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Evidence of winter ascending air circulation throughout talus slopes and rock glaciers situated in the lower belt of alpine discontinuous permafrost (Swiss Alps)

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The winter ascending circulation of air throughout an accumulation of coarse slope sediments (the so-called chimney effect) facilitates the cooling of the ground and even the occurrence of permafrost in the lower part of a deposit. Simultaneously, any freezing is unlikely to occur in the upper part. To date, the chimney effect has been reported mainly for cold and sometimes perennially frozen scree slopes situated at low elevations, far below the regional limit of the discontinuous mountain permafrost. This article reports observations made recently in the western Swiss Alps in several accumulations of coarse sediments (talus slopes, relict or inactive rock glaciers) located at higher elevations (2200–2800 m a.s.l.) within the belt of discontinuous permafrost or close to its lower limit. These observations show that a chimney effect may also occur in debris accumulations situated at 'usual' mountain permafrost elevation. This gives rise to multiple questions, in particular about the impact of the chimney effect on both the thermal regime and the spatial distribution of discontinuous mountain permafrost.

Keywords: *air circulation, discontinuous permafrost, rock glacier, Swiss Alps, talus slope*

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Introduction

The occurrence of extremely low altitude permafrost is frequently reported from mid-latitude regions (Europe, Japan). Besides ice caves, such a marginal permafrost is systematically described as occurring in the lower part of scree slopes. Several studies (Wakonigg 1996, Delaloye et al. 2003, Gude et al. 2003, Sawada et al. 2003) have highlighted that a mechanism of air circulation occurs throughout the whole debris accumulation – the so-called chimney effect, or wind-tube – and provokes the strong overcooling of the ground in the lower part of the slope. Ventilation acts through the porous material depending on the contrast in air temperature, and hence in density, between the interior of the scree and the surroundings. As a consequence, the ascent of relatively warm air towards the top of the scree in wintertime facilitates the aspiration of cold air deep inside the talus slope (Delaloye 2004b). A gravity discharge of cold air then occurs during summer. Permafrost can form and be preserved in ventilated talus slopes located more than 1000 m below the regional limit of discontinuous permafrost, where the mean annual air temperature is more than +5°C.

At higher elevations, i.e. within the belt of discontinuous permafrost – above 2200–2300 m a.s.l. on northern slopes in the Alps as a rough estimate, it is common to observe that permafrost is often restricted to distinct areas, usually located in the lower part of the debris accumulation, whereas the upper part is usually warmer and not underlain by permafrost (Lerjen et al. 2003, Luetschg et al. 2003, Lambiel et al. in press). Haeberli (1975) was the first to describe this 'rule of thumb' of the alpine permafrost distribution. He attributed its origin mainly to late-lying remains of snow avalanches that prevent the ground from warming during the summer. This assumption was commonly accepted and has not been discussed in-depth until recently. Reworking on the Haeberli's talus slope at the Fluëlapass in Eastern Swiss Alps, Lerjen et al. (2003) found, on the one hand, that the permafrost pattern has not significantly changed since the 1970s despite a warmer climate and, on the other hand, that the spatial repartition of permafrost does not fit satisfyingly with the late-lying snow pattern, but rather with the areas covered with coarse debris. The hypothesis of localized cooling caused by air circulation was advanced as a possible explanation.

The hypothesis of a chimney effect has rarely been envisaged acting within the belt of discontinuous permafrost (Harris & Pedersen 1998). Could such a mechanism nevertheless occur throughout a whole talus slope or even throughout part or whole of a rock glacier – especially within the relict and inactive forms? Referring to the understanding of permafrost occurrence in low elevation talus slopes, this article reports measurements and observations carried out on various talus slopes and on an inactive rock glacier in the western Swiss Alps showing evidence of the occurrence of a chimney effect in the belt of discontinuous permafrost.

Background

The mechanism of air circulation within low elevation talus slopes

The available literature (Lambert 1967, Wakonigg 1996, Molenda 1999, Ruzicka 1999, Gude et al. 2003, Sawada et al. 2003) and our own measurements and observations carried out in several sites at low elevation (Delaloye et al. 2003, Delaloye 2004a) allow us to summarize the mechanism of air circulation throughout a talus slope as follows:

- The internal ventilation is a reversible mechanism where both intensity and direction primarily depend on the contrast in air temperature between the interior and the outside of the formation. However, as the talus slope typically has much colder temperature in the base than in the upper part, the reversibility of the ventilation system is much more complicated. Detailed investigations are still required.
- In winter, the warm air, which is lighter than the atmospheric cold air, moves upwards and is expelled out of the upper part of the slope (Fig. 1). The mechanism causes the aspiration of cold air into the lower part of the scree. The process is most efficient during very cold weather and seems to be able to cool the ground rapidly in certain cases down to 15 m depth (Delaloye 2004b). A considerable cold reservoir is thus built within the scree.
- The winter phase of the mechanism operates even in spite of the presence of continuous snow cover 1 m to 3 m thick.
- A gravitational release of dense cold air occurs at the base of the talus slope when the outside air temperature is warmer than inside. The ground and the atmospheric boundary layer are cooled during the summer on the lowermost part of the scree, which prevents the vegetation from growing normally.
- The mechanism of ventilation causes a negative annual thermal anomaly (thermal offset) on the lower part of the slope that can reach 3°C to more than 7°C compared to the surrounding air (Wakonigg 1996, Gude et al. 2003, Kite et al. 2004). A positive thermal anomaly is generated in the upper part of the slope.

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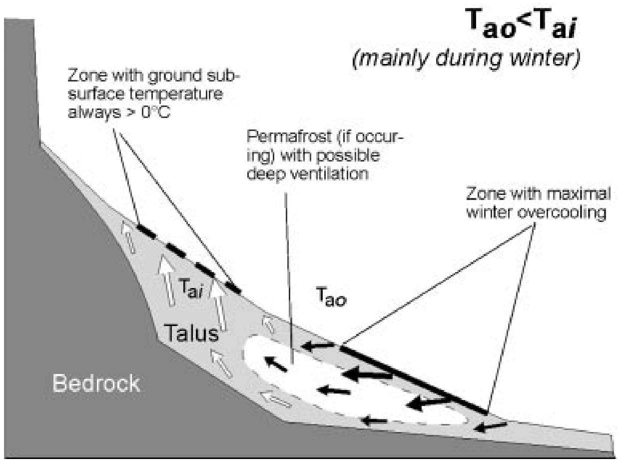

Fig. 1. Schematic model of the winter ascending phase of the ventilation system throughout a low elevation cold talus slope (based on Delaloye 2004a). T_{ao}: temperature of the surrounding air; T_{ai}: air temperature within the upper part of the talus slope; arrows indicate the movement of relatively warm (white) and cold (black) air inside the talus slope.

