1 INTRODUCTION

The stability of rock faces with ice-filled discontinuities is strongly influenced by its temperature. In depth ranges from centimetres to many tens of metres temperature-dependent processes are subject to changes on time scales of hours to centuries (cf. Lunardini 1996; Matsuoka et al. 1998). The frequency of larger and potentially hazardous events resulting from degradation of warm permafrost or from a rising permafrost base could possibly increase as a response to a warming climate (Haeberli et al., 1997; cf. also Noetzli et al., 2003, this issue). Such deep-seated events are usually attributed to loss of ice/rock 'adhesion' upon the phase change from ice to water or elevated water pressure due to the existence of liquid ground water. Additionally, Davies et al. (2001) showed that changing properties of warming ice before the actual phase change may result in failure of rock slopes that would be stable at low temperatures or when ice-free. But where can such thermal conditions be found and how can present or past events be attributed to them? Which rock faces might become potentially destabilized and require further investigations? To address these questions, quantitative data on the spatial distribution of rock surface temperatures is needed because the temperature field at depth is to a large degree determined by surface conditions.

The ability to model and parameterize surface temperatures of rock faces is not only an important asset for the high resolution stage of natural hazard assessment but also for studies of rock weathering in general. Acting on a shorter depth/time scale, an increasing active-layer thickness will subject perennially frozen rock to freeze-thaw cycles and corresponding effects such as joint widening (macrogelivation). Effective frost weathering by granular disintegration and small flaking (microgelivation) is known to occur preferentially in a rather narrow sub-zero temperature range (see Matsuoka 2001 for a summary of typical values for several lithologies). Depending on surface temperatures, corresponding time windows vary strongly at different depths (c.f. Anderson 1998). Whereas studies involving sediment traps can easily rely on in-situ measurements, investigations of rock-wall processes and retreat rates could benefit from the possibility of establishing temperature ranges.

The derivation of climate signals from geothermal analysis of borehole temperature profiles in permafrost (e.g. Isaksen et al. 2000) is a promising means of evaluating the integrated effect of climatic change on ground temperatures. Interpretation of borehole temperatures in alpine topography such as those measured along the European PACE transect (Harris et al. 2001), however, require careful corrections of topographically derived distortions that might otherwise be mistaken for climate signals (Kohl 1999). In the mean annual ground-surface temperature field required for the interpretation of permafrost thermal data, rock-wall temperatures constitute one component in a continuum of surface conditions, ranging from snow-free rock-faces to flat ground with a thick winter snow cover and a mixed-media active layer. Parameterizing rock-wall tem-
temperatures involves considerable problems of representative sampling under conditions of difficult access. In this article, a strategy for systematic investigation of near-surface temperatures of Alpine rock faces in a spatial context is presented. First data obtained in the measurement campaign between the summers of 2001 and 2002 is briefly examined.

2 BACKGROUND

Several researchers report rock surface or near-surface temperature measurements (e.g. Lewkowicz, 2001, Hall and André, 2001; Matsuoka and Sakai, 1999; Wegmann, 1998; Hall, 1997; Matsuoka et al, 1997 or Coutard and Francou, 1989) but the question of their spatial distribution on a regional scale remains open. Aspect-related differences in temperature as summarized in Table 1 lead to the conclusion that air temperature alone is a bad surrogate for rock

