# A scale-oriented approach for the long-term monitoring of ground thermal conditions in permafrost-affected rock faces, Kitzsteinhorn, Hohe Tauern Range, Austria

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## Abstract

Within the research project MOREXPERT (*'Developing a Monitoring Expert System for Hazardous Rock Walls'*) a new study site for long-term bedrock permafrost monitoring has been initiated. Surface and subsurface thermal conditions in steep rock faces are monitored based on a combination of borehole, geophysical and meteorological measurements. MOREXPERT was launched in September 2010, the study area is located at the Kitzsteinhorn (3.203 m; 47°11'17'' N, 12°41'15'' E), Hohe Tauern Range, Austria.

Within the research project ground thermal conditions are monitored on three complementary scale levels: the 'borehole scale', the 'slope scale' and the 'mountain scale'. At each scale level ground thermal conditions are studied applying different methodical approaches and, therefore, with different spatial and temporal resolutions. At the 'borehole scale' five deep boreholes provide ground temperatures from depths of up to 30 m. At the 'slope scale' data from two ERT (Electrical Resistivity Tomography) arrays are used to derive information on ground thermal conditions. At the 'mountain scale' spatially distributed temperature measurements with miniature loggers in a maximum depth of 80 cm deliver information on the heterogeneity of near-surface rock temperatures.

The introduced scale-oriented monitoring approach explicitly takes into account the high lateral and vertical variability of ground temperatures in high-alpine rock faces. Complementary analysis of data obtained at different scale levels allows (constrained) validation and extrapolation of information, eventually yielding a quasi-spatial model of the thermal state of the Kitzsteinhorn's surface and subsurface. Due to its generic design the presented monitoring approach is considered to be transferable to comparable high-mountain study sites.

Im Rahmen des Forschungsprojekts MOREXPERT (*'Entwicklung eines Expertensystems zur Überwachung gefährlicher Felswände'*) wurde ein neuer Standort zur langfristigen Beobachtung von Felspermafrost in Steillagen eingerichtet. Basierend auf einer Kombination von Bohrlochmessungen, geophysikalischen Untersuchungen und meteorologischen Aufzeichnungen werden die thermischen Oberflächen- und Untergrundbedingungen überwacht. Das Untersuchungsgebiet des Projekts, welches im September 2010 gestartet wurde, befindet sich in den Hohen Tauern und erstreckt sich über den gesamten Gipfelaufbau des Kitzsteinhorns (3.203 m; 47°11'17'' N, 12°41'15'' E).

Die Beobachtung der thermischen Untergrundverhältnisse erfolgt auf drei komplementären Skalenniveaus: der ‚Bohrlochskale', der ‚Hangskale' und der ‚Bergskale'. Auf jedem der drei Skalenniveaus werden die Felstemperaturen mit unterschiedlichen methodischen Ansätzen und daher mit unterschiedlichen räumlichen und zeitlichen Auflösungen erfasst. Auf der ‚Bohrlochskale' werden mit Hilfe von fünf Bohrlöchern die Felstemperaturen in einer Tiefe von bis zu 30 m Tiefe untersucht. Auf der ‚Hangskale' werden die Messergebnisse zweier Geoelektrik-Profilstrecken herangezogen, um Informationen über die thermischen Untergrundverhältnisse abzuleiten. Auf der ‚Bergskale' werden mittels räumlich verteilter Temperaturmessungen, durchgeführt mit Miniaturloggern, oberflächennahe Felstemperaturen bis zu einer Tiefe von 80 cm gemessen.

Das vorgestellte skalenorientierte Monitoring stellt einen wertvollen Ansatz zur Erfassung der hohen lateralen und vertikalen Variabilität der thermischen Verhältnisse im steilen Fels dar. Die vergleichende Analyse von Daten verschiedener Skalenniveaus erlaubt eine verbesserte Interpretationsmöglichkeit von Messergebnissen bzw. die Extrapolation von Informationen auf Bereiche, die durch das Monitoring nicht direkt erfasst werden. Ziel ist die Generierung eines quasi-räumlichen, thermischen Modells von Oberfläche und Untergrund des Kitzsteinhorns. Auf Grund seiner generischen Struktur ist das vorgestellte Monitoring als System gedacht, das auf vergleichbare hochalpine Untersuchungsgebiete übertragen werden kann.

## 1. Introduction

Ground surface temperatures (GST) vary largely over short distances depending on topographic variables (elevation, slope aspect, slope inclination), ground surface cover (fine-grained, coarse-grained material) and snow distribution (Brenning et al., 2005; Luetschg et al., 2008; Otto et al., 2012). Recent studies show that even within an altitudinal belt of 300 m variation of ‚mean annual ground surface temperatures (MAGST) can be as high as 6°C, not taking into account steep rock faces where variation is likely to be even larger (Gubler et al., 2011). Apart from its considerable spatial heterogeneity, GST also varies strongly over short observations periods due to the transitory nature of high-mountain climatic and microclimatic conditions (Schneider et al., 2011).

Temperatures at depth are governed by the high spatial and temporal heterogeneity of thermal conditions at and near the surface. However, as temperatures propagate downwards into the ground they become progressively attenuated and phase-shifted, yielding thermal patterns that differ significantly from those at the surface. This vertical variability of thermal conditions is controlled primarily by the thermal properties of the subsurface, the prevalent mechanism of heat transport (heat conduction vs. advection) and the persistence of past climatic conditions large depths (Isaksen et al., 2000).

Within this contribution a permafrost monitoring approach is presented that explicitly takes into account both, lateral and vertical variability of ground thermal conditions in bedrock. The introduced approach is currently implemented within the MOREXPERT project ('Monitoring Expert System for Hazardous Rock Walls'). MOREXPERT has been started in September 2010 and initiates a new long-term monitoring site focusing on permafrost and rock fall interaction in steep bedrock.