- The ventilation process, inducing a seasonal or annual cooling of the lower part of a talus slope, is characteristic of a considerable number of debris accumulations, irrespective of their orientation and their dimensions (Ruzicka 1999, Rist 2003). The distance between the lower and upper openings ranges from less than 10 m to (much) more than 100 m.

Many questions still remain, however, concerning the precise operation of the ventilation system: in particular, the phase changes of water within the ground and their consequences on the thermal regime at depth in the scree.

Indices of air circulation activity

How can we detect the occurrence of an internal ventilation mechanism at the surface of a debris accumulation? From our experience (Delaloye 2004a), several indices may be highlighted, that demonstrate in particular the winter ascending phase of the chimney effect. The ventilation induces thermal behaviours of the ground that are highly contrasted between the lower and upper parts of a slope. The following observations are therefore to be expected:

- The mean annual ground surface temperature (MAGST) is definitely colder at the bottom of a slope section subject to a chimney effect than on the upper sector.
- In the lower part, the ground temperature suffers one or more pronounced decreases in winter, which are systematically linked to a strong cooling of the surrounding air temperature. They are buffered, but especially significant when the snow cover is thick (that proves that the air still ventilates through the thick but porous snow cover).
- In winter, in the presence of snow, the ascent of warmer air within the talus slope prevents the ground surface from freezing in the upper part of the debris accumulation. The ground sub-surface temperature in the upper part, however, regularly cools during the winter, with a slight tendency to warm when the outside air temperature is very cold (reverse thermal relationship due to an intensification of the air ascent; severe temperature decrease occurs simultaneously in the lower part).
- The ascent of warmer air also causes the basal melting of the snow cover. A slow collapse of the snow pack may occur, which then produces sinking forms at the snow surface. Chimneys (funnels) may also open through the snow cover. In spring or when the latter is thin, these zones are the first to be free of snow (snowmelt window).
- A release of cold air is perceptible in the lower part of the slope in summer. It favours the preservation of ground ice close to the surface for several weeks after the snow has completely melted.
- Despite a full understanding, a difference may exist between the (winter, summer or annual) pattern of the ground surface temperature and the positioning of the frozen materials at depth. The zones containing the most ice are evidently located upstream of the sectors where the ground surface temperatures are the coldest.

The relevance of these indices varies according to altitude, orientation and ground composition which roughly determine, on the one hand, the average temperature of the whole debris accumulation and, on the other hand, the thermal threshold of inversion of the ventilation process. For instance, at 2500 m a.s.l. in the Alps, on northern aspects, the average temperature of the ground at depth may be close to 0°C; thus, the temperature of the air that should be expelled in the upper part of the slope during the winter is not necessarily (much) warmer than 0°C; in this case, one cannot hope to observe 'snowmelt windows' or 'chimneys' on the top of a slope.

Concepts of air circulation at high elevation

To date, the various modes of air circulation which are usually considered as acting in coarse materials located within the permafrost belt relate only to the active layer. Because of the absence of soil and vegetation, concepts of air circulation with a vertical principal component (convection) prevail. Lateral movements (advection) are assumed to occur only over short distances within the active layer.

In a superficial blocky layer, the air can move easily in the form of convection cells (Balch effect) controlled by contrasts in temperature. Exchanges with the surrounding air occur, which differ depending on the snow cover conditions. In the absence of snow or when the snow cover is shallow, the convection can operate directly between the ground and atmosphere (Keller 1994, Harris & Pedersen 1998). When the thickness of snow increases, the exchange of air between the ground and the atmosphere may continue to occur by the formation of openings (funnels) through the snow cover (Bernhard et al. 1998), a phenomenon which is maintained during most of the winter and which contributes to the cooling of the active layer and of subjacent permafrost (Hoelzle et al. 1999). The spatial density of these funnels decreases as the snow cover thickens (and as the active layer cools). When the snow cover is continuous, air convection operates only inside the superficial blocky layer where the temperature profile becomes isothermal (Delaloye 2004a). Air advection may also take place in inclined slopes (Bader et al. 1939).

The assumption that a chimney effect concerns the whole of an accumulation of coarse debris (talus, rock glacier), with air circulation at relatively great depth, operating and contributing (partially) to the cooling of certain portions of the ground, has never been proposed explicitly, though it cannot be excluded. The single requirement for air to circulate is that the effective porosity is large enough and it is not completely sealed with ice.

Air circulation within rock glaciers?

The current investigations on air circulation within rock glaciers relate primarily to those affecting the surface layer of active formations (Hanson & Hoelzle 2003, Herz et al. 2003). What happens at greater depth? Significant layers of coarse blocks without fine matrix and incorporated ice were found after drilling beneath a 10–15 m layer of ice and rock mixture in the terminal part of the Muragl active rock glacier as well as at the base of the Murtèl active formation (Arenson et al. 2002). On the basis of thermal measurements, Vonder Mühll et al. (2003) suspected not only water but also air to circulate in the basal blocky layers of the Murtèl rock glacier. However, this is still far removed from an air circulation of chimney-effect type; however, these observations show that the porosity of an active rock glacier can locally be relatively significant. In inactive or relict rock glaciers, the weaker ice content increases potentially the porosity, and consequently the capacity for air to circulate. The presence of frozen materials within rock glaciers morphologically considered as relict (which, according to the definition would be then inactive formations) is frequently discovered (during excavation works at Dent-de-Nendaz or Mont-Dolin/Arolla in the Valais Alps). Is it therefore possible that a chimney effect contributes to cool the interior of the formation and to preserve ice within inactive or relict rock glaciers whose activity period would date back to Late Glacial or early Pleistocene (Frauenfelder et al. 2001, Lambiel & Reynard 2003)?

