Permafrost, Phillips, Springman & Arenson (eds)
© 2003 Swets & Zeitlinger, Lisse, ISBN 90 5809 582 7

Thermal anomaly in a cold scree slope (Creux du Van, Switzerland)

R. Delaloye
Department of Geosciences, Geography, University of Fribourg, Switzerland

E. Reynard & C. Lambiel
Institute of Geography, University of Lausanne, Switzerland

L. Marescot & R. Monnet
Institute of Geophysics, University of Lausanne, Switzerland

ABSTRACT: Permafrost occurs on the scree slope of Creux du Van even if the mean annual air temperature is +5.5°C. A permanent frozen body is present only in the lower half and sunniest part of the slope. The main process leading to the strong thermal anomaly of the ground occurs during the cold winter periods. At that time, a direct relationship between the air temperature measured in a channel at the bottom of the talus slope and the air temperature outside indicates that air is aspirated into the ground allowing the overcooling of the interior of the scree. The talus slope acts like a chimney where natural advection occurs in winter due to air density contrast between cold and dense outside air and warm and light inside air. In summer, the chimney effect is reverse and the permanent expiration of cold air prevents the vegetation from growing normally.

1 INTRODUCTION

The sporadic and atypical occurrence of permafrost in scree slopes is encountered in mid-latitude regions several hundred meters below the altitude of the lower limit of discontinuous mountain permafrost. Cold ground temperature and even outcrops of ground ice are observed in the middle of summer and are reported for numerous locations (e.g. Bertinelli et al. 1993, Wegmann 1995, Möseler & Molenda 1999, Kneisel et al. 2000, Gude et al. 2001, Sawada & Ono 2001, Rovera, pers. comm).

Because of the specific fauna and flora associated with cold talus slopes, for a long time the greatest attention on such sites was paid by zoologists or phytosociologists. In terms of the physical processes involved, they point out many observations about cold ground conditions but do not really explain the origin of the phenomenon. Beside the older theory that evaporation processes occurring in the interior of the scree during the summer are considered as the origin of the negative thermal anomaly of the ground (contradictory discussion and references are offered by Wakonigg 1996), the low rate of exposure to solar radiation (e.g. Hoelzle & Haeberli 1995, Kneisel et al. 2000, Etzelmüller et al. 2001) has also been advanced as a fundamental factor. Wakonigg (1996) and Molenda (1999) provided another explanation where a reversible air circulation through the scree slope is likely to be responsible for ground overcooling occurring only in wintertime. A cold ground temperature during the summer season is therefore the unique consequence of the winter overcooling.

The present paper gives an insight into one particular site located in the Jura Range (Northwestern Switzerland) on the basis of climatic data, ground thermal measurements and geophysics.

2 SITE DESCRIPTION AND OBSERVATIONS

2.1 *Site description*

The talus slope of Creux du Van (46°56′N, 6°44′E) is located at the bottom of a horseshoe-shaped cirque facing east-northeast between 1170 and 1300 m a.s.l. The cirque is closed from its southern to western rim by a 100–150 m high cliff of massive limestone. The fallen blocks build up a well-sorted talus slope at the base of the cliff (Fig. 1).

The mean annual air temperature (MAAT) measured over the period 1998–2001 is +5.5°C (Delaloye & Reynard 2001). The annual precipitation is estimated to be 1600 mm. The exposure of the lower part of the scree to direct solar radiation is restricted to the period

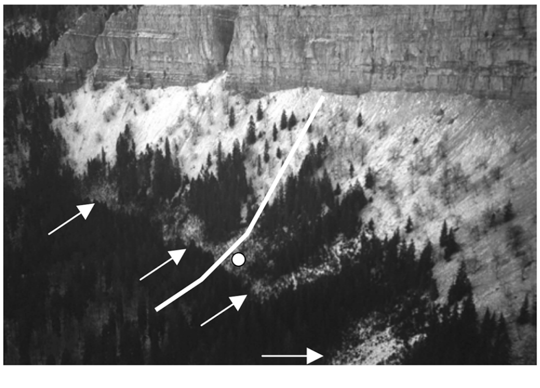

Figure 1. The scree slopes of Creux du Van. The arrows indicate patches of dwarf red spruces. The line locates the profiles presented in Figures 3, 5. The point locates the MADD station.

from early April until the first days of September, nevertheless with a maximum of ten hours' sunshine in June (Delaloye & Reynard 2001). The length of exposure decreases towards the top of the scree and is close to zero at the base of the cliff.

