Interpretation of Geothermal Profiles Perturbed by Topography: the Alpine Permafrost Boreholes at Stockhorn Plateau, Switzerland

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ABSTRACT

The temperature regime of alpine permafrost is altered by the generally warmer atmospheric temperatures of recent decades. Eight boreholes, with depths between 100 and 130 m, have recently been drilled in European mountain permafrost as part of the Permafrost and Climate in Europe (PACE) project. They have been equipped with temperature sensors in order to better understand and quantify the effect of climate change on permafrost temperatures. Their interpretation with respect to signals of surface temperature histories is complicated by topographic effects. An apparent warming signal is present in all of the PACE boreholes but quantification of this effect in mountainous terrain remains difficult. The influence of topography and spatially-variable surface temperatures on temperature-depth profiles is demonstrated with measurements from the Stockhorn borehole and a simple model. A conceptual framework for the interpretation of topographically-disturbed temperature-depth profiles and the modelling of temperature histories based on these data is proposed. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: mountain permafrost; borehole temperatures; climate change; ground surface temperature history; geothermal monitoring

INTRODUCTION

Two boreholes in perennially frozen bedrock have been drilled at Stockhorn Plateau in the southern Swiss Alps above Zermatt (Valais) within the framework of the European Union (EU)-funded project ‘Permafrost and Climate in Europe (PACE): climate change, mountain permafrost degradation and geotechnical hazard’. They are part of the north-south (N-S) transect comprising eight drill sites, extending from the Mediterranean Spanish Sierra Nevada at 37° N, through several sites in the Alps, southern Norway and northern Sweden to polar latitudes in the Svalbard Archipelago at 78° N (cf. Harris et al., 2001). The boreholes have been instrumented with a thermistor chain and with an automatic weather station.

Bedrock temperature-depth profiles (T(z)-profiles) in permafrost provide the basis for: (1) monitoring of ground temperatures and quantification of concurrent changes; (2) investigation and modelling of energy exchange and transfer processes in the shallow subsurface; and (3) modelling past climatic changes based on histories of the ground temperature regime that can be inferred from the T(z)-profiles. For several decades, T(z)-profiles from the arctic have been used to monitor and model changes in ground temperatures and climatic conditions (e.g. Lachenbruch and Marshall, 1986; Lachenbruch et al., 1988; Osterkamp, 2003). This includes research on three-dimensional
effects below relatively flat topography such as the influence of lakes, buildings or the ocean on temperature fields at depth (Gold and Lachenbruch, 1973).

Temperature histories derived by inversion modeling based on T(z)-profiles are affected by several sources of error. These include: (1) advective heat transfer by fluid flow in bedrock, (2) changes in surface conditions (e.g. deforestation, changes in land use), (3) spatially-variable surface temperatures, (4) effects of latent heat, (5) topography, and (6) heterogeneities and anisotropy of the subsurface material properties.

In alpine permafrost, the effects of fluid flow and changes in surface conditions can be neglected. However, spatially-variable surface temperatures and topography (Kohl, 1999; cf. also Sergueev et al., 2003) have a profound effect on the temperature distribution at depth, violating the common assumption of one-dimensional heat transfer. As a consequence, care must be taken in the interpretation of T(z)-profiles below rugged topography. The modelling of temperature histories based on geothermal data requires two- or three-dimensional inversion techniques in order to separate the transient signal from that induced by spatially-variable surface temperatures and topography. This ability to compensate topographic effects provides the possibility to extract information on the past climate in many mountain ranges of the world where available instrumental records are sparse and short, and at the same time, climatic changes are expected to be most pronounced (Barry, 1990; Diaz and Bradley, 1997; Haeberli and Beniston, 1998).

Results of the PACE network of instrumented boreholes contribute to the Global Terrestrial Observing System (GTOS) of the Global Climate Observing System (GCOS) as outlined by Cihlar et al. (1997).

The present paper characterizes the two boreholes at Stockhorn and provides a discussion of a full year’s temperature data with emphasis on the clearly-visible effect of topography on the temperature profile. A conceptual framework for the interpretation of permafrost geothermal data below complex topography is also proposed.