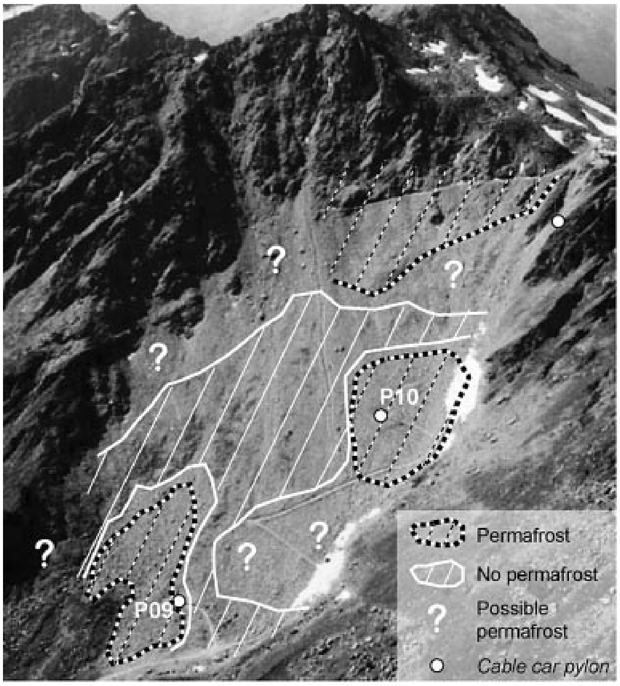

Fig. 2. Synthetic scheme of the spatial repartition of permafrost on the Lapires talus slope based on the interpretation of electrical resistivity and ground surface temperature measurements (BTS and continuous logging). Photo: C. Lambiel, July 2000.

Method

From previous fieldwork and projects initiated since 1996, there is a large amount of self-performed measurements from more than 10 talus slopes and from several relict or inactive rock glaciers, namely (depending on site): electrical resistivity measurements (vertical sounding, mapping and 2D profiling), ground surface temperature data (continuous logging, BTS (bottom temperature of the winter snow cover)), borehole temperature records, and in situ climate data. The measurement strategy was not specifically designed to resolve the question of air circulation within the sediments. The understanding of the principles and consequences of the ventilation in low elevation sites has made a new analysis of the data meaningful. Selected results from two talus slopes and an inactive rock glacier are presented in this article, as well as some complementary observations carried out recently. Indices of the chimney effect have been detected on most sites.

Lapires talus slope

The Lapires site (46°06′N, 7°17′E) is a vast concave talus slope (Fig. 2), more than 500 m wide, north-easterly oriented, extending between 2350 and 2700 m a.s.l. at the foot of the Pointe des Lapires summit (2973 m a.s.l.). It primarily consists of metamorphic clasts. The slope is affected by snow avalanches, the frequency and magnitude of which vary strongly from year to year. The in situ mean annual air temperature (MAAT) was +0.5°C at 2500 m a.s.l. between 1999 and 2003. Excavations carried out in June 1998 down to 7–8 m depth for the installation of two cable car pylons (P09 and P10 (Fig. 2) exposed sediments more or less saturated with ice (Lambiel 1999). The temperatures measured in a borehole drilled near P10 have indicated the occurrence of a temperate permafrost (temperature at or close to 0°C) reaching at least 20 m depth (Delaloye et al. 2001, Vonder Mühll et al. 2004).

The measurements (electrical resistivity, ground surface temperature) carried out on the slope have shown that the distribution of permafrost is discontinuous (Reynard et al. 1999, Delaloye et al. 2001, Marescot et al. 2003). The warm state of the permafrost, however, makes the interpretation of the measurements sometimes difficult, and hence accurate determination of the permafrost zones. In spite of many uncertainties, a map of the spatial distribution of permafrost can be outlined (Fig. 2). Permafrost does not occur in the median sector of the slope as well as locally in the lower part. Permafrost exists in the upper part of the slope, above *c.*2600 m a.s.l. and also discontinuously in the lower half of the slope. In particular, two zones located around P09 and P10 are frozen. They correspond roughly to the sectors where the superficial grain size is the coarsest. However, in the P10 zone, the BTS and apparent electrical resistivity (ρa) do not spatially coincide (Fig. 3): cold BTS values (< −3°C) are obtained downhill of the zone where ρa is high (the latter being interpreted as frozen sediments). Moreover, a window including warm BTS values close to 0°C is located immediately above the sector with high resistivity. These peculiarities are typical for a debris accumulation affected by a process of internal ventilation, which raises the question of whether the latter really operates within this part of the talus slope.

Winter thermal regime of the ground at the foot of P10

The temperature has been recorded since autumn 1998 between 15 cm and 575 cm depth within the removed materials sealing the excavation of P10 (2500 m a.s.l.). The plastic pipe containing the sensors is in contact with the concrete foundations of the pylon. Fig. 4 shows the ground thermal regime registered during winter 2000–2001, as an example. At every depth, secondary variations in temperature, reaching a few tenths of °C, are superimposed during the whole winter to the 'seasonal' thermal regime. Except for close to the surface until mid-December, these variations are reversed compared to those of the surrounding air (i.e. warming by cold weather). The secondary variations are generally synchronous and comparable in amplitude whatever the depth. The temperature never rises up above 0°C, however.

Observations in March 2004

In March 2004, BTS measurements were intensified in the warm sector upstream of zone P10. A ground surface temperature ranging between 0°C and +0.6°C was observed beneath 2 m to 3.5 m of snow. Digging through the snow cover permitted observations that the ground surface was effectively not frozen. Moreover, once the opening was achieved, a slight current of mild air (+0.2°C) escaping from the ground was readily perceptible.

Interpretation

Due to their synchronism, the reversed secondary variations in the removal material at P10 are not conductive heat transfer. They are interpreted as the effect of a slight ascent of warmer air during the coldest phases of the winter coming from deeper frozen (temperature not higher than 0°C) layers of the debris accumulation. However, it is not clear whether the air is only circulating within the removal material or whether the latter is connected with deeper porous layers non-saturated with ice. Close to the surface, during cold weather when the snow cover is still thin at the beginning of the winter, the conductive heat loss of the ground toward the surface may be more intense than heat gain produced by the ascent of air, which masks the reversed secondary variations.