The very steep and unstable uppermost part of the scree consists of gravels and pebbles without soil formation. Metric blocks are numerous in the stable and less inclined lower part and are often covered or separated by an organic soil sometimes reaching a thickness of more than 70 cm. The bedrock under the scree consists mainly of marls.

The distribution of vegetal associations on the talus slope already indicates different ground thermal conditions. The most important particularity is the growth of dwarf red spruces (belonging to the *Tofieldio-Piceetum* association) in several patches on the lower part of the talus slope (Fig. 1). The height of adult trees is not more than 2–5 m. Peat mosses form a quasi continuous cover here. Such patches are surrounded by a forest association (*Asplenio-Piceetum*) where red spruces reach a height of between 10 and 25 m. The uppermost part of the slope is sparsely occupied by different associations of maples (*…-Aceretum*), while areas situated downwards are covered by a mixed forest of beeches and spruces (*Abieti-Fagetum*). Richard (1961) gives more details on the vegetation and soil conditions.

2.2 *Direct observations*

On the lower half of the slope, the presence of ice in the ground or between the blocks is often visible during early summer, while at the same time a cold wind is easily perceptible coming out of the block field (Pancza 1989). Ice is more difficult to observe in August, but fresh air is still expulsed from the scree, which does not seem to occur in autumn. In particularly cold winter conditions, a more or less diffuse discharge of relatively warm air coming out from the ground is detectable at numerous places above the middle of the slope (Fig. 2).

Characteristics of the snow cover also give indications about the thermal regime of the ground. Snow is deeper and preserved for a longer time (sometimes until June) on the lower half of the slope, especially in the dwarf spruce areas (Richard 1961): cold ground conditions prevent snow from basal melting. Conversely, the snow cover is almost always wet on the upper and warmer part of the slope and is often thin. The snow cover is not present during the whole of the winter here and usually disappears completely in March.

3 METHODS

Temperature and electrical resistivity measurements were carried out on the scree to assess the thermal conditions and extent of permafrost.

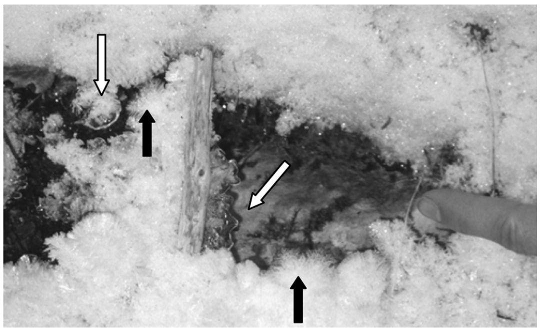

Figure 2. Holes through the snow cover created by the flow of relatively warm air out of the upper half part of the slope. Rounded snow crystals (white arrows) indicate the thawing process involved. Only a few centimeters away, the growth of reef (black arrows) is caused by the immediate freezing of ground air humidity. Picture taken on 18th December 2001 with an air temperature of −8°C and a snow cover of less than 10 cm.

A multi-channel datalogger (MADD) was installed in the middle of a dwarf spruce area in 1997 (Fig. 1) to monitor the air temperature at a height of 2 m, the ground temperature 30 cm below the surface as well as the temperature at 70 cm depth in a channel between blocks where air flows (called here channel temperature) at 1 hour intervals. Ten single-channel dataloggers (UTL) were installed along a profile across the whole scree slope. They have recorded the ground temperature at a depth of 10–20 cm every 2 hours since October 1999.

Permafrost investigations were also performed using two direct current electrical resistivity techniques: vertical sounding (VES) and profiling (EP). Both ice content and temperature, the latter especially near freezing point, control the resistivity of frozen ground (Haeberli & Vonder Mühll 1996).

Three VES (CV1-3) with a Schlumberger array were carried out on the scree (Delaloye & Reynard 2001). CV2, performed in a dwarf spruce area, was repeated several times over the year to control the behavior of ground resistivity affected by temperature variations in depth. Hauck (2001) used a similar approach with EP.