THE FIELD SITE

The two drillholes are located on the Stockhorn Plateau (45°59′12″N, 7°49′27″E) above Zermatt, Valais, Swiss Alps at 3410 m a.s.l. (Figure 1). At the study site, the east-west (E-W) running mountain crest between Gornergrat and Stockhorn widens to a small plateau that is gently inclined to the south. It separates the steep glacier-covered north face of this crest from a non-glaciated southern face. Bedrock is part of the
palaeozoic crystalline Monte Rosa nappe and consists of Albit-Muskovit schist. Patterned ground has developed in the thin debris cover of the drill site area. Vegetation consists of isolated specimens of *Gentiana verna* and *Ranunculus glacialis* and boulders are only rarely covered with epipetric lichens, indicating that perennial snow patches might have been much larger in former times.

The Stockhorn-Gornergrat crest is surrounded by mountain ranges that exceed altitudes of 4000 m. This causes a local climate characterized by reduced cloud cover and high solar radiation. The annual precipitation in the Zermatt valley is relatively low and can be estimated to be 1500 mm at Stockhorn based on King (1990). A mean annual air temperature between $-5^\circ$C and $-6^\circ$C is estimated for the drill site for 1961–1990 (based on Begert et al., 2003; King, 1990). The top station of the Stockhorn funicular is in close proximity to the boreholes and facilitates easy access.

**EQUIPMENT AND MEASUREMENT PROCEDURES**

**Borehole Drilling and Preparations**

The two boreholes were drilled in July 2000 by a research team from Giessen University together with a private company. The 100.7 m ‘deep hole’ was located almost on top of the crest, whereas the 31 m ‘shallow hole’ is 28 m to the south, near the edge of the plateau (Figure 2). A 2-inch (50.8 mm) PVC-casing was inserted into the holes and the space between the PVC-tube and the bedrock was filled with concrete. For the uppermost 3 m a steel lining was used through the active layer for safety reasons. The top of the deep hole was secured with a metal protective cover screwed onto bedrock. A metal pipe with a lid has been inserted 40 cm into the ground at the top of the shallow hole and protrudes about 30 cm from the ground. Several days or weeks after the installation of the drill holes, concrete perforated the PVC-casing of the deep borehole and caused a blockage at 33 m depth. The obstacle was removed in December 2000, but material filled-up the lowest 2 m of the borehole due to these operations and the thermistor chain could subsequently be lowered to only 98.5 m in June 2001.

**Thermistor Chains and Data Logging**

Two thermistor chains with lengths of 100 m and 17 m, respectively, were manufactured with YSI 44006 NTC thermistors following PACE standards (cf. Harris et al., 2001). Their relative accuracy is $\pm 0.02^\circ$C (further technical specifications in Isaksen et al., 2001). Both thermistor strings were connected to a CR10X datalogger. Measurement intervals are 6 h (00, 06, 12 and 18 h) in the shallow borehole and for the upper 5 m of the deep borehole. Thermistors below 5 m in the deep hole are recorded once a day. Data are regularly recorded since June 2001.

**Climate Station**

In June 2002 a meteorological station was installed next to the deep borehole. Data are recorded every 6 h.
together with the borehole temperatures. The measured variables are: short-wave radiation (up- and down, 0.3–3 μm), long-wave radiation (up- and down, 5–50 μm), air temperature, relative humidity, wind direction, wind speed and snow cover height. These measurements allow investigations of the energy transfer processes at the surface and in the active layer. These processes ‘translate’ climatic signals into ground temperatures.

TEMPERATURE DATA 2001/2002

Thermal Profiles

A full year of data from 1 October 2001 to 30 September 2002 has been used for analysis and all statistics presented here refer to that period. Figure 3 shows a graph of the temperature profile of the deep borehole and its gradients.