Long-term data series on ground thermal conditions, comparable to meteorological data, are essential since permafrost distribution potentially responds very slowly to changing climatic conditions. For this reason the projects Permafrost and Climate in Europe (PACE) (Harris et al., 2001), the Swiss Permafrost Network (PERMOS) (Noetzli and Vonder Muehll, 2010) and the Longterm Permafrost Monitoring Network (PermaNET) (Mair et al., 2011) have initiated long-term permafrost monitoring sites in the European Alps. Particularly high mountain peaks in the western European Alps (e.g. Schilthorn, Matterhorn, Aiguille du Midi) have been instrumented for continuous monitoring of permafrost (Gruber et al. 2004a; Ravanel et al., 2011). In Austria, extensive permafrost monitoring with deep boreholes and geophysics was limited to one site, situated at Hoher Sonnblick (3.105 m). The Sonnblick is located approximately 25 km southeast of the MOREXPERT site and features a permanently installed ERT profile and three 20 m deep boreholes (Klee and Riedl, 2011). By establishing a new site at the Kitzsteinhorn, which includes five 20-30 m deep boreholes and comprehensive geophysical monitoring, the MOREXPERT project addresses the need for a larger number of extensive permafrost monitoring sites in Austria (Keuschnig et al., 2011). Nonetheless, the establishment of new monitoring sites and the expansion of the borehole network remain crucial issues in Austrian permafrost research.

## 2. Study Area

The study area of the MOREXPERT project is located in the Federal Province of Salzburg, in the Hohe Tauern Range, Austria's highest mountain range (Fig. 1). It encompasses the entire summit region of the Kitzsteinhorn (3.203 m), covering approximately 3.5 ha and a vertical elevation difference of 300 m (Fig. 2). The Kitzsteinhorn is located just north of the main Alpine divide and has no directly adjacent summits. In combination with its pronounced pyramidal shape these topographical features make the Kitzsteinhorn ideal for the investigation of the influence of aspect and elevation on ground thermal conditions. The small-scale lateral variability of ground thermal conditions in alpine terrain has contributed to the selection of a comparatively small study area.

The Kitzsteinhorn primarily consists of calcareous-mica-schists (Höck et al., 1994). Stress release and intense physical weathering processes, typical for periglacial environments, resulted in the formation of an abundance of joint sets with large apertures. Intense retreat of the Schmiedingerkees

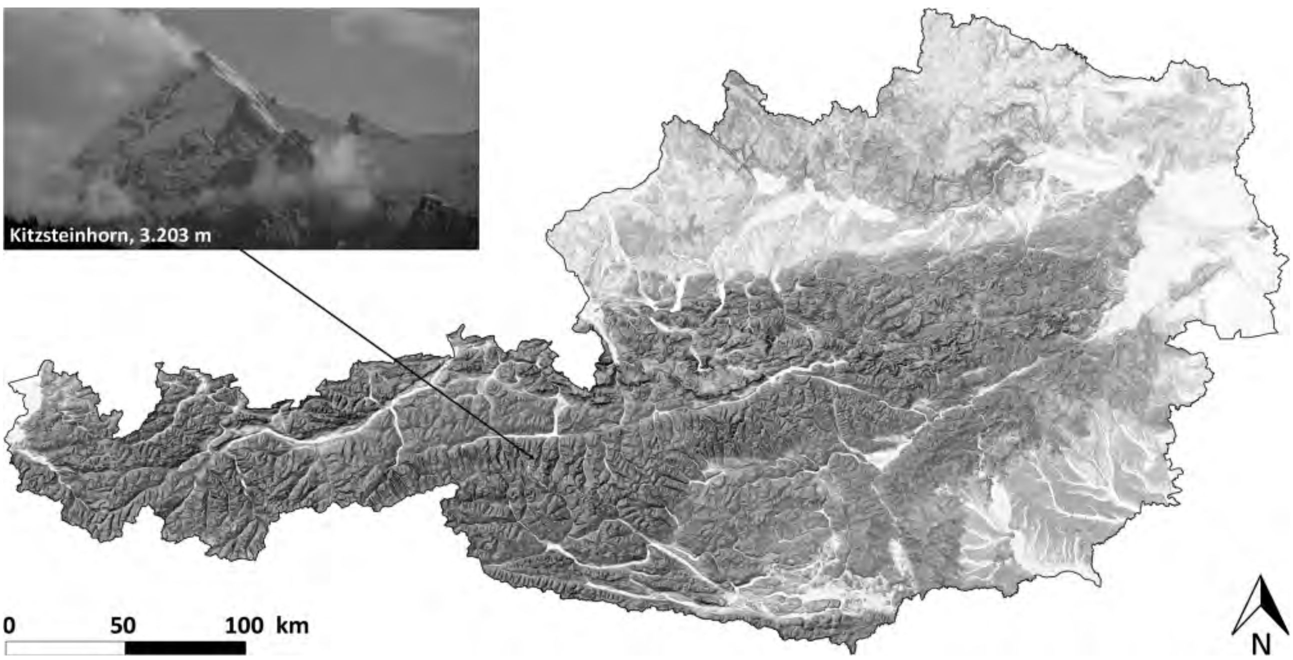


**Figure 1:** The study area of the MOREXPERT project is located at the Kitzsteinhorn (3.203 m), Hohe Tauern Range, Austria.

glacier in recent decades led to the exposure of oversteepened rock faces, which in turn are frequently affected by minor rock fall events (Hartmeyer et al., 2012).

The tourism infrastructure existing within the study area (cable car, ski lifts, ski slopes etc.) provides easy access and convenient transportation of measuring equipment, an essential prerequisite for an extensive long-term monitoring program. The west ridge of the Kitzsteinhorn is tunneled by a gallery ('Hanna-Stollen'), which allows the acquisition of thermal information from depths of up to 80 m below the terrain surface (Fig. 2).

Six weather stations are located within the study area or in its direct vicinity (< 2 km away), permitting continuous observation of external forcing of ground thermal conditions. At the weather stations, which are located at altitudes between 2.400 m and 2.940 m, air temperature, humidity, wind speed, wind direction, snow height and precipitation are recorded.

Furthermore, an abundance of historical data on glaciology and climate allow the compilation of long time series to estimate the influence of changing climatic conditions over the last century (e.g. Tollner, 1951).

## 3. Preliminary Investigations

The success of a monitoring campaign hinges greatly on the suitability of the selected measurement sites. The more pre-information can be attained, the better the monitoring system can be adapted to local conditions and the more efficiently long-term changes can be monitored. For this reason a large number of preliminary investigations had been carried out prior to the start of the actual monitoring.

