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Probable occurrence of sporadic permafrost in non-alpine scree slopes in central Europe

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ABSTRACT: In Central Europe, sporadic permafrost probably occurs in non-alpine mountainous regions in disjunct blocky scree slopes at altitudes well below 1000 m a.s.l., in Germany, France, and the Czech Republic. Ground ice and cold air outflow frequently persist in these localities throughout the summer and boreo-alpine flora and fauna are characteristically present in the lower parts of these scree slopes. Geomorphological, microclimatic and faunal features are the focus of a long-term study. Permafrost-like conditions have been verified by numerous underground temperature measurements in several scree slope systems, by observations of ground ice in mid- and late-summer, and by geophysical surveys. The microclimatic effects are caused by cold air entering the underground part of the scree slope during winter resulting in ice lenses which are not fully melted by the end of summer.

1 INTRODUCTION

In many central European highlands, slope sections covered with blocky material display near-ground climatic conditions that resemble those of high latitude or altitude periglacial areas rather than mountainous regions. Permafrost can be found in some of these screes, although they are located at altitudes between 500 and 700 m a.s.l., whilst the altitude permafrost limit in the Northern Alps is at ca. 2700 m a.s.l. Historical knowledge of these cold conditions goes back at least 150 years and they were frequently used by local people as natural refrigerators for food storage (e.g., Pleischl 1838). Sporadic occurrences of permafrost at low altitudes are also documented for alpine areas, but these are located much closer to the regional permafrost limit (e.g., Harris and Pedersen 1998, Kneisel et al. 2000).

The essential preconditions for this extraordinary microclimatic phenomenon include a steep slope, a thick layer of blocks with an open void system, (i.e. fine material is almost entirely lacking to enable air circulation between the blocks), and a sparse vegetation cover. As a consequence, the air temperature gradient between the boundary layer and the interior of the scree causes intensive circulation with warm air outflow in the upper scree sections during winter and cold air outflow in the basal sections during summer. Hence, the basal parts remain cold throughout the year due to cold air inflow in winter and an absence of sufficient warming in summer.

In addition to the exceptionally cold microclimate these scree sections also represent extraordinary ecosystems inhabited by many cold stenotherm plants (mostly mosses) and different invertebrate groups like mites, spiders, springtails, and beetles (Ruzicka & Zacharda 1994, Molenda 1996). Some of these are normally found in high alpine or polar areas and can be considered to be true faunistic relicts from glacial periods. Genetic DNA-analyses have proven the existence of populations of wingless beetles which have been separated from populations in other screes in the same highlands for at least several thousand years. These observations support the assumption of stable periglacial conditions in the screes since the end of the last glacial period. A recent summary of ecosystem and microclimatic features in German and Czech screes is given in Kubat (2000).

Despite several attempts made in the last centuries there is still no satisfying explanation of microclimatic conditions and the occurrence and distribution of underground ice. This is especially due to the fact that measurements in most cases were undertaken sporadically rather than systematically (Wakonigg 1998). The few studies performed with continuous temperature monitoring under different weather situations, lack the simultaneous investigation of the underground

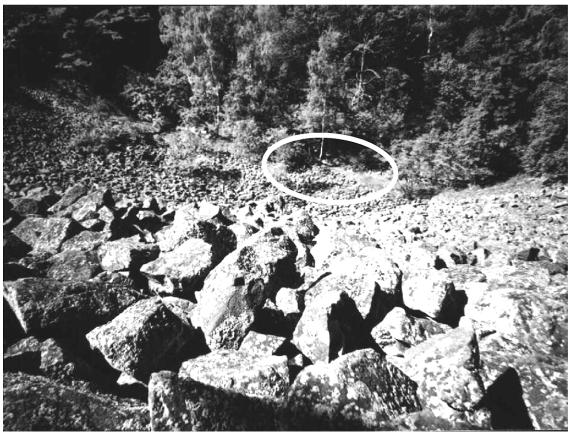

Figure 1. View downslope towards the base section of the Klic scree slope showing the typical blocky material and the surrounding forest vegetation (summer ground ice is common in the circled area).

conditions needed to evaluate microclimatic features in a synoptic way (Harris & Pedersen 1998, Tanaka et al. 1999). For this reason our study of microclimate in the ice-containing screes is based on the continuous monitoring of temperature in several typical screes in Germany and the Czech Republic. This study is a part of the interdisciplinary SCREECOS (SCREe ECOSystem) research project, which covers the geology, geomorphology, microclimatology and biodiversity of scree geo-ecosystems.