The ascent of air warmer than 0°C in the upper sector in March 2004 indicates a transit of the air through an unfrozen part of the talus slope, which is probably beneath the permafrost. Combined with the observation at P10, it suggests that of a chimney effect acting on this part of the slope. The strong winter cooling of the ground on the lower part of the slope, downstream of the perennially frozen sector, could thus be the result of the aspiration of cold air within the talus slope. The intensity of the ventilation process remains to be determined. By extension, the assumption can be advanced that the spatial distribution of permafrost in the lower and median parts of the whole Lapires talus slope could also be related to a process of air circulation within the debris accumulation.

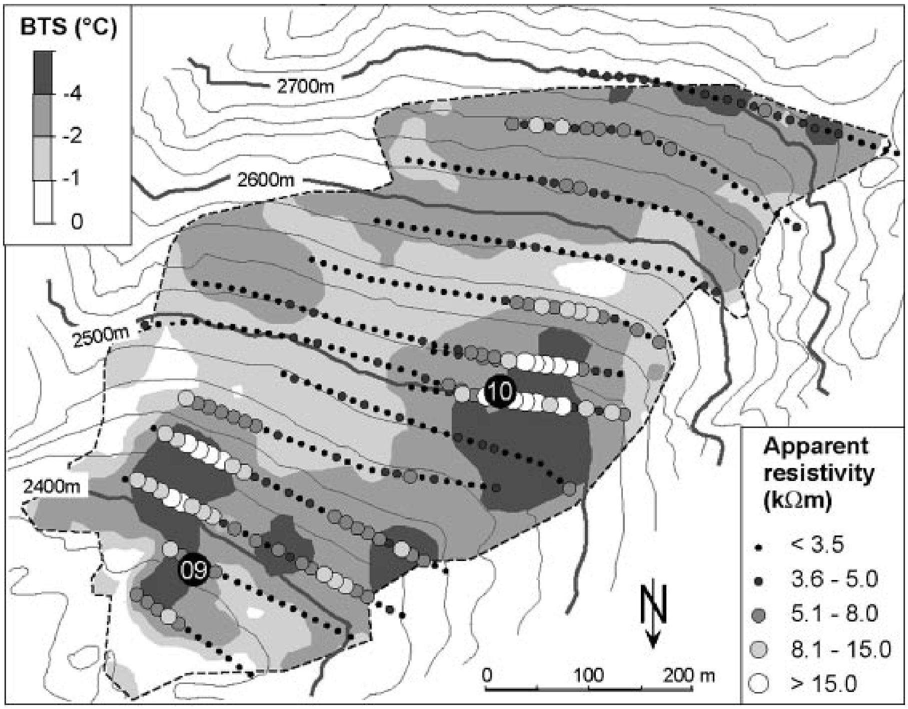

Fig. 3. Lapires talus slope: resistivity mapping (12.5 m inter-electrode spacing, Wenner array) and interpolated March 2001 BTS (kriging on a set of 301 BTS measurements). Numbered black dots are the two cable car pylons.

Petit Mont-Rouge talus slope

A small talus slope (200 m × 200 m) with a lower end at *c*.600 m a.s.l. covered the eastern flank of Petit Mont-Rouge d'Arolla (2928 m a.s.l.) (46°01′N, 7°26′E), which is a summit consisting of dolomitic marbles and breccia. A tiny active rock glacier, containing some large boulders, has developed on the northernmost part of the talus (Fig. 5a). Elsewhere, the size of the blocks usually does not exceed 10 cm to 20 cm. The talus slope is regularly inclined.

Electrical resistivity measurements indicate that permafrost may be restricted to the rock glacier in the northern part of the area. The vertical sounding PMR-S1 (Fig. 6) enables demonstration of a resistant body (90 kΩm) of frozen sediments 6–12 m thick beneath a 2–3 m deep active layer. A few tens of metres upwards on the slope, the decrease in resistivity recorded at sounding PMR-S2 means it is unlikely that permafrost will occur there. The apparent resistivity line (Fig. 6) shows that the decrease is even more pronounced further up the slope, which excludes the presence of permafrost there. Sounding (PMR-S3) located in the lower talus south of the rock glacier, above the bedrock (2.5 kΩm), reveals only a unique 15 m thick superficial layer, with a resistivity (21 kΩm) which makes it difficult to be interpreted. However, low seismic velocities of *c*.500 m/s indicate the probable absence of permafrost within these sediments.

The ground surface temperature between October 2001 and September 2002 is shown in Fig. 7 for PMR-2 and PMR-3, located on the rock glacier

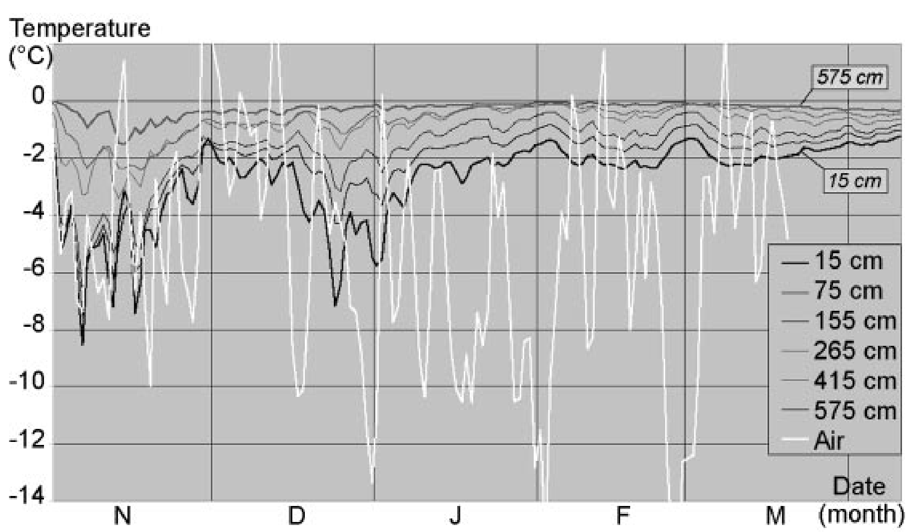

Fig. 4. Daily outside air and ground temperature regime at the foot of pylon P10 on Lapires talus slope between 1 November 2000 and 10 April 2001.