### 3.1 Permafrost Modeling

To get a theoretical overview of the thermal state of the Kitzsteinhorn, permafrost distribution has been modeled using an advanced version of the 'Permakart' model (Version 3.0) (Keller, 1992; Schrott et al., 2012). 'Permakart 3.0' is an empirical-statistical model that calculates the probability of permafrost occurrence based on a topo-climatic key. The underlying topo-climatic key analyzes the relation between altitude, slope and aspect while also taking into account foot-slope positions.

Modeling results reveal that large areas of the Kitzsteinhorn summit pyramid are underlain by permafrost. Particularly the northwest face and to a lesser degree the northeast face display a very high probability of permafrost occurrence (> 75%). South-facing slopes do not seem to be affected by permafrost according to the modeling results (Fig. 3).

### 3.2 Electrical Resistivity Tomography

In order to attain first geophysical evidences of permafrost occurrence at the Kitzsteinhorn, ERT measurements have been carried out inside the 'Hanna-Stollen'. The 'Hanna-Stollen' connects the north side of the mountain (cable car summit station) to the south side at an altitude of approximately 3.000 m. It constitutes a cross-section through the mountain and there-

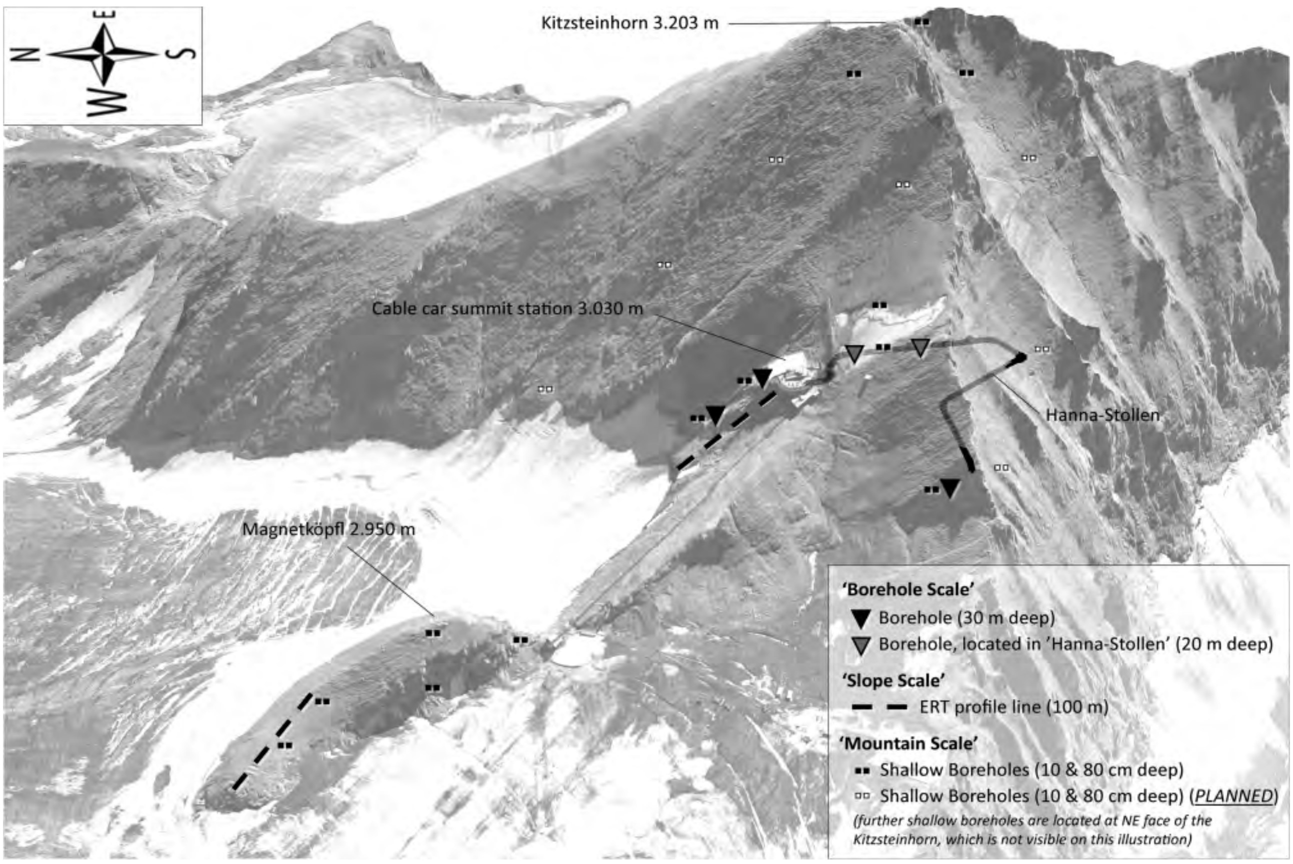


**Figure 2:** 3D-Overview of monitoring sites and investigation scales at the Kitzsteinhorn.

fore represents an intriguing opportunity to investigate the influence of aspect on permafrost occurrence along a single ERT profile line (northern vs. southern exposure).

The vertical distance between the ceiling of the gallery and the terrain surface ranges from approximately 15 m at the north/south ends of the gallery to approximately 70 m in the middle section of the gallery (below the ridgeline). The ERT array was installed in the eastern side wall of the gallery yielding a horizontal (eastward) direction of investigation. Maximum depth of investigation was 21 m during measurements conducted in June 2010. Analysis of ERT data showed high resistivity values of up to 40.000 Ωm in the north section of the tomography. These values correlated well with temperatures below the freezing point (see chapter 4.2. for details on temperature-resistivity relationship), therefore indicating the existence of permafrost in this section (Fig. 4). The central and south part of the tomography shows unfrozen rock as electrical resistivity values in this area clearly correspond to temperatures above the freezing point. The presence of permafrost-affected rock north of the ridgeline corresponds very well with the permafrost boundary attained through modeling of the permafrost distribution with 'Permakart 3.0'.

The south end of the gallery/tomography is influenced by its vicinity to the south wall. Electrical resistivity values in this area correlate to subzero temperatures, which might be attributed to seasonal freezing (remaining winter frost) and/or the effects of a prolonged cold spell prior to the measurements. Further ERT measurements and direct temperature monitoring are certainly necessary to verify these assumptions.