Two EP were also carried out. EP1 was performed along the line of UTLs (Fig. 1) with a 5 m inter-electrode spacing (Marescot et al. 2003). EP2 was repeated several times using fixed electrodes to monitor the resistivity of the active layer near the MADD station over a 33 m long profile. There was a 1 m inter-electrode spacing and the maximal depth of investigation was limited to approximately 3 m.

4 RESULTS

4.1 *Near-surface ground thermal conditions*

The mean annual ground temperature (MAGT) ranges between +0.5 and +2.0°C in the dwarf spruce areas depending on both year and location, which is 3.5 to 5 degrees below the MAAT. In both maple and mixed forest areas, the MAGT varies between +5.0 and +6.7°C, not far from the MAAT.

In April, the uppermost layer of the ground is still at a temperature of 0°C in the talus areas with red spruces whereas the ground temperature is positive elsewhere (Fig. 3a). The temperature remains especially low over the summer time (June–August) in the middle of the area with dwarf spruces (Fig. 3a). The final place to thaw is located at the UTL *v4* in early July (Fig. 3c), a location where the spruces are very sparse and small. Then, warming becomes pronounced here, contrary to the ground near the MADD station (Ma) where the temperature remains stable at +3.5°C for the three summer months (Fig. 3a).

In September and October (Fig. 3b), the ground temperature in the area with dwarf spruces (between +4 and +6°C) is higher than in the summer and is close to the temperature recorded in the upper part of the slope. In the patches of dwarf spruces, freezing begins in November (Fig. 3c). The temperature falls below 0°C during periods of cold weather over the winter. Even below an exceptional snow cover of more than 180 cm in February 1999, the ground temperature reached an extreme low value of –5.6°C at the depth of 30 cm at the MADD station (Delaloye & Reynard 2001). In the upper part of the slope the temperature mainly stays at or above freezing point, except for very short periods of a few hours. At the UTL *v9*, two complete years of measurements never indicated any single value lower than +0.5°C.

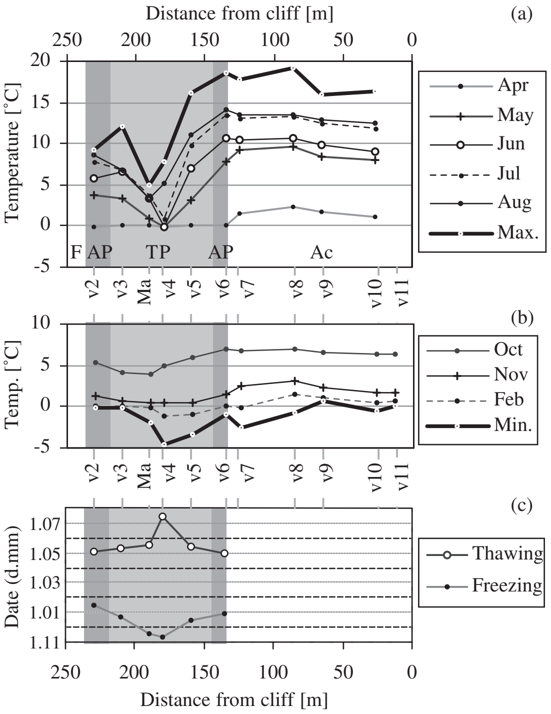

Figure 3. Near-surface ground temperature from September 2000 to August 2001 throughout the Creux du Van scree slope. The bottom of the slope is on the left. The ground temperatures were recorded at 2-hour intervals about 10–20 cm below the surface using UTLs identified as v2, v3… along the profile (Ma = MADD). (a) Mean monthly temperatures during the "warm" season and maximum temperature over the year. (b) Mean monthly temperatures during the "cold" season and minimum temperature over the year. (c) Thawing and freezing dates. The vegetal associations are identified by grayscale bands; F = *Abieti-Fagetum*, AP = *Asplenio-Piceetum*, TP = *Tofieldio-Piceetum* (dwarf spruces), Ac = …-*Aceretum*.

4.2 *Channel temperature*

Simple observations show the reversible airflow through the scree slope in two opposite directions (see 2.2). Figure 4 demonstrates the narrow relationship between air temperature and the ground temperature recorded in the channel between blocks located at the MADD station on the lower slope.