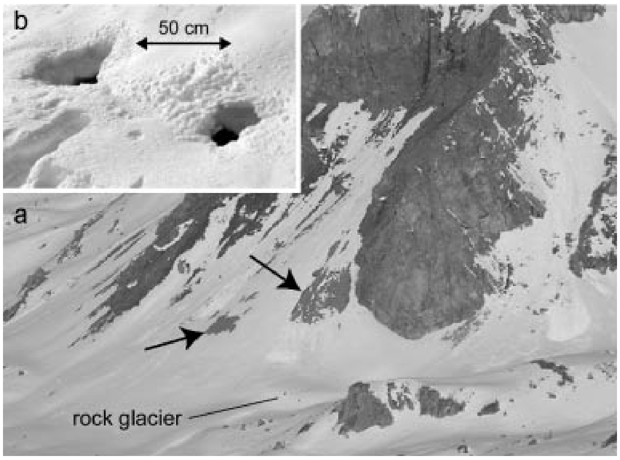

Fig. 5. (a) Early snowmelt patches (arrows) in the upper part of the slope on 16 May 2004. Photo: R. Delaloye. (b) Two funnels through the snow cover in the upper part of the Petit Mont Rouge scree slope. Photo: C. Lambiel, 2 March 2004.

and 30 m higher in the talus slope respectively. In addition to the contrast in winter temperature between the two series, warm temperatures (+0.7°C) were registered at PMR-3 during the cold wave of December 2001 when snow cover was thin. At the same time, the ground surface cooled drastically in the lower part of the slope (PMR-2). The temperatures remain positive until 22 January at PMR-3. On the basis of the temperature measurements, the winter ascent of air within the talus can be suspected.

In March 2003, several sinking forms were readily observed on the snow cover surface in the upper part of the slope; these could have been created by an ascent of warm air within the ground. BTS measurements were carried out in early March 2004 in order to test these assumptions. Several chimneys through which warm air was being ejected (Fig. 5b) were observed slightly above PMR-3. BTS temperatures recorded in the upper part of the slope were all positive (Fig. 6), up to +2°C. A strong negative temperature gradient connected this area to the very cold bottom of the slope. Minima between −6°C and −8°C were recorded on the rock glacier and south of PMR-S3 under a snow cover *c.* 1.5 m thick. However, according to the geoelectrical and seismic prospection, the latter area is not underlain by permafrost. The abnormal low temperatures recorded here and the positive values in the upper part of the slope are probably the result of a chimney effect. The finding of early snowmelt windows that were already opened by mid-May 2004 on the upper slope (Fig. 5a) consolidates the hypothesis of an active ventilation process on this partially frozen talus slope–rock glacier system.

Other ventilated talus slopes

We often found indices supporting the occurrence of a ventilation mechanism in talus slopes located near the lower limit of discontinuous permafrost. On the 10 talus slopes that we have investigated to date, the BTS mapping has frequently revealed warmer ground surface temperatures in the upper part of the slopes. Chimneys with expulsion of warm air are numerous, and particularly well developed after a period of cold and dry weather. The dimensions of the openings on the snow surface usually range from a few centimetres to 0.5 m. Exceptionally large chimneys, more than 1 m wide, are sometimes observed, for example on the upper part of a granite talus slope on

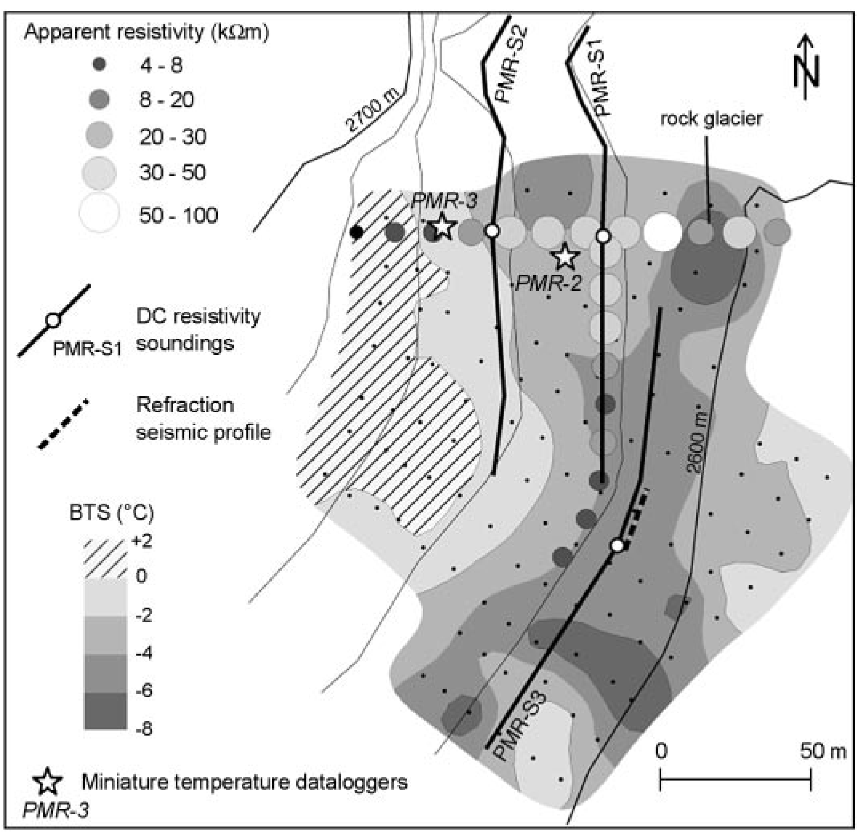

Fig. 6. Some of the measurements carried out on the Petit Mont Rouge scree slope: BTS on 2 March 2004 (interpolated with the kriging method), apparent resistivity mapping (inter-electrode interval: 12.5 m, Wenner array); location of the DC resistivity sounding, refraction seismic profile and miniature temperature dataloggers.