### 3.3 Geotechnical Survey

Joints and fractures constitute pathways for circulating melt water or air and therefore represent zones of potentially intensified heat propagation (Moore et al., 2011). Heat transfer properties of calcareous-micaschist are furthermore influenced


**Figure 3:** Modeled distribution of permafrost at the Kitzsteinhorn based on a DTM with a resolution of 1 m.

significantly by the direction of schistosity (Robertson, 1988). For an investigation that addresses the thermal state of a large rock mass (e.g. Kitzsteinhorn summit pyramid) it is therefore of crucial importance to gather detailed information on these geotechnical parameters. For this reason a mapping campaign has been carried out by GEOCONSULT ZT GmbH (persons in charge: Mag. Giorgio Höfer-Öllinger, Mag. Andreas Schober), which delivered valuable data on joint orientation/aperture and schistosity direction. Two major joint sets exist, dipping steeply to W and SW, respectively. Furthermore, two minor joint sets have been mapped, dipping slightly to SSE and steeply to NW. The joint sets can be grouped into two generations: an older generation which is filled with either quartz or calcite and a recent generation with joint apertures ranging from a few millimeters to up to 20 centimeters. The younger joint generation carries important heat transfer implications due to its large apertures.

Schistosity dips moderately steep to NE. Depending on the direction of the schistosity thermal conductivity potentially dif-

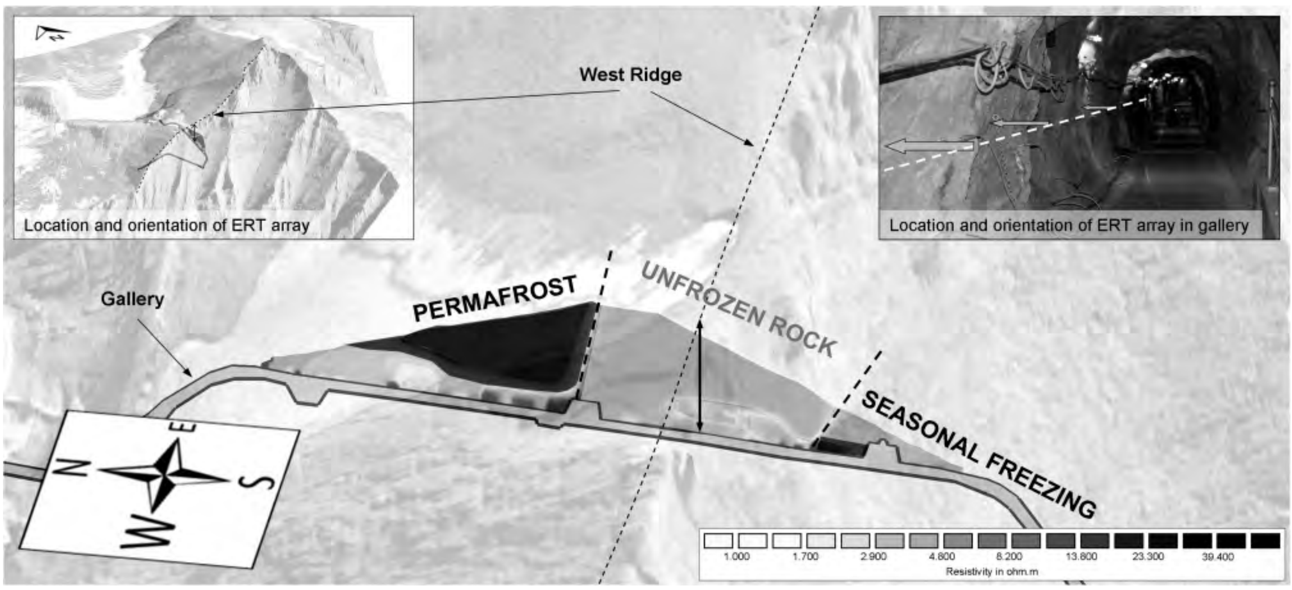


**Figure 4:** Location and orientation of ERT measurements conducted inside the 'Hanna-Stollen'.

fers significantly (Robertson, 1988). Direction of schistosity therefore was an important criterion for the selection of the sites for deep and shallow drilling. The borehole located at the west side of the mountain (Fig. 2) was drilled parallel to the schistosity. Both boreholes located at the north-facing slope below the summit station were drilled perpendicular to the schistosity.

## 4. Scale-oriented monitoring of permafrost-affected rock faces

Due to methodical deficiencies and/or a lack of physical understanding we usually do not have the ability to capture a geomorphic system in its entirety. It is therefore necessary to define levels or scales of observation to separately investigate specific aspects of the system (e.g. sub-systems, subprocesses). Measurement techniques applied at one scale level are not necessarily suitable for studies at other scale levels; equally, conclusions drawn from an examination at one scale do not necessarily apply to other scales (Otto et al. 2008). Careful selection of specific scales of investigation and thorough consideration of possible transferability of information gained at each scale level is therefore of crucial importance.

An assessment of the responses of permafrost-affected rock faces to climatic change requires a comprehensive understanding of their current thermal state. For an accurate characterization of a high-mountain ground thermal regime it is necessary to identify both, (i) the lateral variability of thermal conditions, i.e. small-scale, short-term thermal changes that occur at or near the surface, and (ii) the vertical variability of thermal conditions, i.e. the variation of ground temperatures with depth. Geomorphic processes relevant to this problem vary significantly over space and time meaning that one spatiotemporal perspective (scale level) is not sufficient to investigate the problem. Hence, three different scales of investigation have been defined within the MOREXPERT project, which are introduced within this chapter.

### 4.1 The 'Borehole Scale'

In boreholes temperature data are recorded along a vertical line (thermistor chain). Thus, boreholes can be viewed as 1D-point sources that have no horizontal/lateral extent. Temperature measurements in (deep) boreholes therefore represent the smallest scale of investigation within the MOREXPERT project in terms of areal extent. Furthermore, the 'borehole scale' is the only scale level where direct temperature measurements are conducted within the actual permafrost body. For this reason it is the only scale that provides direct permafrost evidence.

The 'borehole scale' consists of a total number of five boreholes that have been drilled into permafrost-affected bedrock (Fig. 2). Two of the five boreholes were drilled inside the 'Hanna-Stollen'. Both 'gallery boreholes' (20 m in depth) were drilled to enable ground temperature measurement in depths that otherwise could not be reached from the surface (distance to terrain surface up to 80 m) and for the validation of geophysical measurements (electrical resistivity tomography, reflection seismology). As the gallery boreholes do not cover thermal conditions at or near the surface they play a minor role in this contribution. The main emphasis is put on the three boreholes located outside the gallery. Two of them were drilled below the cable car summit station on a north-facing rock slope at an altitude of 3.030 m and 3.000 m, respectively. The remaining borehole was drilled on a west-facing rock slope, at an altitude of 2.970 m. All three boreholes located outside the gallery were drilled perpendicular to the terrain surface and reach a depth of 30 m.

