A rapidly moving small rock glacier at the lower limit of the mountain permafrost belt in the Swiss Alps

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ABSTRACT: Surface and internal movements, structure and thermal conditions were investigated on a small talus-derived rock glacier in the Upper Engadin. A borehole 5.4 m deep drilled on the upper part of the rock glacier displayed ice-saturated sediments, consisting of pebbles, cobbles and fine debris. The mean annual temperatures were close to 0°C within the uppermost 5 m of ground. Whereas the lower part moved downslope only slightly, the upper part showed rapid movement (50–$150\,\mathrm{cm\,a^{-1}}$), accelerating over a 3-year period. Inclinometers also showed large deformation of permafrost at depth. A DC resistivity tomogram indicates that permafrost is thinner than 20 m. Permafrost close to the melting point is deformed rapidly and is sensitive to inter-annual variation in ground temperature. Such rapid movement is considered to be temporary and eventually followed by inactivation of the rock glacier because of permafrost melting and a lack of debris input.

1 INTRODUCTION

The activity of talus-derived rock glaciers depends on a variety of mechanical and thermal factors. "Dynamic inactivity" results from reducing shear stress within the perennially frozen core of a rock glacier, which is caused either by a temporal decrease in debris input or by a downslope decrease in slope gradient (Barsch 1996). A numerical simulation indicates that a sudden decrease in debris input leads to gradual deceleration of the advance of a rock glacier (Olyphant 1987).

"Climatic inactivity" results from climatic warming that eventually induces the melting of the frozen core (Barsch 1996). Warming of permafrost may temporarily accelerate a rock glacier however, because ice becomes more deformable with rising temperature (e.g. Morgenstern et al. 1980). In fact, a positive correlation has been found between the permafrost temperature and annual surface velocity observed on a rock glacier located near the lower limit of mountain permafrost (Hoelzle et al. 1998).

Although such mechanical and thermal conditions have been considered to affect the movement of rock glaciers, field studies have rarely explored these conditions. This study addresses the movement of a small rock glacier located near the lower limit of mountain permafrost, because rock glaciers of this nature are vulnerable to environmental changes. Investigations involved excavation with drilling, triangulation survey, inclinometer measurement, a DC resistivity imaging and ground temperature monitoring.

2 GENERAL SETTINGS

2.1 *Location and landform*

The study site, Büz North (BN) rock glacier, is located on the northeastern slope of Piz dal Büz (2955 m ASL) in the Upper Engadin, Switzerland (Fig. 1). The bottom temperature of the winter snow cover (BTS) indicates a marginal condition for permafrost presence (Ikeda & Matsuoka 1999).

BN rock glacier originates from a talus slope at 2840 m ASL and terminates at 2775 m ASL. BN includes an upper lobe (BNU), 70 m long and 120 m wide, and lower lobe (BNL), 90 m long and 100 m wide. BNU has a steep front 10 m high, while BNL lacks a distinct front. The upper surface is flat and inclines at 25° on BNU and 17°–23° on BNL. The surface clasts consist mainly of shale pebbles and cobbles, with a few limestone boulders. The rockwall above BN rock glacier has a height of only 2–20 m and a surface area of about 1000 m².