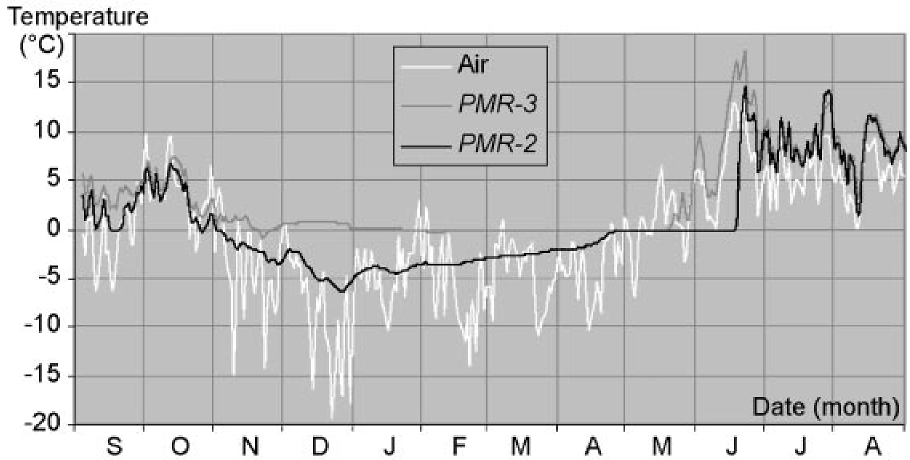

Fig. 7. Daily ground surface temperature recorded by temperature logger PMR-2 and PMR-3 on the Petit Mont Rouge talus slope (Fig. 6) and air temperature at Réchy (2795 m a.s.l., 10 km north) between September 2001 and August 2002.

the northern flank of the Génépi summit (46°02′N, 7°03′E) at 2350 m a.s.l. (Fig. 8). On slopes that are not affected by a significant avalanche activity, early snowmelt windows are observed in spring (May–June). The alignment of snowmelt windows at 2460 m a.s.l. in the upper part of the limestone talus slope on the north-eastern flank of the Tita Neire summit (46°15′N, 7°10′E) is particularly noticeable (Fig. 9). Even if snow drift by wind and small avalanches favour such a pattern of snowmelt, the shape and regularity of the early snow-free area are likely evidence for the ascent of warm air within the debris accumulation during the winter. No prospection of permafrost within the Génépi and Tita Neire talus slopes has been carried out, but with regard to the sites' elevation and aspect, the probability that permafrost will be detected in the lower part of the slopes should be high.

Inactive rock glacier at Alpage de Mille

Site description

RG1 is a north-eastern oriented, 300 m long rock glacier (46°01′N, 7°12′E). RG1 extents between 2440 and 2340 m a.s.l. at the foot of a headwall *c*.120 high (Fig. 10). The rock glacier surface is made up exclusively of decimetre- to metre-sized gneissic blocks, all densely covered with lichens. The upper part of RG1 is almost flat. At 2400 m a.s.l. a sudden change of slope occurs, below which the rock glacier tongue develops. There is no ridge-and-furrow on RG1. The well-developed vegetation cover on the headwall testifies its current very low rate of denudation. Small talus cones, which are partially vegetated, bind the headwall to the rooting zone of RG1. Morphological criteria make RG1 to be considered as inactive (Delaloye & Morand 1998). The formation of the rock glacier is undoubtedly old, probably dating back to the end of the Late Glacial or to the beginning of the Pleistocene.

The vertical electrical sounding Mi-S03, carried out longitudinally on the centre of the rock glacier, showed the presence of a frozen layer (resistivity *c*. 200 kΩm) at least 15 m thick in the upper half of formation (Delaloye & Morand 1998). The active layer reaches *c*.4 m in thickness. However, the resistive layer drastically decreases in thickness and resistivity downstream of the slope break. The resistivity mapping confirmed the result and allowed extending it to the whole rock glacier (Fig. 11). In the lower two-thirds of the tongue (below 2380 m a.s.l.), the presence of ground ice seems doubtful, and even improbable ($\rho a < 8$ kΩm).

The snow cover usually varies between 1 m and more than 3 m at the beginning of March. It can be sometimes much more thin in restricted portions of the convex central part of the rock glacier.

Fig. 8. Warm air expulsion in the upper part of the Génépi talus slope on 27 March 2004. Photo: C. Denis.

Fig. 9. Early snowmelt windows on the upper part of the Tita Neire talus slope in July 1990. Photo: P.X. Meury; the dashed line indicates the uppermost limit of the debris accumulation.

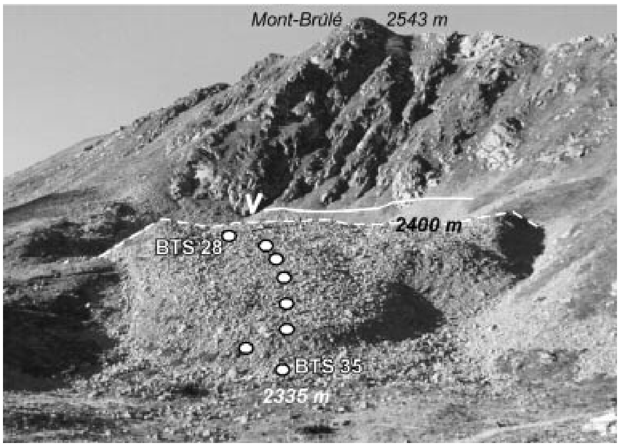

Fig. 10. Lower half of the rock glacier RG1 at Alpage de Mille Photo: R. Delaloye, October 2002. The upper rather flat area, above the change of incline at 2400 m a.s.l. (dashed line), is not visible. On 11 March 2004, funnels were observed at V and BTS values between 0 and +0.8°C were measured along the white line on the right. Photo: R. Delaloye.

Interannual spatial variation of BTS

Twenty-one BTS measurements have been repeated over 9 consecutive years (1996–2004) at the same locations (+/−10 m) on RG1, each year *c.* 10 March (maps 1996–2002) (Vonder Mühll et al. 2004). The mean of the 21 BTS values has varied between −2.4°C in 1997 and −4.9°C in 2003. The spatial analysis of the interannual variations of the BTS reveals some particularities.

The spatial distribution of temperature at the surface RG1 is not identical each year. The terminal part of the rock glacier, in which the electrical resistivity surveys did not reveal the presence of frozen materials, is always cold (< −2°C), and in some years it is the coldest part of the rock glacier. In fact, two main types of temperature pattern can be distinguished on RG1 along a longitudinal profile (Fig. 12): the years when the frontal zone is colder than the upper flat part of the rock glacier (type I), and the years when this is not the case (type II). The 2004 BTS profile (not represented on Fig. 12) was rather of type I, with a frontal zone only slightly colder (−4.5°C) than the upper part (−4.1°C).