Once the uppermost decimeters of the ground have thawed in May, the temperature of the air flowing in the channel remains very cold and is negatively correlated to the air temperature. This relationship is no longer true at the end of August (Delaloye & Reynard 2001). In September and October two relationships are noticeable: (1) a direct correlation between both channel

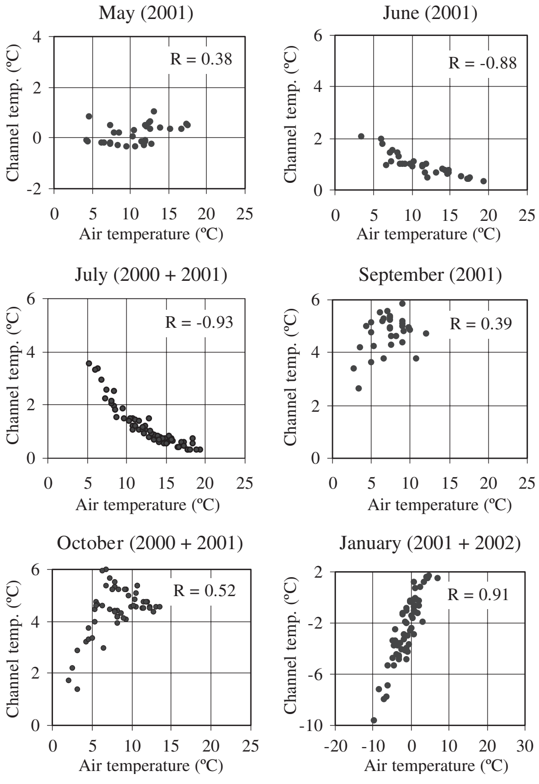

Figure 4. Relationships between the air temperature measured 2 m above the ground surface and the channel temperature. Data recorded at the MADD station (dwarf spruce area). Values are daily means. R is the correlation coefficient.

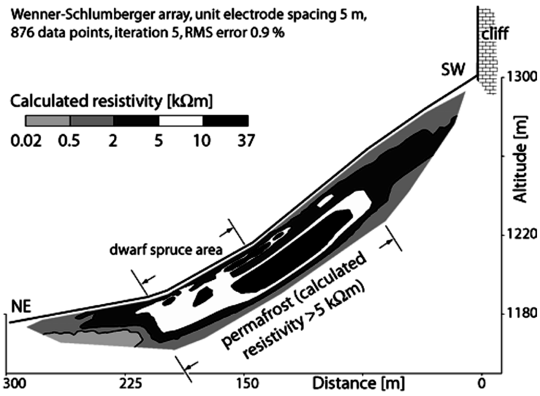

Figure 5. Electrical resistivity profiling through the whole scree slope. The inversion of the profiling has been performed with the RES2DINV software (Loke and Barker 1996).

and air temperatures exists when the daily air temperature is below approximately +7°C and (2) a negative correlation seems to take place for an air temperature above +7°C.

During winter, there is a direct relationship between both channel and air temperatures. During the very cold period of December 2001 and January 2002, the coldest air temperature was −17.8°C. A few hours later, the channel temperature was recorded at −14.5°C. Simultaneously, relatively warm air with a positive temperature was emerging from the upper part of the scree (Fig. 2). A temperature higher than +1.8°C was never recorded in the channel for the whole winter season, even during mild weather conditions when the air temperature is significantly positive, a situation which is common in this site.

4.3 *Electrical resistivity investigation*

The three VES detected the presence of a 10–20 kΩm resistive frozen body about 15–20 m thick in the dwarf spruces area (Delaloye & Reynard 2001). The soundings were performed in late September and the active layer was estimated to be 2 m thick. A slightly higher resistive body was also found immediately above the upper limit of the *Asplenio-Piceetum* area but under a thicker active layer (more than 3 m).

The EP along the whole slope (Fig. 5) allows appraisal of the shape, location and resistivity of the frozen body in the scree. The results corroborate with those of the VES. Frozen ground with relatively low calculated resistivity (between 5 and 37 kΩm) is clearly not restricted to the area with dwarf spruces, which, however, coincides with the minimal thickness of the active layer.