2.2 *Methods*

The surface velocity of BN was measured annually from August 1998 to July 2001 by the triangulation survey of twelve marker boulders. The total error produced by the survey system is less than $1\,\mathrm{cm\,a^{-1}}$. Ground surface temperatures have been monitored hourly with miniature data loggers placed on BNL in early August 1998 and on BNU in early August 1999
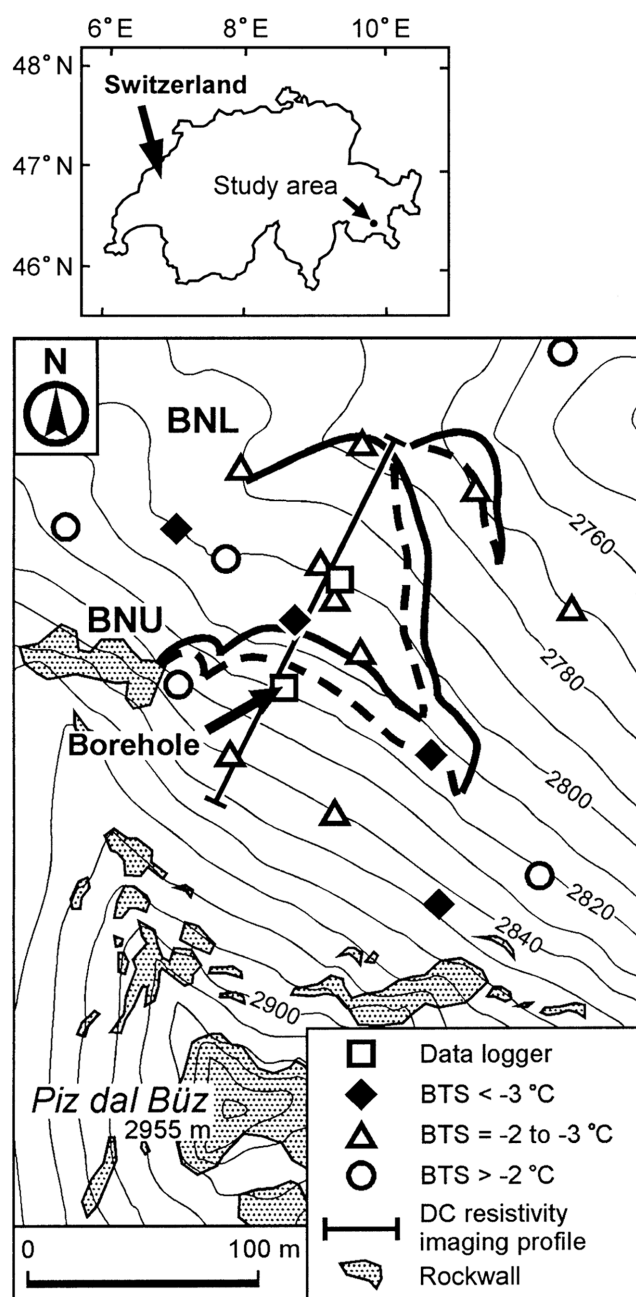
Figure 1. Location map (upper) and contour map (lower) of BN rock glacier. Contour interval 10m. The solid and broken lines show the base and top of the frontal slope of a lobe, respectively.

(Fig. 1). The two-dimensional internal structure of BN was estimated by means of the DC resistivity imaging. The Wenner–Schlumberger array was used for sounding of a profile parallel to the flow line on which electrodes were placed at 5 m intervals. The internal structure of BNU was also directly observed by excavation and drilling in early August 2000. A 3 m deep pit was excavated and then an additional 2.4 m deep borehole (6 cm in diameter) was drilled down from the bottom of the pit. Two cores (c. 10 cm long) were taken from 4 m and 5 m deep, respectively, to determine the gravimetric ice content. Seven thermocouple

probes were installed at depths of 0, 0.5, 1, 2, 3, 4 and 5 m, and two inclinometers, 35 cm long and 2.7 cm in diameter, were installed at 4 m and 5 m, respectively. The inclinometers sensed internal movement at a resolution of 0.005°. The hole was backfilled immediately after the installation. This data has been recorded in data loggers at 1 to 3-hr intervals since August 9, 2000.

2.3 The borehole stratigraphy

The pit and borehole stratigraphy on BNU mainly comprises angular shale pebbles and cobbles, with sands and silts. The exception is the uppermost 50 cm of an openwork layer. The frost table lay at about 1m deep when the pit was excavated. Below the frost table, the debris was entirely ice-saturated to the base, including a number of small ice lenses (<2 cm thick) and lacking visible air voids. The gravimetric ice content was 50% at a depth of 4 m and 28% at 5 m. The borehole did not reach the bedrock.

3 MOVEMENT

3.1 Surface movement

Surface movement showed large spatial and temporal variations (Fig. 2). All points moved downslope in consistent directions over three years. The vertical displacement of the marker boulders corresponded roughly to the values expected from the horizontal displacement and the slope angle. Most of the marker boulders on BNU moved parallel to the upper surface, indicating the advance of the front. In contrast, the uppermost point on BNU subsided by 45 cm during the three years, apparently compensating for the frontal advance.

The surface velocity of BNU was much higher than that of BNL. In the first year, BNU moved downslope at a rate of 50–80 cm a^{-1}, while BNL moved only at 2–20 cm a^{-1}. The velocity on BNL decreased from the upper part (8–20 cm a^{-1}) to the lower part (<7 cm a^{-1}). Similar spatial variation in velocity was observed in the following two years.