By all accounts a borehole depth of 30 m is sufficient to clearly surpass the depth of the zero annual amplitude (ZAA), i.e. the depth where the seasonal temperature amplitude is attenuated to 0°C (Gruber et al., 2004a). Since the Kitzsteinhorn boreholes have not been completely instrumented yet, there is no temperature data available to confirm the actual depth of the ZAA. However, data from Alpine boreholes (e.g. Hoher Sonnblick, located 25 km SE of Kitzsteinhorn) and Scandinavian boreholes document that temperature signals below a depth of 15-20 m are free of any seasonal or shorter-term temperature variation (Gruber et al., 2004a; Harris et al., 2009; Klee and Riedl, 2011).

Below the ZAA heat transfer is dominated by conduction due to the frozen state of water. Thermal 'disturbance' through non-conductive heat transfer (e.g. heat advection by circulating ground water) is impeded causing the preservation of thermal signals for long time periods. Near-surface warm-side deviations from the linear temperature gradient below the ZAA deliver a valuable indication of recent warming trends at the surface (Harris et al., 2003). Temperature data from deep boreholes therefore provide important evidence of past surface temperatures and long-term climatic changes that frequently date further back than local recordings of climatic conditions (Harris and Isaksen, 2008). In addition, a downwardly directed analysis of permafrost temperatures may deliver valuable information as well. If the borehole reaches deep enough to identify the local geothermal lapse rate, it is possible to esti-

**Figure 5:** Air flush rotary drilling at the Kitzsteinhorn west face in September 2010 (borehole depth 30 m) (Photograph by Ingo Hartmeyer).

mate the depth of the permafrost bottom via downward, linear integration of the gradient (Gruber et al., 2004a). As permafrost thickness typically reacts very slowly to climatic changes it provides important information on past climatic conditions on a century time scale.

Above the ZAA thermal conditions are subject to seasonal variations as involved processes operate on significantly shorter time scales than in great depths. Here, borehole temperatures serve to identify important variables such as active layer thickness or the mean temperature at the top of permafrost. The latter represents an important indicator for the sensitivity of a permafrost body, particularly if it displays values close to 0°C. Active layer thickness is primarily controlled by summer temperatures and has a high environmental and geomorphological significance. A thickening of the active layer, induced for instance by extreme summer temperatures, is likely to increase the scale and frequency of mountain slope instabilities, as evidenced during the heat summers of 2003 and 2005 (Gruber et al., 2004b; Gruber and Haeberli, 2007; Noetzli and Vonder Muehll, 2010).

Within the active layer non-conductive heat transfer plays an increased role due to the periodical availability of liquid water (Gruber and Haeberli, 2007). Intensive freeze-thaw cycles and rapidly changing ground surface temperatures have a large significance for shallow weathering of bedrock and in further consequence for the triggering of small rock fall events (Matsuoka, 2008). Barring a thick snow cover, which is rather uncharacteristic for steep rock faces, near-surface thermal dynamics are directly coupled to climatic forcing and therefore display very short lag times and large amplitudes (Williams and Smith, 1989; Isaksen et al., 2007).

In general, thermal gradients in boreholes are influenced by past and present ground surface temperatures, regional geothermal heat flux and variations of lithology with depth (Harris et al., 2003). Particularly the influence of lithology on the type and rate of heat transfer is often overlooked and therefore plays a prominent role within the present study. Thus, well cuttings have been collected during drilling to identify potential variations of thermal bedrock properties with depth. In addition, borehole imaging has been conducted with an optical scanner by TERRASCAN GmbH to localize and assess geotechnical discontinuities (joints, fractures). During optical scanning a probe was lowered into the borehole which delivered continuous, detailed, and scaled images of the borehole walls. Recorded parameters include dip, dip direction, joint frequency and aperture. Complementary analysis of borehole temperatures and data on discontinuities has the potential to deliver valuable information on the relevance of non-conductive heat transfer and therefore is of major importance for the understanding of subsurface heat fluxes (Ravanel et al., 2011).

All boreholes were drilled by 90 mm diameter air flush rotary drilling (Fig. 5). For temperature measurement Pt100 thermistors with an accuracy of ±0.1°C are used. The depths of the temperature sensors were selected in accordance with the PACE borehole strategy (Harris et al., 2001). Thus, attenuation of thermal variability with depth is taken into account by a down-hole increase of the sensor spacing. Temperatures will be recorded in two-hour intervals to resolve short-term variations at and near the surface (Tab. 1).

Currently, the boreholes are instrumented with a purpose-

| | Borehole Depth | Borehole Diameter | Depth of Temperature Sensors | Aspect of Slope | Gradient of Slope | Altitude (mouth of bore) |
|---|---|---|---|---|---|---|
| **Borehole 1** *located next to cable car summit station* | 30 m | 90 mm | 0.1, 0.4, 1, 2, 3, 5, 7, 10, 15, 20, 25, 30 m | North | 45° (borehole drilled perpendicular to terrain surface) | 3.030 m |
| **Borehole 2** *located 50 m north of cable car summit station* | 30 m | 90 mm | 0.1, 0.4, 1, 2, 3, 5, 7, 10, 15, 20, 25, 30 m | North | 45° (borehole drilled perpendicular to terrain surface) | 2.990 m |
| **Borehole 3** *located 50 m north of west gallery exit* | 30 m | 90 mm | 0.1, 0.4, 1, 2, 3, 5, 7, 10, 15, 20, 25, 30 m | West | 45° (borehole drilled perpendicular to terrain surface) | 2.970 m |
| **Borehole 4** *located inside gallery, approx. 40m south of cable car summit station* | 20 m | 90 mm | 0.3, 0.7, 2.3, 4.3, 6.3, 8.3, 10.3, 12.3, 14.3, 16.3, 18.3 m | Borehole located inside gallery, drilled perpendicular to eastern side wall of gallery | | 3.020 m |
| **Borehole 5** *located inside gallery, approx. 80m south of cable car summit station* | 20 m | 90 mm | 0.3, 0.7, 2.3, 4.3, 6.3, 8.3, 10.3, 12.3, 14.3, 16.3, 18.3 m | Borehole located inside gallery, drilled perpendicular to eastern side wall of gallery | | 3.015 m |