4.4 *Electrical resistivity monitoring*

In order to study the progress of the thawing front in the active layer in summer and the penetration of the cold wave in depth during winter, the VES CV2 was carried out five times between May 2001 and January 2002 (except a previous sounding in October 1998) at the same location near the MADD station (Fig. 6). Electrical profiling of the active layer (EP2) near the MADD station was repeated seven times during the same period. Table 1 summarizes the data of EP2 by comparing the mean relative variation of the whole sets of the apparent resistivity measurements (n = 44) obtained in the profiling.

A slight decrease in the values of apparent resistivity was detectable in the active layer during the first part of the summer season between May 21st and June 30th (Fig. 6, Tab. 1). No real shift was then detected between June 30th and August 28th (Tab. 1). The apparent resistivity of the active layer then decreased until the end of October following the warming and thawing of the ground (Fig. 6, Tab. 1). The active layer began to freeze again by early November. The ground temperature was 0°C at a depth of 30 cm from November 13th to December 4th. The resistivity was very similar to the May situation when the ground was thawing (Tab. 1). Almost no change was detectable below the active layer between May and December (Fig. 6). Cold and dry weather affected the period between early December 2001 and mid-January 2002. The snow cover was less than 10 cm thick until December 26th and then reached 50 cm for the remaining period. The ground temperature decreased to −6.9°C at the MADD station on December 20th. As a result, the resistivity of the active layer increased by one order of magnitude (Tab. 1). However, only the active layer was affected by this strong increase in resistivity (Fig. 6) due to the drop in temperature below 0°C and the phase change. One month later (January 18th), the ground temperature was still approximately −5°C. The resistivity increased not only in the active layer, but in permafrost down to a depth of about 15–20 m (Fig. 6).

5 DISCUSSION

5.1 *Permafrost occurrence and extent*

Permafrost occurs on the lower part of the Creux du Van scree slopes. The resistivity measured in the frozen ground is low but nevertheless much higher than for similar unfrozen ground. This low resistivity should be related to the availability of free water due to the permafrost temperature being very close to freezing point (Haeberli & Vonder Mühll 1996).

The permafrost body is 15–20 m thick and its extent is greater than the dwarf spruce areas in surface. This type of vegetation is restricted to areas where the active layer remains thin. The maximal thickness of the active layer reaches about 2 m here in October,

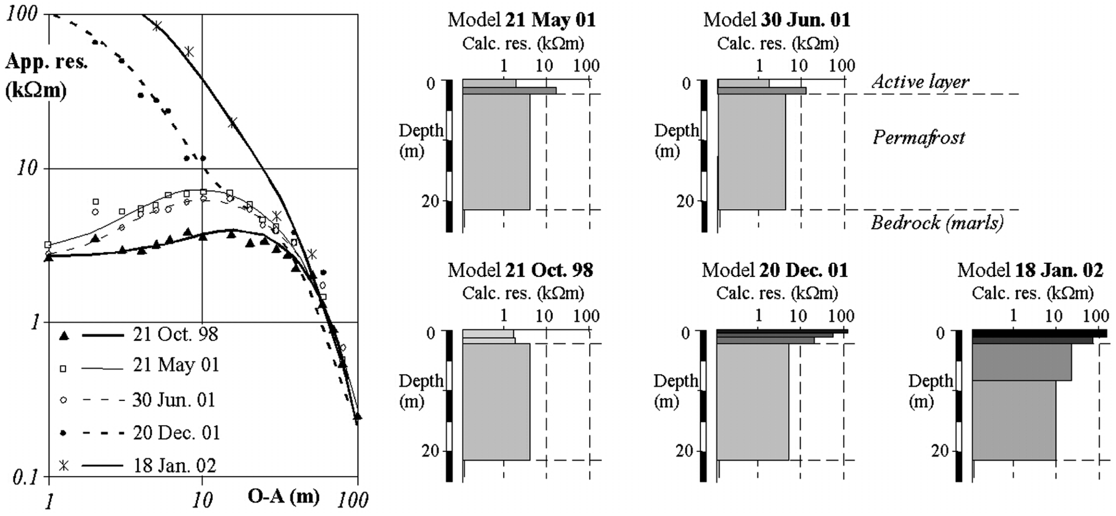

Figure 6. Repeated electrical resistivity vertical sounding CV2 near the MADD station. Symbols correspond to measurements while lines are the resistivity curves calculated from the models on the right.

