similar to the conditions found at the equilibrium line altitude of modern glaciers, though somewhat drier. Thus, the altitudinal belts where active, inactive, and relict rockglaciers are found can be used as proxy for paleoclimatic conditions that were suitable for active rockglaciers to develop. Such reconstruction is, however, substantially complicated by the fact that rockglacier evolution is not only dependent on climatic conditions, but also on debris supply and interactions with glaciation. For instance, insufficient debris production might inhibit formation of a rockglacier under otherwise suitable geoecological conditions or, the topographic and local climate conditions might favor a glacier to occupy the potential geoecological niche of a rockglacier. In addition, former rockglacier forms might have been removed by glacial erosion, or covered by modern glaciers. As a result, reconstruction of ancient rockglaciers and their paleoclimate requires the consideration of the complete and complex spatiotemporal history of periglacial, glacial, and mass-wasting processes throughout the existence of the rockglaciers investigated.

Geostatistical investigations on the basis of surface velocity measurements and climatic parameters, laboratory tests, and numerical modeling show that the deformation rate of rockglaciers is, among other factors (e.g., slope, composition, or thickness) dependent on the ground temperature. Warmer rockglaciers show in general higher surface velocities than colder ones. Consequently, ground temperature warming, for example as a result of atmospheric warming or changes in snow cover, is expected to increase rockglacier deformation. Indeed, early investigations confirm a significant recent acceleration of many rockglaciers in the European Alps, where an air temperature increase of close to $+1^\circ$ C was observed since the 1980s.

From theoretical considerations rockglacier permafrost will react in three stages to atmospheric warming: (i) increase in seasonal thaw depth (i.e., active layer thickness), (ii) ground temperature warming, and (iii) thermal adjustment towards a new thermal equilibrium accompanied by reduced thickness of the permafrost body (decreasing permafrost table and increasing permafrost base).

See also: **Carbonate Stable Isotopes**: Thermokarst Topography. **Glacial Landforms, Ice Sheets**: Evidence of Glacier and Ice Sheet Extent. **Periglacial Landforms**: Permafrost.

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Talus Slopes

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Introduction

Talus slopes are coarse, clastic landforms produced by mass-wasting processes. They may be broadly defined as distinctive accumulations of loose, coarse, usually angular rock debris at the foot of steep, bare, rock slopes. The terms talus (North American) and scree (English) are synonymous and refer to both the landform and its constituent material. Alternate terms include debris slopes (Gardner, 1980) and colluvial fans (Blikra and Nemec, 1998). Talus slopes occur in a wide range of environments but most significantly in those where physical weathering