**Table 1:** Details of the locations, orientations and dimensions of the boreholes.

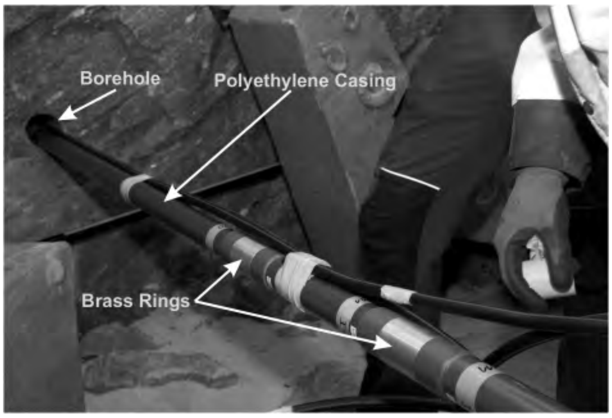


**Figure 6:** Borehole instrumentation inside the 'Hanna-Stollen' with a purpose-built temperature measurement system developed by GEODATA ZT GmbH (December 2011). The black tube serves to fill up the annulus with concrete after the insertion (Photograph by Robert Delleske).

built system for borehole temperature measurement which has been developed by GEODATA ZT GmbH. The measurement system consists of a polyethylene casing that prevents water entry into the borehole. The casing is segmented by non-corrosive brass rings that are connected to the temperature sensors. The insertion of brass rings enables improved thermal coupling between the temperature sensors and the ambient rock. The annulus (space between casing and bedrock) is filled with concrete to allow good thermal connection to the surrounding rock (Fig. 6).

In conclusion, the 'borehole scale' can be characterized as an investigation level with a very long 'thermal memory'. Due to the large investigated vertical spectrum it is possible to study both, (i) thermal fluctuations in near-surface areas that result from short-term variations of atmospheric conditions and (ii) deep-seated ground thermal 'signals' that reflect past climatic conditions and long-term climatic variations.

Since boreholes deliver point information only, it is – at this scale level – not possible to factor in the high lateral heterogeneity of thermal conditions typical for complex, high-alpine terrain. To account for the spatial heterogeneity other investigation scales have to be taken into consideration (see chapter 4.2, 4.3).

### 4.2 The 'Slope Scale'

At the 'slope scale' subsurface electrical resistivity is monitored by the application of (2D-)ERT (Electrical Resistivity Tomography). During ERT measurements an electric current is injected into the ground using two electrodes. The resultant voltage difference is then recorded at two potential electrodes. Repeated measurements with changing electrode location and spacing provide a dataset of the apparent subsurface resistance. The underlying resistivity distribution can then be calculated through inverse modeling (Hauck and Kneisel, 2008; Krautblatter et al., 2010).

ERT is well-suited to distinguish between frozen and unfrozen subsurface regions as a marked increase of electrical resistivity occurs at the freezing point of water-containing materials such as moist rock or soils (Mellor 1973; Sass, 2004; Krautblatter and Hauck, 2007). For this reason ERT is one of the most commonly applied geophysical methods for permafrost-related investigations (Hauck and Kneisel, 2008). Within the MOREXPERT project ERT data will primarily be utilized to identify the intra- and interannually varying thickness of the active layer as well as near-surface freeze-thaw cycles.

For monitoring purposes, ERT measurements are repeated at certain time intervals using the same survey geometry (time-lapse ERT). Thus, temporal and spatial permafrost variability can be assessed (Hilbich et al., 2008; Krautblatter et al., 2010). Rock faces are particularly well-suited for the quantitative interpretation of ERT data as bedrock has a relatively homogenous constitution and an accurately defined pore volume. Joints and fractures however represent distortions that potentially alter the subsurface electrical field considerably (Krautblatter et al., 2010).

Two permanent ERT-arrays have been installed on north-facing rock slopes (Fig. 2). The first array is situated directly below the cable car summit station at an altitude between 2.950-3.030 m (Fig. 7). Stainless steel screws and rock anchors were drilled into the rock to ensure firm electrode-rock contact. The profile is 100 m in length and has an electrode spacing of 2 m. The second profile is located on the north ridge of the Magnetköpfel at an altitude between 2.860-2.900 m (Fig. 2). It is 80 m long, electrode spacing is 1 m. The Magnetköpfl profile is operated by the 'Geological Survey of Austria' (person in charge: Mag. Robert Supper).

Stainless steel screws and rock anchors were drilled into the rock to ensure firm electrode-rock contact. Both arrays are 100 m in length and display an electrode spacing of 2 m. Measurements are performed applying Wenner and Schlumberger configurations. To account for the transitory nature of near-surface thermal changes, ERT data is acquired in time intervals of two to three hours. Data acquisition runs fully automatic and is controlled via remote access.

In addition to permanent ERT monitoring, sporadic ERT measurements are conducted in the 'Hanna-Stollen' and at the Magnetköpfl west face. These measurements are repeated with longer time intervals creating seasonal or annual time-sections of the monitored rock face.

Since ground temperatures are the principle parameter in any permafrost monitoring campaign, boreholes as only means of direct measurement play a crucial role. However, due to high costs and considerable technical efforts, drilling in remote high mountain areas is unfeasible within the scope of many studies. Even in the European Alps, the best-studied mountain range worldwide, only a very limited number of deep boreholes (> 10 m) exist (Noetzli and Vonder Muehll, 2010; Mair et al., 2011). Furthermore, borehole temperatures may not always be representative for the surrounding area (e.g. due to topographic effects). Thus, geophysical approaches for the characterization of ground thermal conditions represent an essential complement to borehole measurements.

While ERT field measurements do not provide direct information on ground temperatures, it is possible, under laboratory conditions, to measure electrical resistivity as a function of temperature (Mellor, 1973; Krautblatter et al., 2010). Laboratory calibration of numerous rock samples has been carried out at the cryo-laboratory at the University of Bonn (person in charge: Dr. Michael Krautblatter). During laboratory calibration different rock samples from the study area were subjected to multiple controlled freeze-thaw cycles. During freezing and thawing electrical resistivity was recorded in short intervals, which eventually produced a bilinear temperature-resistivity relationship for the investigated rock samples.