<table>
<thead>
<tr>
<th>Author</th>
<th>Temperature Difference °C</th>
<th>Sensor Depth mm</th>
<th>Elevation m a.s.l.</th>
<th>Latitude</th>
<th>Averaging Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lewkowicz (2001)</td>
<td>0.2</td>
<td>15</td>
<td>270</td>
<td>80N</td>
<td>month (polar night)</td>
</tr>
<tr>
<td>Lewkowicz (2001)</td>
<td>1.5</td>
<td>15</td>
<td>270</td>
<td>80N</td>
<td>month (polar day)</td>
</tr>
<tr>
<td>Lewkowicz (2001)</td>
<td>&gt; 5</td>
<td>15/20</td>
<td>270</td>
<td>80N</td>
<td>month (spring)</td>
</tr>
<tr>
<td>Hall (1997)</td>
<td>1.32</td>
<td>?</td>
<td>300</td>
<td>71S</td>
<td>5 days (polar day)</td>
</tr>
<tr>
<td>Hall &amp; André (2001)</td>
<td>~8</td>
<td>on surface</td>
<td>30</td>
<td>67S</td>
<td>1 minute (11 Dec)</td>
</tr>
<tr>
<td>Matsuoka et al. (1997)</td>
<td>~5 &amp; ~4</td>
<td>centimeters</td>
<td>2850</td>
<td>46N</td>
<td>year</td>
</tr>
<tr>
<td>Wegmann (1998)</td>
<td>3.3</td>
<td>centimeters</td>
<td>3560</td>
<td>46N</td>
<td>year</td>
</tr>
<tr>
<td>Wegmann (1998)</td>
<td>5.0</td>
<td>?</td>
<td>3600</td>
<td>46N</td>
<td>year</td>
</tr>
<tr>
<td>Wegmann (1998)</td>
<td>7.7</td>
<td>centimeters</td>
<td>2730</td>
<td>46N</td>
<td>year</td>
</tr>
</tbody>
</table>

surface temperatures. Net short-wave radiation is likely to be the major controlling factor causing this observed lateral variation of several degrees Celsius in rugged topography.

Data recorded during Antarctic/Arctic winters by Hall (1997) and Lewkowicz (2001) demonstrate that, in the absence of solar radiation, rock-surface temperatures follow air temperature closely. The influence of rock albedo is evident a priori and has been demonstrated semi-quantitatively by Hall (1997) who showed surface temperature averages to differ by 1.1 °C for dark and light colored rocks in otherwise comparable situations for one Antarctic summer. A temperature difference between rock faces of E/W exposition that theoretically should receive a similar input of solar energy can often be observed. This is likely due to the influence of diurnal variations in cloud cover such as convective clouds in the afternoon that reduce solar radiation totals on W-slopes.

Snow cover has two important effects on rock surface temperatures: 1) smoothing of radiation-induced lateral differences and of high-frequency fluctuations by insulation of the ground from the atmosphere 2) increasing ground temperatures by insolation during winter when most energy loss takes place. This is demonstrated by Coutard & Francou (1989), who at 6 cm depth and an interval of 2 hours measure a daily range of 24.6 °C without snow and only 1.2°C under snow cover at two almost identical sites (February, south-facing, 3000 m a.s.l., 45N). Matsuoka & Sakai (1999) in the Japanese Alps measure 2.4 °C warmer mean annual ground surface temperatures at 3120 m at a snow-covered site than at a comparable snow-free place. For a discussion of the special case of thin snow cover, see Keller & Gubler (1993). Timing and duration of snow cover are treated by Zhang et al. (2001). The almost complete absence of snow cover combined with the direct coupling of surface and subsurface energy balance (without complex thermal offset in a mixed-media active layer) makes near-vertical rock faces a system that is most likely easier to characterize than ground temperatures on flat terrain. Based on the above reasoning, a lateral variation of mean annual rock-surface temperatures in the order of 5-10 °C is expected for sites of similar elevation in the Alps. It is expected that this spatial differentiation is largely related to net short-wave solar radiation. Hoelzle & Haeberli (1995) and Gruber & Hoelzle (2001) demonstrate successful statistical modeling of a ground temperature proxy (BTS – bottom temperature of the winter snow pack c.f. Haeberli 1973) that is subject to noise induced by snow cover and a mixed-media active layer. The absence of these sources of error makes statistical parameterization of rock-wall temperatures a promising task.