Movement accelerated from the first to third year at all but the slowest point. The second year velocities were, on average, 1.2 times faster than the velocities during the first year. The third year velocities were twice the first year velocities, reaching 110–145 cm a^{-1} on BNU.

Despite the presence of a silty matrix in the active layer, the majority of the surface velocity is attributed to movement in permafrost because soil movement caused by solifluction at the adjacent slopes was only 1–3 cm a^{-1} (Matsuoka et al. 1997, Matsuoka 2001).
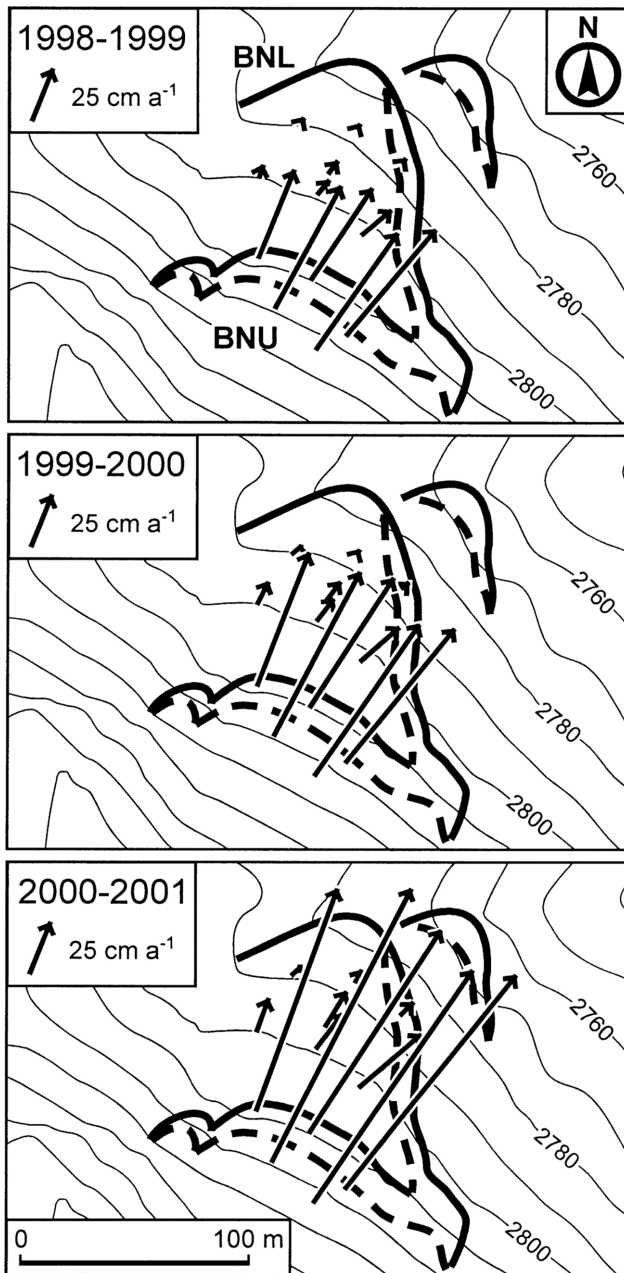
Figure 2. Annual horizontal displacement of boulders on BN rock glacier over three years (1998–2001).

In addition, the marker boulders are not susceptible to solifluction. These movements are also unlikely to have resulted from active layer slides or debris flow, because the marker boulders did not exhibit any movement due to such rapid flow during the observation period.

3.2 Internal movement

The two inclinometers indicated large deformation of permafrost at BNU. Both sensors continuously inclined downslope through the third year (2000–2001).