2 METHODS

The methods used for permafrost related investigations in the scree slopes include micrometeorological measurements in the near-surface atmosphere and in the open voids of the scree, sub-surface geophysical surveys, and zoological analyses of cold living stenotherm invertebrates.

Numerous screes were equipped with miniature dataloggers (Onset HOBO) in order to monitor meteorological effects, either with two temperature sensors installed at different depths or one temperature and one humidity sensor. Most installations were in the basal part of the scree and typical depths ranged from 0.10 to 1.5 m; logging intervals were 2 or 3 h. Measurements started in 1995 and were undertaken at about 20 scree sites for periods of several weeks up to several years. In addition, a meteorological station suitable for energy balance calculations, was set up to log data at 1 min intervals on a scree in the Harz (Central Germany). Ground temperatures are monitored with numerous temperature sensors in this scree site (mainly Campbell equipment). The experimental design was planned to permit a complete analysis of sensible, latent and radiation heat fluxes at the surface and in the interior of the block slope.

Geophysical methods applied to several scree slopes included refraction seismic tomography and 2-dimensional DC resistivity tomography.

In refraction seismic surveys the seismic velocity of the subsurface was determined by measuring the travel-time of seismic waves from the source (sledgehammer) to a spread of receivers at the surface. The seismic velocity of ice (ca. 3500 m/s) lies in the range of most rock types, but is significantly higher than that of air (<300 m/s) or water-saturated material (<1000 m/s). In the refraction seismic survey a 12-channel system (Geometrics Smartseis) with sledgehammer-induced shots at a geophone spacing of 2.5 m was applied.

In DC resistivity surveys the electrical resistivity of the ground is measured by injecting current into the ground and measuring the resulting electric potential. As the method requires good electrical contact between electrodes and the surface, it is difficult to apply to the blocky surface of the screes without any fine material. In addition, differentiation between possible ice occurrences and subsurface air voids is difficult, as both act as electrical insulators with extremely high resistivities. The DC resistivity equipment consisted of a 48-channel instrument (IRIS Instruments Syscal R1). Electrode spacings of 2.5 and 5 m were used.

The combination of the two geophysical methods has proved reliable for permafrost detection in recent years and usually is sufficient to differentiate between water, ice, air and rock occurrences (Hauck 2001, Vonder Mühll et al. 2001).

Floral and faunal surveys comprise the investigations of disjunct island-like biotopes inhabited by communities of lichens, mosses and various taxonomic groups of invertebrates such as spiders, mites, collembollans and beetles (Ruzicka & Zacharda 1994, Molenda 1996). The physical structure of the screes make zoological investigations difficult, particularly in deeper subterranean strata. Arthropods living on the surface (epigeic) are collected by hand-sorting, using a small aspirator containing ethanol as a preservative, or they are extracted from sod or litter using Tullgren funnels. Arthropods inhabiting internal spaces between scree fragments are collected with large winged pitfall traps made of rigid plastic, about 13 cm high and 10.5 cm in diameter. These are positioned approximately 10, 50, and 100 cm beneath the surface of the scree and contain a mixture of 7% formalin and 20% glycerol, plus a few drops of detergent. They are left in place for one year, after which they are removed and the catch is processed in the laboratory.

3 SCREE SLOPE SITES

Scree slopes with periglacial microclimatic conditions are distributed over most Central European highlands.

Table 1. Geographic scree characteristics and mean annual ground temperatures at depths of 0.3–1 m in the basal (MABT) parts of scree slopes at Odertal and Klic, and corresponding mean annual air temperatures (MAAT). For Odertal the MAAT originates from a nearby official station (corrected for altitude differences) and for Klic MAAT is measured on site (restricted accuracy due to non-standard equipment).