3 RESEARCH STRATEGY

3.1 Sampling Strategy and Site Selection

The cost and effort involved in installing data loggers in steep rock faces is obvious and therefore their total number has to be kept small. At the same time, an even distribution of measurements over the assumed range of surface temperatures is desired. As a first approximation, the model described in Gruber
and Hoelzle (2001) has been employed to simulate BTS values as a proxy for MAGST in the test areas. Pixels steeper than 45° derived from a digital elevation model (DEM) with a grid size of 25 m have been used to identify rock faces. Thus, potential sampling areas together with a temperature proxy could be laid over a topographic map. Aiming at an even distribution of 20 loggers over the BTS range of 0 to -15 °C, individual sites have been pre-selected at altitudes from 2000 to 4500 m covering the entire range of expected permafrost conditions in Alpine rock-walls. As the BTS model likely underestimates rock-surface temperature differentiation by solar radiation it has been attempted to cover different slope aspects evenly. For the recovery of realistic daily surface temperatures, the interval of recording and measurement as well as sensor depth must be considered. Thermistors are placed at a depth of 10 cm, avoiding the difficult and error-prone direct measurement of rapidly fluctuating surface temperatures. The surface area and time over which the measured signal is integrated by heat diffusion within the rock increase with sensor depth. As a consequence, the alteration of the signal caused by the sensor and its wiring is reduced and high-frequency signals are dampened, allowing for accurate sampling at an interval of two hours.

3.2 Logger Design and Installation

Loggers have to be water-proof, resistant to temperature fluctuation and extremes, tolerant to minor rock-fall and fast to install without many tools. Battery life and storage capacity should well exceed 1 year. UTL-1 data loggers (see: Hoelzle et al. 1999) were redesigned for this project as these have been employed successfully before. They have the capacity to store 7944 8-bit measurements in the range between -30 and +40 °C and an accuracy of better than ±0.25 °C is given by the manufacturer. A screw-in metal lid with rubber “O”-rings ensures waterproof sealing of the logger.

Our main alteration was the construction of a water-proof and protective sensor arm that also establishes the logger/sensor geometry. The sensor side of this arm is 10 cm long to ensure placement at equal depths and the logger side has a length of 12 cm in order to keep thermal disturbance at the surface directly above the sensor at a minimum (Figure 1). After inserting the 8 mm arm into a 10 mm drill hole together with some silicon sealant, the logger is screwed to the rock wall using a clamp and a wall-plug in a second 10 mm hole. The sensor arm is made of PVC and was screwed and glued into the
logger housing consisting of DELRIN plastic. Prior to installation, all loggers were equipped with a new lithium battery and a silica gel pack to ensure dry electronics, calibrated in a 0 °C ice bath and programmed in the laboratory.

### 3.3 Site Access, Safety and Logistics

The sites finally chosen for instrumentation have to be easily accessible in order to keep the total time used for placement and recovery of data logger small. Generally, sites were chosen that could be reached from the top in one rappel. The equipment carried for logger placement on belay (Figure 2) included a HILTI drill, bolt plates, screw and wallplug, a screw driver, a wrench and a hammer, loggers, silicon, a camera, compass and clinometer as well as usual climbing aids.

### 3.4 Local Placement of Data Loggers

After selecting a site according to its elevation, exposition and expected temperature, the local placement of data loggers is of great importance. Rockfaces that from afar appear to be exposed in one direction usually exhibit many individual facets of distinctly different steepness, exposition or local shading. The facet chosen for measurement should resemble the general character of the large face as close as possible. Near-vertical situations are preferable due to a minimum snow cover and a vertical distance of several meters should be kept to flat terrain below in order to avoid coverage by snow piles. It has been attempted only to measure on surfaces that are homogeneous and free of visible fractures or discontinuities within a radius of more than 30 cm.

### 3.5 Auxiliary Information Requirements

During and after logger installation, several parameters are recorded. The coordinates (usually at the belay point) are determined with a hand-held GPS receiver. Slope angle and azimuth at the logger are measured and the elevation is determined using a barometric altimeter.