The measured inclinations were used to calculate a creep parameter in a simple flow law for glacier ice

(Glen 1955, Paterson 1994):

$$\dot{\varepsilon} = dV/dz = A\tau^n \qquad (1)$$

where $\dot{\varepsilon}$ is the strain rate, which is identical to the vertical velocity gradient (dV/dz), τ is the shear stress, A is the constant for a given temperature and ice type and n is an experimentally derived exponent. Strain rates were calculated to be $0.058\,a^{-1}$ at 4 m depth and $0.19\,a^{-1}$ at 5 m depth. The shear stress at a depth of $|z|$, with axis perpendicular to the surface, is:

$$\tau = \rho g|z|\sin\alpha \qquad (2)$$

where ρ is the mean density of rock glacier components, g is the acceleration due to gravity ($9.8\,m\,s^{-2}$) and α is the surface gradient. The exponent n was fixed to 3 (cf. Morgenstern et al. 1980). Assuming that an average of the two measured strain rates represents the strain rate over 4–5 m depth ($|z| = 3.8 - 4.7$ m), using $\rho = 1800\,kg\,m^{-3}$ and $\alpha = 25°$, the creep parameter A was $1.2 \times 10^{-13}\,kPa^{-3}\,s^{-1}$.

The next step is to determine the thickness of moving debris H. Equations (1) and (2) yields:

$$V_s = A(\rho g\sin\alpha)^n \int_0^H |z|^n\,dz \qquad (3)$$

where V_s is the downslope movement at the surface. Assuming that the creep parameter at a depth of 4–5 m is representative of the whole frozen layer, neglecting deformation of the active layer (uppermost 2 m) and using the average surface velocity in the third year ($140\,cm\,a^{-1}$), the downslope movement at the rock glacier surface results from the deformation of a thickness of 8.6 m. The calculation indicates that 90% of the surface velocity originates from deformation below 5 m depth. The estimated thickness approximates the frontal height (c.10 m) of BNU.

4 THERMAL CONDITIONS

4.1 Ground surface temperatures

Figure 3 displays three years of ground surface temperatures recorded on BNU and BNL. The records on BNL were interrupted from early August to the middle of September 2000.

Continuous subzero temperatures below 0°C indicate that both sites were covered with snow for more than nine months per year. In the first and second years, the bottom temperature of the winter snow cover (BTS) on BNL gradually decreased in the early winter, and remained nearly constant at about −1°C until May when BTS rapidly rose to 0°C by damping of snow. In the third year, the lowest BTS on BNL was −0.5°C,
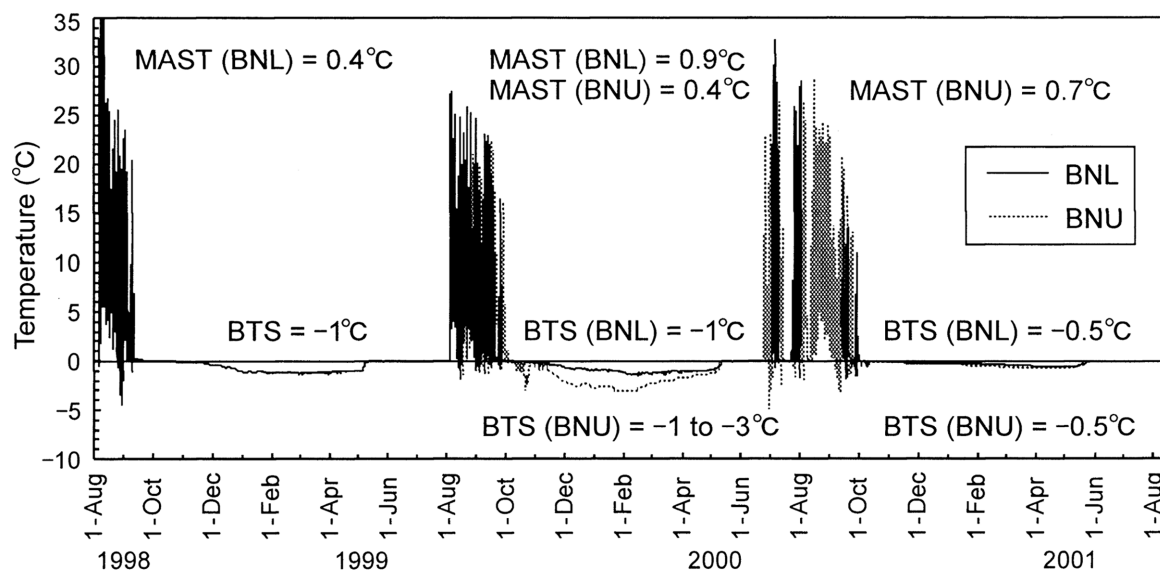
Figure 3. Three years of data on ground surface temperatures on the upper lobe (BNU) and lower lobe (BNL). Note that records on BNL were interrupted from early August to middle September 2000.

which was slightly higher than the previous two years. BTS on BNU decreased to −3°C in the second year, while the lowest BTS on BNU was only −0.5°C in the third year. In the third year, the adjacent active and inactive rock glaciers also recorded BTS values much higher than the first and second years. A large snowfall in the early winter 2000 prevented ground from cooling, producing exceptionally high BTS values.