The depth of zero annual amplitude (ZAA), where the annual temperature wave is attenuated to <0.1°C, is located at about 17.7 m in the deep hole. The mean annual ground temperature (MAGTZAA) is determined at this depth to be −2.5°C. Downward extrapolation of the gradient between 84 and 98 m suggests the permafrost thickness to be about 170–180 m. The uppermost 20 m of the profile in Figure 4 show the active layer thickness to be 3.1 m. Plate 1 displays temperature variations for some shallow sensors in the deep borehole. Note the long period of almost constant temperatures just below 0°C of the 3.3 m sensor. This so-called ‘zero-curtain effect’ is caused by transfer of latent heat during freezing and thawing of water contained in the rock or soil. All sensors in the active layer except the one at 0.3 m recorded a zero-curtain in autumn but not in spring, suggesting slow water removal by sublimation and transfer of water vapour along the temperature gradient below the snow. At the beginning of May, the sensors between 1.3 m and 3.3 m were almost isothermal at about −3.5°C.

Figure 3  Temperature profile and gradient in the 100 m deep borehole on Stockhorn, Switzerland. Diamonds indicate measured mean annual temperatures (October 2001 to September 2002) and gradients calculated between them. The continuous line is a spline interpolation of the temperatures values.

Figure 4  Temperatures and temperature envelope for the top 20 m of the 100 m deep borehole. Diamonds indicate the annual mean. Daily curves for 8 November 2001 (11), 8 February 2002 (2), 8 May 2002 (5), and 8 August 2002 (8) are shown.
Plate 1  Daily temperature curves for shallow sensors of the 100 m deep borehole. Nearly isothermal conditions of the top 3.3 m in May 2002 indicate the BTS effect.
Plate 2  (A) Steady-state temperature distribution in a simplified geometry representing Stockhorn. (B) T(z) profiles extracted from the calculated temperature field for the hypothetical boreholes shown by vertical thick lines in A.
suggesting insulation by a thick snow cover. This effect is also known from the bottom temperature of the snow (BTS) method (Haeberli, 1973). The mean temperatures between the surface and about 5 m depth in both profiles showed peculiar features (Figure 5). In the deep hole this was a strong warm-side deviation above 5 m. The shallow hole had the warmest mean temperature at around 2.5 m depth with decreasing temperatures above and below. These features may be caused by two reasons. (1) Borehole equipment: the protrusion of the protective covers through or into the winter snow cover effectively removes heat from the ground directly at the boreholes. In summer, the metal covers may actually warm the ground. The steel liner used in the upper 3 m of the boreholes also modifies the heat conduction at the top of the boreholes. At shallow depths, this perturbation can contribute strongly to the measured signal and cause a positive or negative mean temperature deviation. (2) Transient effects: the short time period of 1 year over which the temperature average has been calculated makes the possible influence of short term transient effects in the upper part of the profile large.

**Climate Signals and Topographic Effects**

The uppermost 30–40 m of the T(z)-profile in the deep hole (Figure 3) exhibit a pronounced warm-side deviation from a straight line that can be fitted to the temperatures of the lowermost sensors. At first sight this suggests a warming of 0.5 to 1.0°C at the ground surface during the last decades based on the upward extrapolation of deeper gradients. However, the evidence presented in this section suggests that great care has to be taken in the interpretation of geothermal data in complex topography. While the warm-side deviation of the upper part of the T(z) profile likely reflects warming, the quantification of this effect remains difficult and it may be both over- or underestimated without consideration of topographic effects.

A cross-section through the top of Stockhorn is shown in Figure 2. Horizontal and vertical axes as well as the position, distance and depth of the boreholes are all shown at the same scale. Despite their horizontal distance of 28 m only, the temperature profiles (Figure 5) of the deep and the shallow borehole have distinct differences as summarized in Table 1. From these differences it is evident that the position of the borehole on the Stockhorn plateau has a major influence on its temperatures and temperature gradients at depth.

**TWO DIMENSIONAL MODELLING**

Modelling of rock temperatures below mountainous topography and variable surface temperatures helps to explore and visualize their effect on temperature profiles. To achieve this, the finite element (FE) program FRACture (Kohl and Hopkirk, 1995) was used for forward modelling of rock temperatures in steady-state and with simplified boundary conditions. One of the features of this code is the integration of complex topography and surface conditions into a robust and well-tested numerical code.