Table 1. Mean apparent electrical resistivity in the active layer in the dwarf spruce area.

	Mean apparent resistivity*			Mean apparent resistivity	
Date	kΩm	%	Date	kΩm	%
May 21	6.4	100	Nov. 13	7.0	110
June 30	5.6	87	Dec. 4	6.7	104
Aug. 28	5.5	85	Dec. 20	>54.2	>843
Oct. 30	4.9	77			

* Calculated from a set of 44 measurements with inter-electrode spacing between 1 and 5 m (Wenner configuration).

which is consistent with the thermal measurements made by Richard (1961).

5.2 *Near-surface ground thermal conditions*

The temperature measurements show that only the lower half part of the slope is affected by near-surface cold ground conditions (all year long except a short period in autumn) (Figs 3a, b).

The low rate of exposure to solar radiation is probably a necessary condition for the occurrence of this strong negative thermal anomaly of the ground – a lack of sunshine in winter contributes to the ground cooling, however it is not a determining factor. On one hand, it is only in winter that solar radiation is lacking. It becomes relatively important in summer when the radiation intensity is maximal. On the other hand, the coldest ground conditions occur in the sunniest part of the slope. The upper half slope, which is less sunny, remains relatively warm especially during winter and some places never freeze.

5.3 *Air circulation*

According to e.g. Wakonigg (1996) and Molenda (1999), the thermal state of the ground is controlled by air circulating throughout the whole scree slope. The narrow but reversible relationship between the air temperature and that of the channel between blocks at the base of the scree slope clearly illustrates the process (Fig. 4). The air is aspirated into the scree at the base of the slope when the outside daily temperature is below approximately +7°C and is expelled when the outside temperature is higher than +7°C. This threshold is evident in October, but appears to be at a lower temperature in summer as no inversion happens until at least +5°C. Ruzicka (1999) reports a similar threshold at +9°C for sites in the Czech Republic.

The thermal gradient existing between the interior of the scree and outside commands both air flow direction and intensity since cold air has a greater density than warm air. In winter, when the air temperature is lower than the scree temperature, relatively warm air is expelled at the top of the talus slope and replaced by cold air aspirated at the base of the slope (Fig. 2). This process is accentuated by very cold weather conditions, as illustrated during winter 2001–2002, leading to a severe freezing of the ground for a depth of several meters (Fig. 6).

The presence of a thick snow cover does not seem to seriously affect the process of ground overcooling, even if a snow cover about 100 cm deep is normally enough to protect the ground against atmospheric conditions. Indeed, when forced, air is able to flow through the snow cover (Delaloye & Reynard 2001) since the porosity of the snow is mainly effective.

By ground freezing in the interior of the scree, a "cold" reservoir is produced in winter under the form of latent heat of fusion. A large amount of energy will then be needed to thaw the ground ice during summer time.

Cold air is expulsed at the base of the slope during the summer season when the outside air temperature is warmer than the scree, especially when the area is exposed to direct solar radiation which potentially causes a warmer temperature above the ground surface. Hot weather corresponds to extreme cold conditions for the soil, as air close to freezing point is expulsed from the scree (Fig. 4). The permanent expiration of cold air prevents the vegetation from growing normally.

6 CONCLUSIONS

The main conclusion of our study is that the strong negative thermal anomaly existing in the cold scree slope of Creux du Van and the occurrence of permafrost are essentially caused by advective energy fluxes due to air density contrasts and not by conductive exchanges.

The scree acts like a chimney during the cold winter periods. Warm and light air is expelled out of the upper part of the scree and is replaced by cold and dense air aspirated inside the lower part of the slope. The process leads to the overcooling of the scree in winter and to the occurrence of permafrost.

Such a process probably exists in a multitude of sites. A necessary condition however, is a certain porosity which allows air to flow through the scree. Permanent ice remains in summer time certainly do not occur in each talus slope affected by cold air circulation. In the Creux du Van, permafrost is therefore assumed to be the consequence of the large dimensions of the scree slope allowing a large amount of ice to be built in winter. Ice will then not thaw completely during the summer time.

ACKNOWLEDGMENTS

Special thanks are due to Dr. Richard Fortier, an anonymous reviewer and the editor reviewer for their useful comments, to Meredith Blake for editing the English text and to numerous students and other people for their precious help in the fieldwork.