The mean annual ground surface temperature (MAST) on both BNU and BNL was close to 0°C and rose slightly from 1998 to 2001. The increase in MAST on BNL from the first to second year (from 0.4 to 0.9°C) probably reflected the earlier snowmelt in the second year. MAST on BNU (0.4°C) in the second year was slightly lower than that of BNL. MAST on BNU reached 0.7°C in the third year. Such a rise in MAST resulted mainly from the high BTS despite the longer duration of snow cover.

The high BTS (>-3°C) and slightly positive MAST imply that the permafrost in BN is close to the melting point. In addition, the higher BTS on BN compared with values on typical rock glaciers mainly reflect the matrix-supported active layer that impedes intensive cooling in early winter (Ikeda & Matsuoka 1999).

4.2 Subsurface temperatures

The lack of ground cooling in early winter 2000 affected the subsurface thermal regime in BNU. The temperatures remained at −0.1 to 0.0°C over 1–5 m depth through the winter. In addition to the early snow cover, large thermal disturbance by excavation may have prevented cooling of the uppermost part (2–3 m) of permafrost.

5 INTERNAL STRUCTURE

The DC resistivity tomogram shows that the resistivity values in BN are of the order of 10° kΩm (Fig. 4), which is the lowest range for permafrost in active rock glaciers (Haeberli & Vonder Mühll 1996). Such low values probably result from the debris-rich frozen layer at temperatures close to the melting point. Massive ice, which has a high DC resistivity (>10 kΩm), is unlikely to exist in BN.

Two elliptic layers with relatively high DC resistivities (>4.5 kΩm), which are distinguished from the surroundings by a large resistivity gradient, underlie the frontal part of BNU and the upper part of BNL (Fig. 4). The former is about 20 m thick and the latter about 10 m thick. The higher DC resistivities in these layers may reflect slightly colder permafrost than the other part (cf. Hoekstra & McNeil 1973). In contrast, the upper part of BNU and the lower part of BNL show low DC resistivities (<2 kΩm). These parts probably lie at the melting point or higher temperatures. Thus, the permafrost layer observed in the borehole is thin and situated in a marginal location of this permafrost body.

6 DISCUSSION AND CONCLUSIONS

6.1 Deformation properties of permafrost

Both triangulation and inclinometer measurements showed large deformation of permafrost in BNU. An analysis based on the observed inclination indicated that deformation of BNU occurred entirely within the
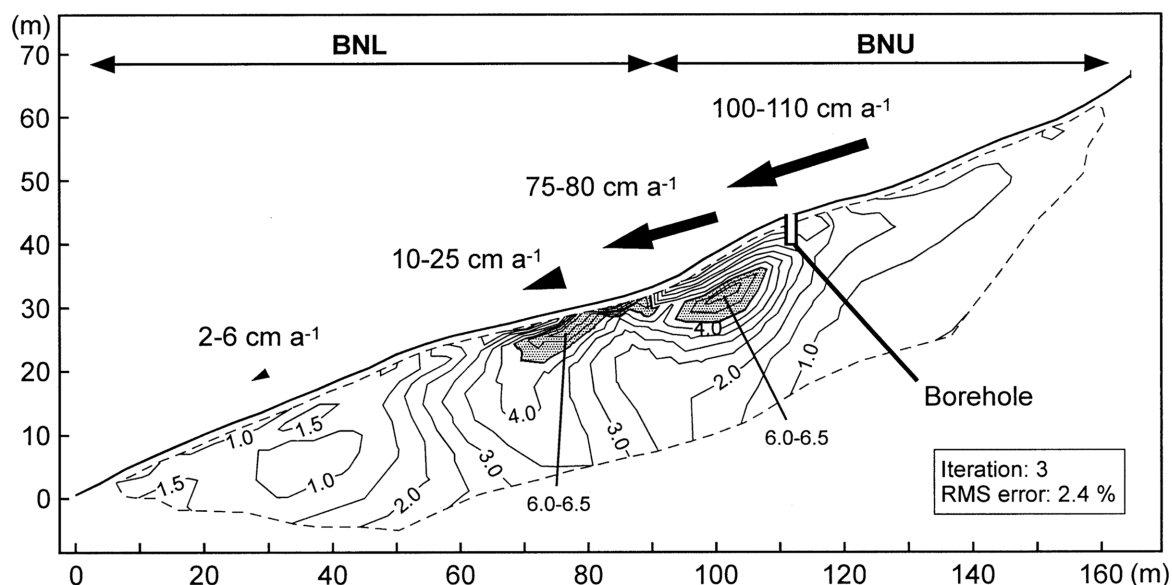
Figure 4. DC resistivity tomogram of BN rock glacier. DC resistivity values in kΩ m. The arrows indicate the average velocities for 1998–2001.