**Estimation of Boundary Conditions**

A mean annual air temperature (MAAT) of −6°C at 3500 m a.s.l. and an environmental lapse rate of −0.0055°C/m is assumed (cf. King, 1990). This
temperature is modified by the input of solar radiation, active-layer processes and snow cover. The variation of near-surface temperatures with elevation is mostly due to the lapse rate of air temperature, whereas the N-S difference between ground temperatures is largely caused by differences in solar irradiation. Therefore, steep terrain exhibits larger lateral variation in temperatures than flat terrain. In addition, a thick and homogeneous snow pack that smoothes out lateral variations is not likely to form on steep slopes. Three sources of information are available for the estimation of the N-S variation of ground temperatures on Stockhorn: (1) the BTS can be regarded as a crude proxy of MAGT in the upper metres (the model described by Gruber and Hoelzle, 2001 predicts a N-S difference of about 3.5°C for the drill site); (2) measurements of rock temperatures in steep walls indicate 5–8°C difference between N and S (Gruber et al., 2003); and (3) the measured difference in mean temperature at the top of permafrost (TTOP) between the two holes is about 1.5°C.

Considering the general slope steepness mostly between 33° and 42° for Stockhorn, the N-S difference in ground surface temperatures will be greater than that predicted by the BTS model (calibrated in more gentle terrain) but less than that measured in rock walls. The difference between northern and southern slopes was assumed therefore to be 4.5°C with −4°C in the northern and +0.5°C in the southern slope. This is in agreement with the measured difference of about 1.5°C in TTOP/MAGT between deep and the shallow boreholes and approximately reproduces the measured TTOP temperatures (Table 1). The glacier on the northern slope was neglected.

Model Run

The N-S transect through the E-W trending Stockhorn ridge shown in Figure 2 was approximated by a trapezium (Plate 2A) having a width of 150 m at the top, 30° steep flanks and an altitudinal range of 2000 to 3500 m. Below that, a rectangle down to −1000 m with a lower boundary condition heat flux of 80 mW m⁻² and no heat transfer across the sides was generated. The boundary condition for the surface temperature of the mountain was given at the upper angles of the trapezoid to be −4°C on the northern side and +0.5°C on the southern side. The temperature at the two lower angles was +4.25°C and +8.75°C, respectively. After generation of the FE mesh, boundary conditions for the surface elements were derived by linear interpolation between the angles of the trapezium. In the diffusive steady-state thermal energy equation the thermal conductivity is the only petrophysical parameter of importance. It was set to 3.0 W K⁻¹ m⁻¹ and directional isotropy was assumed.

Model Results

In Plate 2A the model result is displayed. The bent isotherms illustrate that there is a strong lateral heat flux from S to N. In Plate 2B, three temperature profiles retrieved from the model are shown. Although only 150 m apart in total, they all differ strongly in temperature and temperature gradients. Depending on the positioning of the borehole, the MAGT at a certain depth in the model can differ by several degrees. With standard assumptions on one-dimensionality, different degrees of transient warming or cooling could be misinterpreted. These differences in temperatures and temperature gradients predicted by the model can also be observed in the measured data (Figure 5). However, the model (Plate 2B, profile 1 or 2) did not reproduce the strong warming observed in the upper part of the measured profile (Figure 3).

INTERPRETING GEOTHERMAL DATA IN MOUNTAIN TOPOGRAPHY

The differences between the thermal profiles of the deep and the shallow holes (Figure 5 and Table 1), as well as the similarity of the measurements and the model underscore the importance of jointly treating topographic and transient effects when interpreting T(z) data measured in complex topography. Accurate knowledge of the spatial distribution of ground temperatures is needed for this treatment of topographic effects. In this context, the term ground surface temperature (GST), as used in the geothermal community is equivalent to the mean TTOP below which energy transfer is dominated by conduction. Above the top of permafrost the active layer together with seasonal snow cover represent a complex system that translates climatic variables into ground temperatures at depth. The active-layer depth, however, changes spatially and between years and the concept of TTOP is restricted to permafrost areas only. It is therefore more practical to use the MAGT at a certain depth, e.g. MAGT₅ at 5 m, as an equivalent of the term GST. This depth should be greater than the maximum active-layer thickness that is expected for most of the area under investigation.