Two 30 m deep boreholes are located on the ERT array below the cable car summit station. This overlap allows parallel analysis of electrical resistivity values and borehole temperature data. Dual temperature calibration of ERT data using laboratory data and in-situ borehole temperatures significantly adds to the validity and significance of ERT results. Conversely, analysis of ERT data serves to assess the spatial representativeness of the boreholes by revealing the spatial heterogeneity of thermal conditions within the tomography.

As a rule of thumb the depth of investigation in ERT is restricted to about one sixth of the array length. Depth of investigation at the 'slope scale' is therefore reduced by half (approx. 15 m) compared to the borehole scale (30 m). Hence, the 'thermal memory' of the investigated vertical section is reduced significantly. However, as information on ground thermal conditions is collected along a two-dimensional profile line, a 'lateral dimension' is added at the 'slope scale'. In contrast to the 'borehole scale' information is not derived from a 1D-point-source (i.e. borehole). At the 'slope scale' it is therefore possible to take into account the lateral variability of ground thermal conditions typical for alpine terrain.

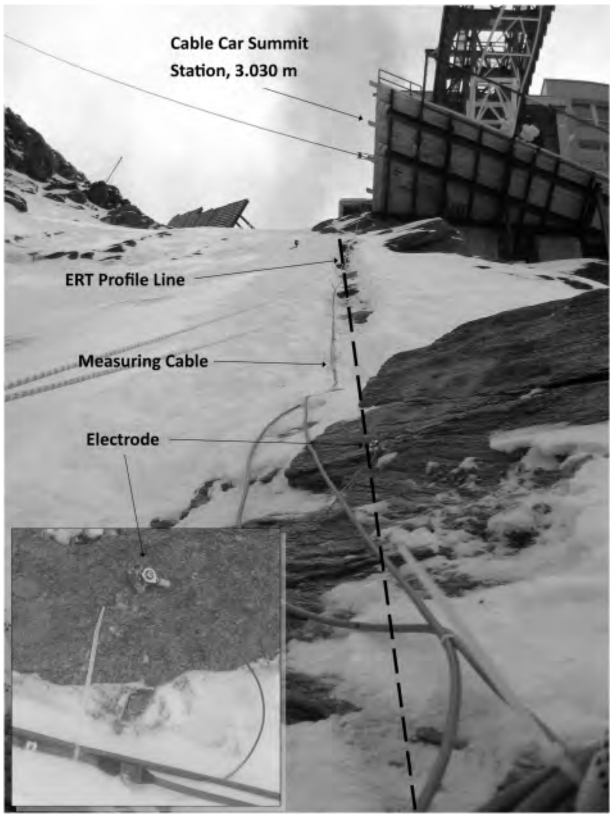


**Figure 7:** Permanently installed ERT array below the cable car summit station (3.030 m) (Photograph by Markus Keuschnig, view towards south).

### 4.3 The 'Mountain Scale'

At the 'mountain scale' GST (10 cm depth) and NST (near-surface temperatures) (80 cm depth) are measured at a large number of sites covering different elevations, slope aspects and slope inclinations. In terms of areal extent the 'mountain scale' therefore represents the largest scale of investigation.

Despite not being a direct measure of permafrost occurrence, GST and NST are important parameters for the understanding of the ground thermal regime as they provide valuable information on the thermal evolution of both active layer and permafrost (Noetzli and Vonder Muehll, 2010). In steep rock faces GST is strongly coupled to atmospheric temperatures and solar radiation effects. This strong coupling can be attributed to the general absence of buffering mechanisms (i.e. sediment cover, thick snow cover) in steep bedrock (Williams and Smith, 1989; Harris and Isaksen, 2008). GST therefore varies markedly over short distances and short observation periods, which in turn has a significant influence on permafrost distribution (Luetschg et al., 2008; Gubler et al., 2011).

Due to the high spatial and temporal variability of GST and NST, measurement at a single site is of low significance. Thus, a large number of temperature measurements are required to adequately resolve the heterogeneity of GST and NST. For this reason a new methodological strategy for near-surface rock temperature measurement has been developed, following approaches by Gruber et al., 2003 and Kellerer-Pirklbauer et al., 2008. The newly developed strategy involves the distribution of several dozens of miniature loggers over the entire summit pyramid of the Kitzsteinhorn. Temperature measurement is carried out in depths of 10 cm (GST) and 80 cm (NST). For practical purposes each borehole is equipped with just one miniature logger. Every measurement site therefore consists of

**Figure 8:** Drilling of a shallow borehole for iButton® temperature measurement at the Kitzsteinhorn south face (Photograph by Ingo Hartmeyer).

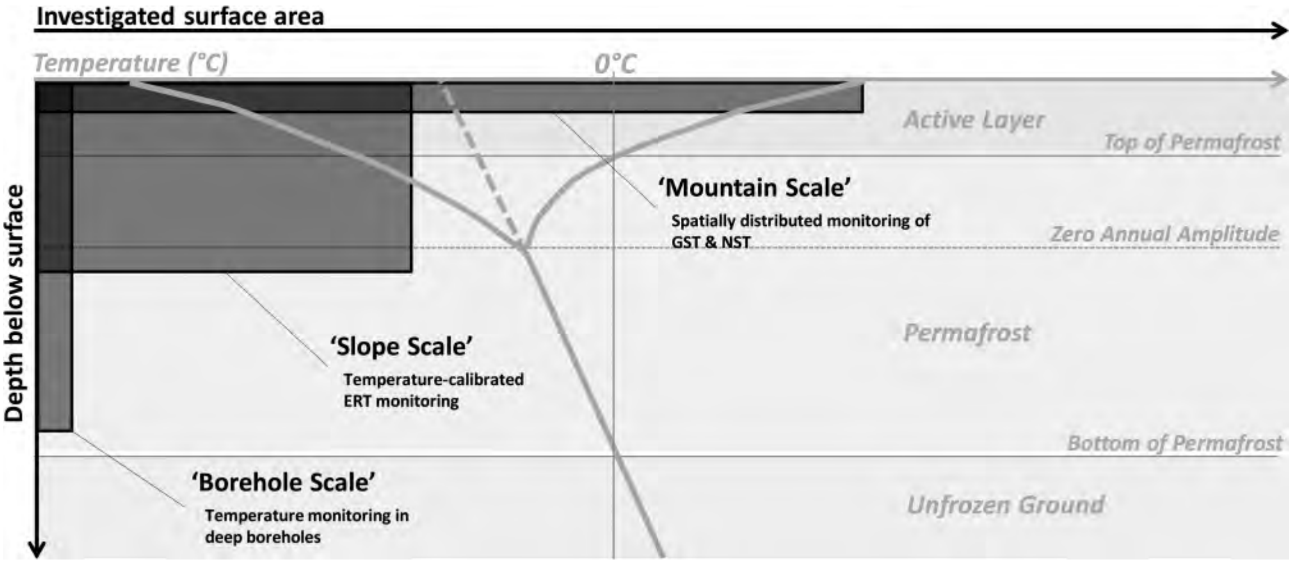


**Figure 9:** At the Kitzsteinhorn the ground thermal regime is investigated at three different investigation scales (conceptual illustration).