top 10 m. The large deformation is probably favoured by permafrost close to the melting point, which is indicated directly by the ground temperatures and indirectly by the low DC resistivities.

The calculated creep parameter A is significantly higher than the previously reported values of ice and ice-rich permafrost. In fact, the A value is one to two orders of magnitude higher than a value at $-1°C$ ($5.0 \times 10^{-15} kPa^{-2.9} s^{-1}$) calculated from the borehole deformation of Murtèl I rock glacier (Wagner 1992) and a recommended value of glacier ice at $0°C$ ($6.8 \times 10^{-15} kPa^{-3} s^{-1}$: Paterson 1994). Thus, the deformation of BNU is likely to be too large to originate from simple deformation of ice at the melting point.

The unusually large deformation of BNU is attributed to the presence of water. First, the unfrozen water content of frozen ground increases with rising temperature and surface area (Dash et al. 1995). The permafrost layer in BNU probably includes some unfrozen water because of the interstitial fine debris at a temperature close to $0°C$. Whereas interlocked debris tends to strengthen permafrost at low temperatures (Hooke et al. 1972), such unfrozen water may lubricate permafrost near the melting point (Arenson et al. 2002). In addition, subpermafrost water may also contribute to the rapid movement.

6.2 *Short-term variation in movement*

The observed inter-annual variation in surface velocities probably reflected the change in the ground temperature (see Figs 2, 3), because the surface velocity on BN increased with rising MAST. The lack of

ground cooling in the third winter (2000–2001) probably accelerated the deformation of permafrost.

Shallow permafrost responds significantly to annual to inter-annual variations in ground surface conditions (e.g. Haeberli et al. 1999, Harris 2001). A large fluctuation may also occur in the deformation properties of permafrost near the melting point. As a result, the movement of BN is sensitive to inter-annual change in ground temperature.

6.3 *Long-term variation in movement*

In contrast to the rapid movement of BNU, the lower part of BNL moved very slowly (see Figs 2, 4), which may indicate ongoing inactivation of BNL. Both MAST and BTS on the upper part of BNL were higher than those of BNU (Fig. 3). Although no temperature data is available, these values are considered to rise towards the lower part of BNL, because seasonal snow cover disappears much earlier in the lower part. This condition favours the degradation of permafrost close to the melting point. The thinning of permafrost probably results in the decrease in DC resistivity from the upper to lower part, which corresponds to the decrease in surface velocity.

In the light of the mass balance, the amount of debris supply also influences the movement of BN. The rapid movement of BNU is unlikely to balance with the debris supply, because the rockwall above BNU is too small to feed a large amount of debris. An unreasonably high rate of the rockwall retreat ($>50 cm a^{-1}$) is required to compensate the talus volume lost by the observed movement of BNU. This suggests thinning of BNU over the observation period, which may in turn

result in deceleration of movement (cf. Olyphant 1987). The slow movement of BNL may partly represent such an adjustment. In addition, long-term slope deformation of more than 1 m at the surface and down to a depth of several metres has to result in a volume of rock glacier far exceeding the value estimated from the observed slope geometry of BNU, because the downslope movement of the debris is decelerated towards the unfrozen frontal part. The present high velocities, despite the small frontal slope, therefore indicate that the recent acceleration is a transient feature. Consequently, small rock glaciers located near the lower limit of mountain permafrost experience a large variation in movement at both inter-annual and long-term time scales.

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