Scree slope (region)	Lat/Long	Expos.	Altitude (m)	MABT (°C)	MAAT (°C)	ΔT (K) MAAT-MABT
Odertal (Harz, Germany)	51°44′/10°33′	WSW	600	1.6 (1996–99)	6.2 (1960–90)	4.6 (1996–99)
Klic (Bohemian Mtns., Czech Rep.)	50°49′/14°04′	SSW	580	0.1 (2000)	ca. 7.5 (2000)	ca. 7.3 (2000)

Several of these screes have been chosen for investigations of the occurrence of perennial ground ice within the research project SCREECOS. While the microclimatic monitoring program covers numerous screes the combination with geophysical measurements were concentrated at the Klic and Kamenec screes in the Northern Bohemian Mountains (Northern Czech Republic) and at the Odertal scree in the Harz Mountains (Central Germany). The altitudes of these screes range between 350 and 700 m a.s.l. and they reveal the typical features: an almost complete lack of vascular plants while the surrounding slopes are covered with forest, steep blocky material with a gradient of at least 25°, an open void system between the blocks without fine-grained soil material, and an air circulation system through the inner scree mass.

The Bohemian screes evolved on basaltic inselbergs and, basically, developed by two processes: (1) *in-situ* weathering and disintegration of the basalt lava cover lying on hill-slopes composed of various Cretaceous sediments, and (2) weathering and rockfall from the neo-volcanic cliffs with adjacent talus formation (the Klic site). Finally, fine-grained fragments are eroded to leave the blocks as surface cover. In contrast, the scree in the Harz consists partly of lateral moraine material that collapsed after valley glacier retreat, as well as rock fragments from a cliff accumulated mainly in the upper part. The screes are typically several thousand square metres in extent. Scree orientation seems to have a minor influence on the microclimate since the air circulation system is present in north- as well as in south-facing slopes.

4 PERENNIAL GROUND ICE

Our field investigations on the three scree sites Odertal, Klic and Kamenec suggest the existence of permafrost conditions in some scree sections, but evidence is not clear for all three screes. Whereas in the Kamenec and the Odertal screes the hypothesis of permafrost conditions is primarily based on the temperature measurements, because the geophysical surveys revealed insufficient indications, at the Klic site the geophysical measurements are sufficiently definitive to suggest the existence of perennial ground ice lenses.

4.1 *Temperature monitoring*

Temperatures in the open void system of the scree base sections are valuable indicators of interior conditions since the cool air originates from the inner part of the scree during summer. Air flows into the scree in the upper part and flows out of many fissures at the bottom of the scree in this season, while in winter the air-flow direction reverses.

This effect can be clearly detected within the temperature records of the Klic scree (Fig. 2). In summer, temperatures in the upper part correspond closely to boundary layer conditions, whereas in winter this influence is strongest in the basal part. In contrast, the summer temperatures in the basal part and the winter temperatures in the upper part reflect thermal conditions in the interior part of the scree sections from which the air outflow occurs. Since the flow is dispersed in the upper part but confined to a number of voids in the basal part, temperature data from the latter reflect more precisely the interior conditions.

Mean annual air temperatures, calculated from data obtained at nearby official meteorological stations or measured directly at the scree, are approximately 6–8°C. However, ground ice is frequently found in the base part of the screes even in mid- to late-summer at depths of ca. 0.5 m. This causes the temperature of the outflowing air to remain at approximately 0°C throughout the summer. Normally, ground temperatures in this depth should equal the mean air temperature, i.e. the data reveal a temperature anomaly of 4.6–7.3 K.

For most of the year temperatures in the basal parts of the screes remain close to 0°C, but significantly lower temperatures occur frequently from December to March. Air-flow through openings in the snow cover influences the thermal regime by turbulent heat exchange and prevents the use of BTS values as indicators of permafrost.

4.2 *Geophysical surveys*

In order to detect possible subsurface ice occurrences within the screes, DC resistivity and refraction seismic tomography surveys were conducted in summer 2001.