two shallow boreholes with respective depths of 10 cm and 80 cm. The large number of deployed loggers contribute to the reduction of uncertainty when measured GST and NST are extrapolated to areas not covered by measurements. Thus, an accurate estimation of near-surface ground thermal conditions for the entire summit of the Kitzsteinhorn is facilitated. In addition, spatially distributed measurements of GST in the vicinity of the drill sites help to evaluate the spatial representativeness of the deep boreholes (Noetzli and Vonder Muehll, 2010).

Until now 28 shallow boreholes with a maximum depth of 80 cm have been drilled (Fig. 8). The drilling of approximately 50 further shallow boreholes is currently in progress. To enable a small drilling diameter (18 mm) and therefore minimize the extent of the drilling works, iButtons® are used for temperature measurement. The iButton® is a coin-sized, commercially available miniature temperature logger that integrates a battery, a computer chip, a real-time clock and a temperature sensor in stainless steel can. To the authors' knowledge the present study represents the first time that iButtons® are applied for temperature measurement in bedrock.

iButtons® are well-suited for monitoring purposes as a total of 8192 8-bit readings or 4096 16-bit readings can be stored in a protected memory section. The integrated digital thermometer measures temperature with a resolution of 0.0625°C. The operating temperature range reaches from -40°C to 85°C, with an accuracy of ±0.5°C from -10°C to 65°C. To validate the measurement accuracy of the deployed iButtons, parallel temperature measurements with iButtons and UTL3-loggers (accuracy ±0.1°C) were conducted in the study area for several months. These measurements clearly demonstrated that the accuracy of the iButtons is significantly higher than specified by the manufacturer. All temperature data acquired with iButtons stayed well within the accuracy range of the UTL3 (±0.1°C) (Keuschnig et al., 2012).

Each iButton® was attached to the lower end of a polyethylene rod (17 mm diameter) with a cold-resistant adhesive. After insertion only the upper end of the rod sticks out of the borehole allowing convenient removal and reinsertion during memory readout. In accordance with iButton® measurements of GST carried out in Switzerland, the recording interval was set to three hours, enabling an operation period of 512 days (Gubler et al., 2011).

Water entry represents a prominent reason for iButton® measurement errors (Lewkowicz, 2008). To avoid water entry as well as advection of water and air in the borehole, the mouth of bore was sealed with weather-proof silicone. Programming and readout of all iButtons® is performed using the 'Thermo23' software by Maxim Integrated Products, Inc.

In comparison to the 'borehole scale' and the 'slope scale' vertical investigation depth is further reduced and amounts to less than one meter (80 cm) at the 'mountain scale'. 'Thermal memory' of the investigated vertical section therefore is at a minimum at the 'mountain scale' allowing only the identification of short-term thermal variations (e.g. diurnal and seasonal cycles). Ground thermal responses to conditions that date back further in time are not preserved near the surface and thus cannot be resolved at the 'mountain scale'.

## 5. Synthesis

Ground thermal conditions in high-alpine rock faces vary considerably over short distances and short observation periods. Reactions to environmental changes tend to be similarly variable in space and time, implying fast, sensitive responses at some locations and slow, lagged responses at other locations (Haeberli et al., 2010). This problem has been tackled with a monitoring approach that explicitly investigates the spatial and temporal heterogeneity of ground thermal conditions on three complementary scale levels.

At the 'borehole scale' ground thermal conditions are investigated along a vertical line (borehole thermistor chain). Due to the large depth of investigation (30 m) vertical attenuation and phase-shifting of ground temperatures can be examined at this scale level. As a consequence past climatic conditions which are preserved as deep-seated ground thermal signals can be studied. The 'borehole scale' is therefore provided with a long 'thermal memory' ('thermal inheritance'). Since boreholes have no horizontal extent, lateral variability of ground thermal conditions cannot be resolved.

The 'mountain scale' is set up diametrically opposite to the 'borehole scale'. Here, spatially distributed monitoring of GST and NST in bedrock facilitate the investigation of the small-scale lateral heterogeneity of ground thermal conditions. At the 'mountain scale' Investigation depth is reduced to a minimum as attention shifts from a vertical analysis towards an investigation of lateral variability.

In terms of its spatial and temporal extent the 'slope scale' can be viewed as a transitional scale between the 'borehole scale' and the 'mountain scale'. Compared to the 'borehole scale' depth of investigation is reduced considerably (to 15 m) while a 'lateral dimension' is added as information on thermal conditions is collected along a two-dimensional profile line (ERT array).

Within the MOREXPERT project all three methodical approaches (deep boreholes, shallow boreholes, ERT) have been implemented in complementary fashion (Figs. 2 and 9). Temperatures measured in deep boreholes can be used to calibrate ERT data. Conversely, ERT data deliver information on the lateral heterogeneity of ground thermal conditions and therefore serve to assess the representativeness of measured borehole temperatures. The combination of information from the 'borehole scale' and the 'mountain scale' plays an equally important role as thermal gradients from deep boreholes can be used to estimate temperatures in large depths for areas that are covered only by near-surface temperature sensors.

Thus, the chosen monitoring approach facilitates complementary analysis of data obtained at different scale levels and therefore allows (constrained) validation and extrapolation of information. Ultimately, the chosen approach is intended to yield a quasi-spatial model of the thermal state of the surface and subsurface at the Kitzsteinhorn. Due to its generic design it is considered to be transferable to comparable high-mountain study sites.

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