Interannual spatial variation

Theoretically, the interannual variation of the ground surface temperature at the time of the BTS measurements primarily depends on the snow cover development (Keller 1994, Haeberli 1985) as well as on the mean air temperature during the first winter months when the snow cover is still not thick (Delaloye 2004a). On RG1 this second factor may prevail since the very coarse nature of the ground surface usually prevents the complete closing of the snow cover before the month of December. Consequently, direct exchanges of air between the ground and the atmosphere are facilitated and depend on the contrast in temperature between the interior of the ground and outside. In addition, if an ascent of air of chimney-effect type occurs in the rock glacier, a period of cold weather preceding the BTS measurements could have cooling on the lower part of RG1 as a consequence.

In order to verify if one or the other of the envisaged process controls the BTS spatial pattern, the BTS series have been compared for each location with variables describing (in the absence of a sufficiently long series of snow data) the mean air temperature during the first part of the winter and during

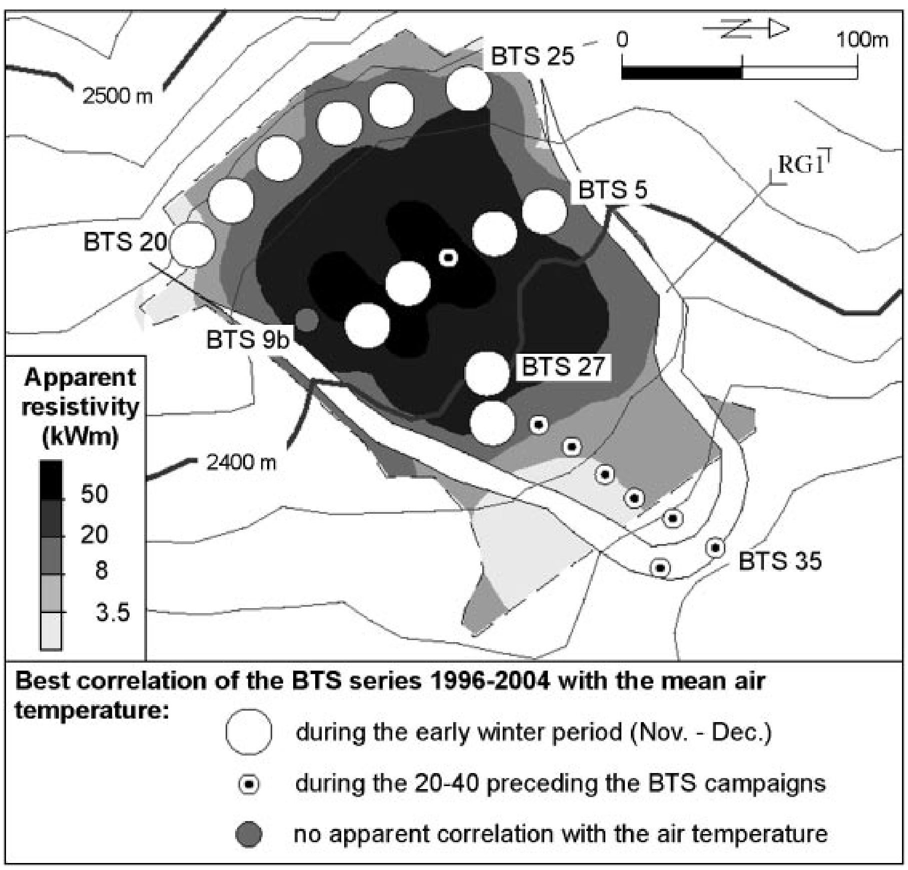

Fig. 11. Ground apparent resistivity map (15 m inter-electrode spacing, Wenner array) and best correlation found between the individual BTS series 1996–2004 and the mean air temperature during a preceding period of the winter on rock glacier RG1 at Alpage de Mille.

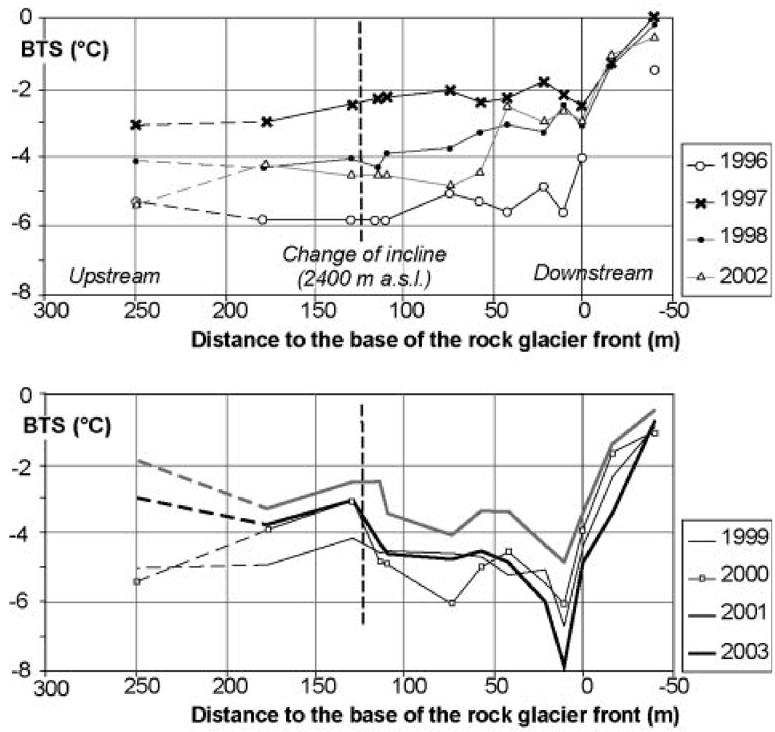

Fig. 12. Longitudinal BTS profiles along RG1: (above) years with temperature at the front warmer or close to the temperature in the upper part of the rock glacier; (below) years with colder temperature at the front.

the month preceding the measurement campaigns. Air temperatures have been recorded at 2 m height on RG1 since autumn 1997. The required data for winters 1995–1996 and 1996–1997 as well as for certain short periods when the series is incomplete were reconstructed using linear regression from the data recorded at the Réchy station (2795 m a.s.l.), which is 25 km to the west of Alpage de Mille. The correlation coefficients (r) obtained between the 9-year series of BTS measurements and some air temperature variables are shown in Table 1. Disregarding whether the correlation coefficients are necessarily significant or not, it is possible to distinguish two groups of BTS series: BTS values that are dependent on air temperature during the beginning of winter (group I), and those which rather depend on the air temperature during the month preceding the data acquisition (group II). Fig. 11 shows that group I comprises BTS points located in the upper two-thirds of RG1, a sector which is characterized by a relatively flat morphology and frozen sediments at depth (high resistivity). Group II mainly consists of points situated in the frontal zone of the rock glacier where ρa is low.