Because topographic shading has a major effect on solar radiation input in rugged terrain horizon lines need to be determined for the calculation of solar illumination. Usually, horizon shading is derived from DEMs. In rock walls however, their facet-structure and micro-topography often introduces significant horizons that locally influence temperature measurements but that are not resolved in DEMs. In this campaign, local horizons are therefore recorded using a digital camera (Nikon Coolpix 990) with a fish eye converter (Nikon FC-E8). A device to mount the camera in the remaining hole after removal of the data logger has been constructed (Figure 3). The camera is installed on a platform held by a ball-joint and equipped with a compass and a spirit level. One image with a vertical camera nadir is taken and the azimuth of a marker in the image is read from the compass. This information allows for subsequent extraction of horizon lines in the office and to calculate more realistic solar radiation.

### 4 SAMPLING PROGRAM

In summer and autumn 2001, 21 data loggers were installed at elevations between 2000 and 4500 m a.s.l. at sites where the transportation infrastructure present at high altitude in the Swiss Alps facilitated quick access. Loggers were placed in the following areas: Gornergrat/Stockhorn, Monte Rosa and Kleinmatterhorn/Gandegg close to Zermatt, Birg/Schilthorn and Jungfraujoch in the Bernese Alps and Corvatsch/Furtschellas close to St. Moritz.

In autumn 2002 all data loggers were reclaimed except for one that could not be reached. Photographs of the sky hemisphere for later extraction of horizons were taken at most sites but failure of the camera and bad weather made this impossible in some cases. Only one logger had been physically damaged. It had a broken sensor arm and was filled with ice.
5 FIRST RESULTS AND EXPERIENCES

14 complete time series (see example in Figure 6) of one year and several shorter ones have been obtained from the measurements. Detailed description and analysis of the dataset will be published elsewhere, but first results indicate that:

• the lower limit of permafrost is somewhat higher than that established on more gentle terrain (eg. Haeberli, 1975)
• the lower limit of negative mean annual rock temperatures in the south is about 1000 m higher than in the north (Figure 4)
• diurnal temperature cycles and thus the influence of e.g. clouding are discernible in the data (Figure 5)

Unfortunately, even at low elevation sites, several data loggers stopped recording after only a few days or weeks. This was most likely caused by a batch of spoiled batteries. Individual loggers may have stopped recording due to low temperatures such as one north-facing at 4500 m that stopped below -25°C during a severe temperature drop. On the other hand, the south-facing logger on the same altitude recorded -27°C that night and thus survived similar conditions of low air-temperatures without problems, suggesting this not to be the sole cause of failure. The data registered by all loggers could be read without problems after replacement of the battery. The data logger with the broken sensor arm was completely filled with clear ice but was also readable after drying. The recording of local horizons using a digital camera with a fish eye lens was generally successful. Unfortunately, the required good visibility puts a constraint on possible times for field work and thus several sites could not be photographed due to fog or snow fall.

6 CONCLUSION AND OUTLOOK

The data collected during this campaign is of good quality and will suffice as a basis for the intended analysis and modeling of the spatial distribution of Alpine rock-face temperatures. This is expected to provide necessary information for research related to the stability of frozen rock-walls under a warming climate and to be beneficial for investigations of weathering and landform evolution.

The experiences and data collected in the course of this project bring additional benefits for calibration and verification of energy-balance models. The direct coupling between atmosphere and rock temperatures constitutes a unique opportunity for quantitative spatial evaluation of relative and absolute model accuracy. A combination of rock-wall temperature measurements, together with measurements of level (and thus potentially snow-covered) rock surfaces will likely provide more quantitative data for analysis and modeling of ground temperature conditions than BTS alone. Corresponding strategies of combined BTS and rock-surface measurement campaigns are currently being developed.

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