REFERENCES

Bertinelli, F., Petitcolas, V., Asta, J., Richard, L. & Souchier, B. 1993. Relations dynamiques entre la végétation et le sol sur éboulis froid dans les alpes françaises méridionales. *Revue d'Ecologie Alpine* II: 93–104.

Delaloye, R. & Reynard, E. 2001. Les éboulis gelés du Creux du Van (Chaîne du Jura, Suisse). *Environnements Périglaciaires* 8: 105–113.

Etzelmüller, B., Hoelzle, M., Heggem, E.S.F., Isaksen, K., Mittaz, C., Vonder Mühll, D., Ødegård, R.S., Haeberli, W. & Sollid, J.L. 2001. Mapping and modelling the occurrence and distribution of mountain permafrost. *Norwegian Journal of Geography* 55/4: 186–194.

Gude, M., Dietrich, S., Mäusbacher, R. & Molenda, R. 2001. Exceptionally cold microclimatic conditions in blocky scree slopes in Central Europe. *Abstracts Proceed. 1st Europ. Perm. Conf., Rome, 2001*: 33.

Haeberli, W. & Vonder Mühll, D. 1996. On the characteristics and possible origins of ice in rock glacier permafrost. *Zeitschrift für Geomorphologie*, Supplement Bd. 104: 43–57.

Hauck, C. 2001. Geophysical methods for detecting permafrost in high mountains. *Mitt. der VAW/ETH Zürich,* 171.

Hoelzle, M. & Haeberli, W. 1995. Simulating the effects of mean annual air-temperature changes on permafrost distribution and glacier size: an example from the Upper Engadin, Swiss Alps. *Annals of Glaciology* 21: 399–405.

Kneisel, C., Hauck, C. & Vonder Mühll, D. 2000. Permafrost below the Timberline Confirmed and Characterized by Geoelectrical Resistivity Measurements, Bever Valley, Eastern Swiss Alps., *Perm. Perigl. Process*. 11: 295–304.

Loke, M.H. & Barker, R.D. 1996. Rapid least-squares inversion of apparent resistivity pseudosections using a quasi-Newton method. *Geophys. Prosp.* 44 : 131–152.

Marescot, L., Loke, M.H., Chapellier, D., Delaloye, R., Lambiel, C. & Reynard, E. (2003). Assessing reliability of 2D resistivity imaging in permafrost and rock glacier studies using the depth of investigation index method. *European Journal of Environmental & Engineering Geophysics* (in press).

Molenda, R. 1999. Die Rolle von Blockhalden bei der Entstehung disjunkter Areale: zoogeographische Aspekte. *Decheniana* – Beihefte (Bonn) 37: 163–170.

Möseler, B.M. & Molenda, R. (eds) 1999. Lebensraum Blockhalde – Zur Ökologie periglazialer Blockhalden im ausseralpinen Mitteleuropa. *Decheniana* – Beihefte (Bonn) 37.

Pancza, A. 1989. Un pergélisol actuel dans le Jura Neuchâtelois. *Bulletin de la Société Neuchâteloise de Géographie* 32/33: 129–140.

Richard J.-L. 1961. Les forêts acidophiles de résineux. In: *Les forêts acidophiles du Jura. Commission Phytogéographique de la Société Helvétique des Sciences Naturelles*. Ed. Hans Huber, Bern, Switzerland.

Ruzicka, V. 1999. The freezing scree slopes and their arachnofauna. Blockhalden mit Frostvorkommen und ihre Spinnenfauna. *Decheniana* – Beihefte (Bonn) 37: 141–147.

Sawada Y. & Ono, Y. 2001. Mechanism of sporadic permafrost preservation in the blocky slope at Mt. Nishi-Nupukaushinupuri, central Hokkaido, Japan. *Abstracts Proceed. 1st Europ. Perm. Conf., Rome, 2001*: 41.

Wakonigg, H. 1996. Unterkühlte Schutthalden. *Arbeiten aus dem Institut für Geographie der Karl-Franzens-Universität Graz* 33: 209–223.

Wegmann, G. 1995. *Permafrostvorkommen auf geringer Meereshöhe. Eine Fallstudie im Brüeltobel (AI).* Diploma thesis, Geogr. Inst., Univ. Zürich (unpubl.).