Interpretation

BTS measurements are somewhat imprecise, as much at the spatial level (+/−10 m) as in the measurement accuracy (+/−0.5°C). Moreover, the thermal gradient of the snow cover may strongly influence the measured BTS values (+/−1.5°C between the ground temperature a few tens of cm beneath the surface and BTS (Delaloye 2004a). Consequently, the fact that relationships could be found between the BTS and the mean air temperature during a preceding phase of the winter is rather unexpected. These dependencies show the interannual regularity of the process of heat exchange that occurs between the surrounding air and the rock glacier during the winter. This conclusion is also confirmed by the spatial homogeneity of the results.

Delaloye (2004a) noted that between 1998 and 2004 a good relationship occurred between the date of snowing up on RG1 and the mean temperature of the air in December, a late snowing up being followed by cold months and vice versa. These two factors therefore act in the same way on the intensity of the ground cooling in early winter. Thus, the winter ground thermal regime in the upper part of the RG1 appears to be primarily influenced by heat transfers between the ground and the atmosphere, the intensity of which depends on the characteristics of installation of the snow cover (as reported from the Gruben rock glacier by Haeberli 1985) and on the air temperature during the initial period of the winter. The ground thermal dependence on air temperature in early winter excludes the dominating influence of the weather conditions later in the season. It shows also, in this sector of the RG1, the prevalence of convective air circulation limited only to the active layer. This characteristic could be related to the flat morphology of this zone of RG1, which is not favourable to a circulation of air over large distance, and to the presence of a notable volume of ice at depth, limiting possible air displacements to the superficial layer of blocks only.

At the rock glacier front, the direct dependence between the ground temperature in March and the air temperature in February shows, on the one hand, that a marked cooling of the ground occurs during the periods of cold weather; this cooling can be regarded as consecutive to an ascending movement of air within in the rock glacier, which causes the aspiration of surrounding air through the snow cover mainly into the lower part of the formation. On another hand, the frontal part of RG1 tends to warm during

Table 1. Correlation coefficient between the 9-year BTS series and the mean air temperature respectively in December (r_{Dec}) and during the 30 days preceding the BTS campaign (r_{30}). For location of the BTS, see Fig. 11.

BTS	20	21	22	23	24	25	9b	9	8	7	6	5	27	28	29	30	31	32	33	34	35
r_{Dec}	0.58	0.83	0.90	0.77	0.98	0.65	0.26	0.66	0.58	0.02	0.46	0.47	0.54	0.60	0.47	0.44	0.40	−0.03	−0.19	−0.31	−0.19
r_{30}	0.13	0.11	0.11	0.26	−0.27	0.06	−0.21	0.34	0.29	0.77	0.07	0.01	0.40	0.56	0.66	0.50	0.75	0.90	0.83	0.87	0.87

mild weather. This leads to the assumption of absence of ventilation in the rock glacier during these periods. The ground surface warming could be caused by convective heat flow from deep within the formation, heat flow supported by the absence of ice sealing the pores and allowing the convection of air to great depth (which does not seem plausible for BTS 7, however).

On RG4, an apparently relict rock glacier close to RG1, BTS values measured on the lower end (2240 m a.s.l.) of the formation are often even colder than on RG1. They are also well correlated to the air temperature during the period preceding the BTS, which leads to the same conclusions as for RG1.

Observations in March 2004

What is the mode of air circulation within RG1 during cold weather? If there is an ascent of relatively warm air, its effect should be observed somewhere in the uppermost part of the rock glacier or on its margins.

In March 2004, new BTS measurements were performed *c.*30 m above the BTS line 20–25, on the steep upper part of the talus cones connecting RG1 to the headwall (Fig. 10). Ground surface temperatures were recorded between 0 and $+0.8°C$ beneath 2.5 to 3.7 m of snow. At the south-western end of the line, chimneys were observed between the thick snowpack and the rockwall. Air was flowing out at a temperature of $+0.2°C$.

Thus, these observations support the assumption of a deep circulation of air (chimney effect) within the rock glacier, connecting the frontal part to the uppermost limit of the formation via a transit beneath the frozen sediments.

Conclusions

Our observations show that a ventilating process of chimney-effect type, involving a deep circulation of air even beneath frozen materials sealed with ice, may also occur in loose sediments deposits (talus slopes, inactive or relict rock glaciers) situated in the lower belt of discontinuous mountain permafrost or close to its lower limit.

The winter ascent of relatively warm air from the deep parts of the sedimentary accumulation causes a positive anomaly of the ground temperature in the upper(most) section of the debris accumulation, which limits the potential for permafrost to occur. The ascent of relatively warm air provokes the aspiration of cold air through the sometimes thick, but porous snow cover, into the blocky deposits and favours the cooling of the lower part of the slope. Given the elevation of the sites concerned, the mean annual ground temperature at depth is close to 0°C. It is therefore not necessary that a chimney effect causes a thermal anomaly as strong as at low elevation to support the presence of permafrost: 1°C or 2°C could certainly be enough.

These results pose many more questions: How frequent and efficient is the process of internal ventilation in a mountain permafrost environment? What is the effect of the density of the snow cover on the ventilation? What is the impact of the 'chimney effect' on both thermal regime and spatial distribution of discontinuous mountain permafrost? How stable is the process with climate evolution? Might permafrost be preserved in some talus slopes, inactive and apparently relict rock glaciers by a ventilation process for thousands of years? A vast effort of research, requiring observations, measurements, monitoring, and modelling is to be encouraged.

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