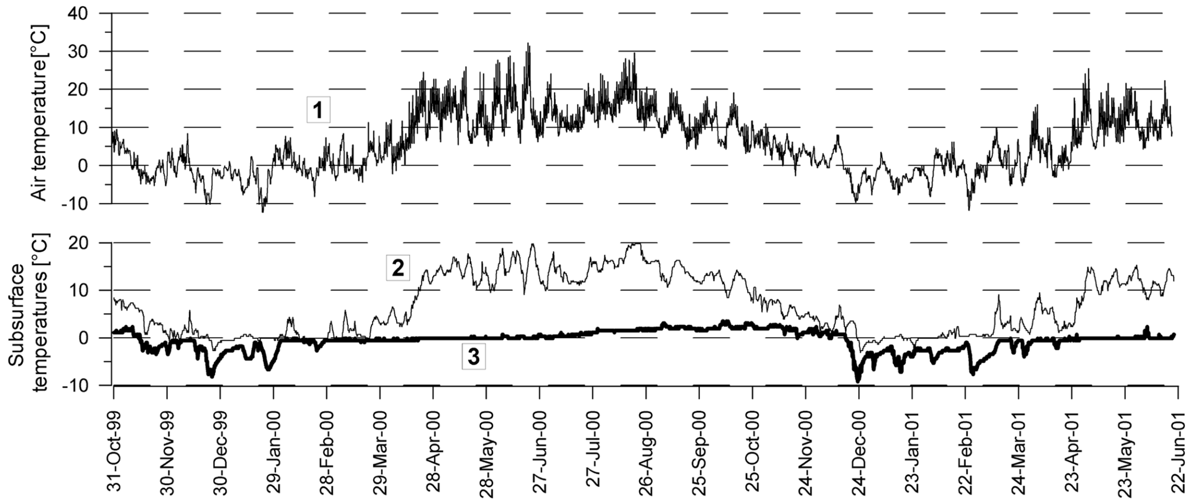

Figure 2. Temperature curves for the Klic scree site. 1: air temperature 3 m above ground (annual mean 2000: ca. 7.5°C; restricted accuracy due to non standard equipment); 2: ground temperature in the upper slope (sensor depth: 0.6 m, annual mean 2000: 8.5°C); 3: ground temperature in the lower slope (sensor depth: 0.4 m, annual mean 2000: 0.1°C).

Figure 3 shows results of seismic and resistivity measurements at the Klic and Kamenec sites. The resistivity results (Fig. 3a) reveal that the blocky layer, indicated by the extremely high resistivities (dashed line in Fig. 3a) due to the large air voids has a thickness of about 10 m at the Klic site. Similar results were obtained at the Kamenec site (not shown). As air voids without any ice content would result in low velocities, the seismic results of the Klic scree indicate the possible presence of small ice lenses within the blocky layer (Fig. 3b). At 5 m depth between horizontal stations 35 and 45 two velocity anomalies of 2000–3000 m/s are present with decreasing velocities above and below (white arrow). As the resistivity results indicate that the thickness of the blocky layer is around 10 m, these velocity anomalies cannot be due to solid bedrock, but may well be due to ice occurrences.

In contrast, velocities at Kamenec (Fig. 3c) are less than 1000 m/s throughout the uppermost 10 m, indicating that the high resistivities can clearly be interpreted as air-filled voids between the blocks of the scree. No indication of larger ice volumes in the subsurface was found at this site.

The geophysical results for the Odertal scree show a complex structure. In the northern part, the high-resistivity area extends only to 5 m depth, indicating a shallow side-arm of the scree. In the southern part, two high-resistivity areas at the surface mark the two main parts of the scree. The equally high resistivities in the southern part at greater depths, indicate that the blocky layer may reach a thickness of more than 15 m. The seismic results again show velocities of less than 1500 m/s throughout the uppermost 10–15 m. At 15 m depth a pronounced high-velocity layer of 2500–3500 m/s is present. This may indicate a possible ice occurrence, but more probably it is due to bedrock. Unfortunately, the limited data quality of the resistivity results do not allow an unambiguous interpretation.

4.3 *Cool living stenotherm invertebrates*

Beside the particular microclimate these cool lower parts of the screes represent extraordinary ecosystems inhabited by many species of cool-living stenotherm plants (mostly mosses) and invertebrates of many taxonomic groups, including mites (Acari), spiders (Araneae), springtails (Collembolla) and beetles (Coleoptera). Some of these normally live in high alpine or polar areas and can be considered to be true faunal relicts from glacial periods (Molenda 1996). Genetic DNA-analyses proved the existence of different, genetically separated populations of wingless beetles, who have inhabited disjunct, island-like biotopes in the cool screes located in the same geographic areas for at least several thousand years.