Calculating MAGTx Histories

The derivation of estimates about MAGTx histories generally involves two problems: (a) to find a valid
physical model describing the subsurface heat flux and (b) to obtain a unique and stable \( M_{\text{GT}} \) result from the \( T(z) \) data, based on that model. The physical model for mountain permafrost can be assumed to have negligible influence of fluid flow and to be influenced by topographic multi-dimensionality as well as spatially-variable \( M_{\text{GT}} \).

For the inversion of \( M_{\text{GT}} \) histories from \( T(z) \) data, Wang (1992) provides an overview of several approaches developed for one-dimensional cases. These approaches may be used only in cases with negligible topographic disturbance. In mountain topography, the information contained in a \( T(z) \) log is a complex superposition of spatially-variable temperature signals below a surface that has a distinctly different geometry than that assumed in the one-dimensional case. As a consequence, a fully three-dimensional, transient model is needed in the process of \( M_{\text{GT}} \) estimation. This requires the parameterization of the spatial \( M_{\text{GT}} \) boundary condition together with a function describing its behaviour in time. It is evident that this implies great uncertainties and involves a large number of assumptions. Therefore, only very robust approaches for \( M_{\text{GT}} \) inversion should be used. Furthermore, the treatment of latent heat is of importance for transient models in warm permafrost (cf. Wegmann et al., 1998).

For the estimation of \( M_{\text{GT}} \) histories in topographically complex situations, Kohl and Gruber (2003) describe an inversion scheme based on the FE-forward code FRACTure and the computer program UCODE. In combination, UCODE and FRACTure perform inverse modelling, posed as a parameter-estimation problem, by calculating parameter values that minimize a weighted least-squares objective function using non-linear regression. With this tool complex multi-dimensional inversion studies can be theoretically accomplished and first results for a two-dimensional case study are reported by Kohl and Gruber (2003). However, numerical instability and non-uniqueness represent well-known problems in inverse modelling and obtaining useful results can become more difficult for highly heterogeneous conditions.

### Interpreting \( M_{\text{GT}} \) Histories

Histories of \( M_{\text{GT}} \) inverted from \( T(z) \) profiles are a valuable indicator of the past evolution of the ground thermal regime. However, the \( M_{\text{GT}} \) is distinctly different from the real surface or air temperatures (cf. Lachenbruch et al., 1988). The buffer layer between the atmosphere and the top of alpine permafrost (including active layer and snow cover) is characterized by complex and spatially-variable processes of heat transfer. The quantitative understanding of these processes is still limited. Therefore, the deduction of climatic changes from the obtained \( M_{\text{GT}} \) history is subject to large uncertainties and not straightforward. In particular, the seasonal snow cover in winter influences ground temperatures depending on timing, structure, duration and thickness (cf. Zhang et al., 1996, 2001; Goodrich, 1982). Because the snow cover is highly variable in space (wind drift, avalanches, solar radiation) and time (inter-annual characteristics) only limited quantitative data on its role are available. Overall, it is a noisy parameter that is estimated to have a warming effect on ground temperatures of 1 to 4.5°C for the Alps (cf. Hoelzle et al., 2003; Keller, 1994; Vonder Muehll et al., 1998; Imhof et al., 2000).

The effect of changing snow characteristics may outweigh or compensate the effect of changing air temperatures in some instances.

### DISCUSSION AND CONCLUSION

The presented measurements on Stockhorn demonstrate that the \( T(z) \) profile is heavily disturbed by topography. This effect could be reproduced in a simple model experiment demonstrating the coexistence of both positive (temperature increasing with depth) and negative near-surface geothermal gradients even in steady state. The value of geothermal monitoring in mountains is not affected by topographic effects, but for the interpretation of transient signals contained in the \( T(z) \) profile it is a major obstacle. A warming signal can be inferred from the data (along with all other PACE boreholes in more gentle topography), but its quantification remains difficult. The required separation of topographic and transient effects from geothermal profiles of alpine permafrost has two prerequisites: (1) an accurate description of the spatial field of \( M_{\text{GT}} \) and (2) suitable modelling tools for three-dimensional inversion of \( T(z) \) profiles.

Research on the interpretation of geothermal data from the PACE network of permafrost boreholes is expected to promote the ability to handle three-dimensional effects. Improved guidelines for the selection and instrumentation of mountain permafrost drill sites are likely to evolve.

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