These conditions provide excellent habitats for boreo-alpine invertebrate species. For example, the predatory mite *Rhagidia gelida* is known to live only in arctic regions (Spitzbergen, Bear Islands, Siberia at 70–71°N, Northern Canada and Alaska), i.e. in the areas with permafrost and mean July air temperatures of +10°C or less. However, this mite also lives in screes on top of the Giant and Jeseniky Mts (about 1500 m altitude) located along the northern border of the Czech Republic. Surprisingly, the small disjunct populations of this mite also occur in the very restricted areas of only some 100 m^2 in so-called ice-holes at the bases of a few ice-retaining screes at altitudes of only 300–500 m. Our observations have documented that the occurrence of the mite *Rhagidia gelida* is strictly restricted in the ice-holes by the temperature of substratum which ranges from only +1.5 to +10°C during hot

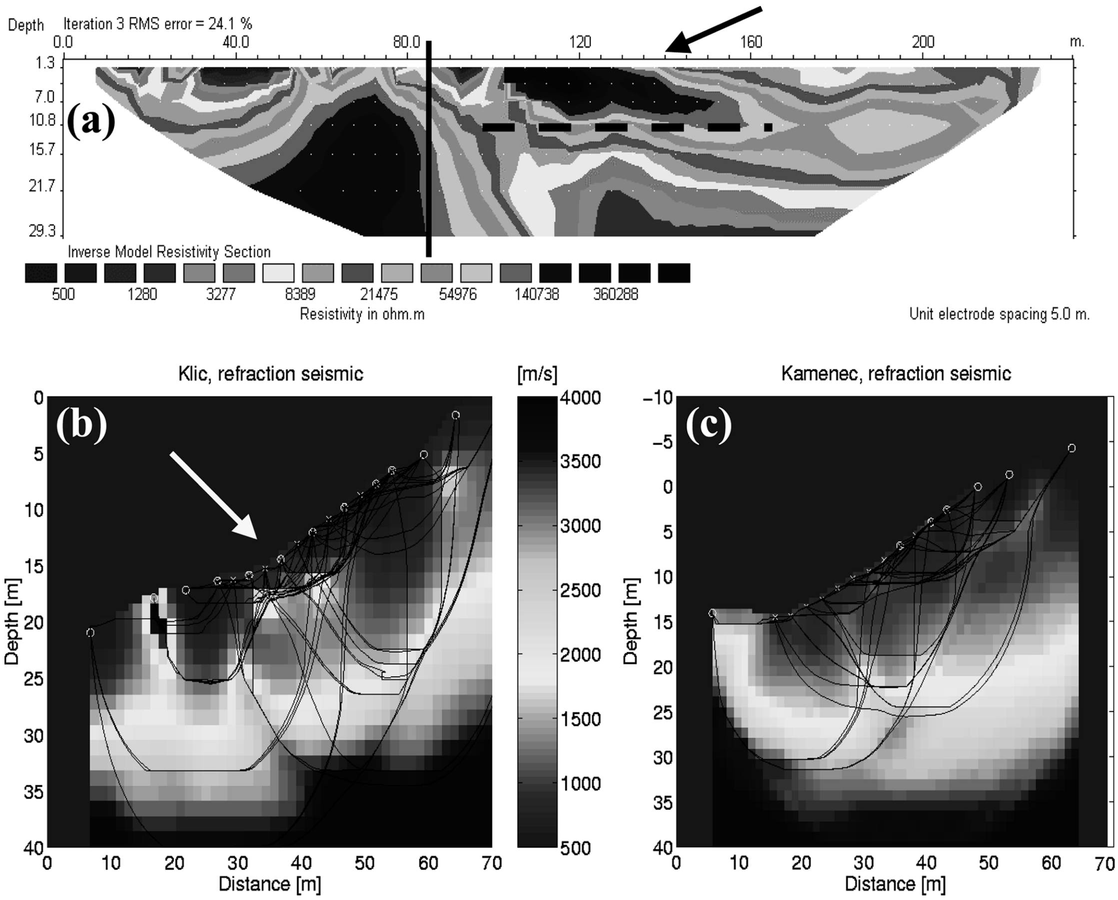

Figure 3. (a) Resistivity and (b) seismic velocity results at the scree at Klic and (c) seismic velocity results at Kamenec. The two profiles (a) and (b) are orthogonal two each other and cross at the centre. The two velocity anomalies at horizontal distances 35 and 45 in (b) (white arrow) indicate the possible occurrence of ground ice. The black arrow in (a) marks the location of the scree slope, the solid and dashed line its lateral and vertical extent, respectively.

summer days. Hence, the disjunct populations of this mite in the screes are considered to be faunal relicts from the last glacial period, conserved under the very limited conditions of the stable, permanently cool, periglacial microclimate of the screes. The small disjunct populations of this mite cannot be the air-borne ones because they are not able to move on a web filament as spiders do. Biologically, and also historically, the occurrence of this mite is confined to the environment with such a low temperature and as a biological glacial relict it bio-indicates that the periglacial microclimate has persisted in these screes since the last glacial period.

5 DISCUSSION

As shown above, periglacial microclimatic conditions partly accompanied by perennial ground ice are found in various scree sites located well outside the alpine permafrost zone in Central Europe. Admittedly, permafrost presence has not yet been proven in the screes since it is based on the above mentioned indices and remain with uncertainties due to the relative rareness of this phenomenon, small spatial distribution and the limited methodological possibilities to investigate the sites because of the nature conservation status. On the other hand, the application of several different techniques together with historical knowledge leads to the conclusion that permafrost is highly probable, at least in the Klic scree. For this scree, year-round frozen ground conditions are indicated by ice observations in summer, ground temperatures around 0°C in summer, cold stenotherm invertebrates, and geophysical surveys revealing ice like features.

For the other screes, permafrost is also probable, since ground temperatures and invertebrate inhabitants suggest continuously frozen ground; Geophysical data, however, do not provide clear evidence for ground ice. But, as with permafrost analyses in general, detection is complicated and uncertainties remain, especially in marginal areas of the distribution, where rugged terrain, snow and ground surface characteristics, and shadowing effects are present (Hoelzle et al. 2001). These problems are especially true for screes, because permafrost has a minimal extent compared to alpine or polar sites. Nevertheless, the indicators are assumed to be strong and evident enough to postulate permafrost at least in the Klic scree.

The preconditions necessary for the special microclimatic system are as follows. The highly effective circulation of air through the scree interior causes an enormous heat exchange with the atmosphere, observable by the warm air inflow at the upper scree part with temperatures of up to 20°C compared to the outflow at 0°C. Although resublimation of snowmelt or precipitation water penetrating into the scree releases heat, the winter airflow can chill the scree interior well below 0°C. The ground ice formed by the winter heat output seems extensive enough to be preserved throughout the summer.

Although all the necessary essential preconditions for the development of the permafrost conditions in general and the perennial ground ice have not been discovered and described in detail yet, our investigations suggest that the preconditions must be various and numerous as discussed below. Based on the investigation of more than 20 scree in central Europe, an essential precondition for the occurrence of the cool or even ice-containing scree is a steep slope of about 25° or more which is covered with a relatively thick layer (several metres) of primarily coarse bedrock fragments, i.e. a diameter of at least 10 cm, and an open void system between them. Fine bedrock fragments that prevent air circulation are almost entirely lacking in these screes. However, the velocity of the air circulating through the scree is evidently controlled not only by the interior roughness but also by the temperature gradient between the inner parts of the scree and the boundary layer.

At relatively low altitudes the snow cover is usually sparse and this enables the cool ambient air to penetrate into the internal underground voids and chill the fragments of bedrock. This is assumed to be the reason why the permafrost-containing screes are more likely at relatively low altitudes than in high mountains below the permafrost limit, where the thick and dense snow cover usually persists from the beginning of winter until late spring.

In summary, screes with periglacial conditions are widely distributed among the temperate climate highlands in Europe, but the restrictive boundary conditions to allow the development of the special microclimate induces a high sensitivity to environmental change. On the other hand, many scree systems seem to be well preserved and evidently have survived over the Holocene climatic fluctuations as documented by the cool living stenotherm relict fauna.

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