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Characterisation of potentially unstable mountain permafrost – A multidisciplinary approach

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ABSTRACT: A multidisciplinary study including geophysical, geotechnical and glaciological techniques has been conducted on an Alpine rock glacier. Lateral extensions were obtained from air photographs, whereas vertical extensions of seismic refraction tomography provided critical information on major internal features, as well as bedrock topography. Four boreholes were drilled down to bedrock in a zone of degrading permafrost. Detailed information on the rock glacier stratigraphy was obtained, undisturbed cores were extracted to study mechanical properties and temperature monitoring, deformation measurements and georadar cross-hole tomography were carried out. The combined analysis of these data leads to a unique interpretation. Significant shear deformation occurs at the interface between an ice rich layer and a zone of sandy gravel at ~20 m depth. Below the sandy gravel, a conspicuous, 5 m layer of boulders with large voids was found. This prevents accumulation of high pore pressures, which are a prerequisite for rock glacier instability.

1 INTRODUCTION

Permafrost covers extensive areas of the Alps above ~2500 m elevation (Keller et al. 1998). Significant portions of Alpine permafrost exist in the form of rock glaciers. These amalgamations of boulders, ice, water and air form on gently to moderately dipping mountain slopes. Subject to gravitational forces, they creep slowly down-slope. The rock components range in size from fine-grained particles to large boulders, and the interstitial pores are filled mainly with ice, which is a critical factor for kinematic behaviour as well as stability. Alpine permafrost is very sensitive to climate change (Cheng & Dramis 1992, Haeberli et al. 1993) and as a result of global warming, the ice contained in many rock glaciers is melting, with the potential for deterioration of the mechanical properties. In particular, the instabilities caused by melting ice may result in catastrophic debris flows that are significant hazards in populated mountain areas (Haeberli et al. 1997, 1999).

Assessing the stability of rock glaciers requires advanced knowledge of their internal structures. Critical details include the distribution of solids, ice, water and large voids, which can be delineated with high-resolution geophysical techniques. These parameters form the basis for assessments of the mechanical stability. Together with in-situ geotechnical testing, stability criteria can be established and potential risks of failure can be estimated. Such predictions can be further constrained with glaciological techniques, such as geomorphological investigations and temperature measurements. In other words, only a combined application of geophysical, geotechnical and glaciological techniques is expected to be successful for such a complex geomorphic feature. This has been achieved in the framework of a multidisciplinary project, aimed at delineating internal structure and investigating the stability of a typical rock glacier. Key results from these investigations are reported in this contribution. In particular, the benefits of the multi-disciplinary nature of the study are highlighted.

2 MURAGL TEST SITE

The Muragl valley, located in the eastern Swiss Alps, contains a number of moraines, a small glacier superimposed on discontinuous Alpine permafrost and a well-developed rock glacier. As shown in Figure 1a, the Muragl rock glacier flows from a small cirque into the main valley. It is 100–300 m wide, about 700 m long and extends over an altitude range of 2600–2800 m. It is distinguished by rapid horizontal movements of up to 0.5 m/a (Kääb & Vollmer 2000) and exhibits pronounced flow lobes with transverse furrows and ridges. The irregular pattern of the flow lobes may be the result of periodic mass movements, perhaps reflecting several generations of rock glacier evolution. Bedrock beneath the rock glacier is a gneissic rock mass.

The Muragl test site could not be accessed by motorised vehicles, which required all equipment to be a)

b)

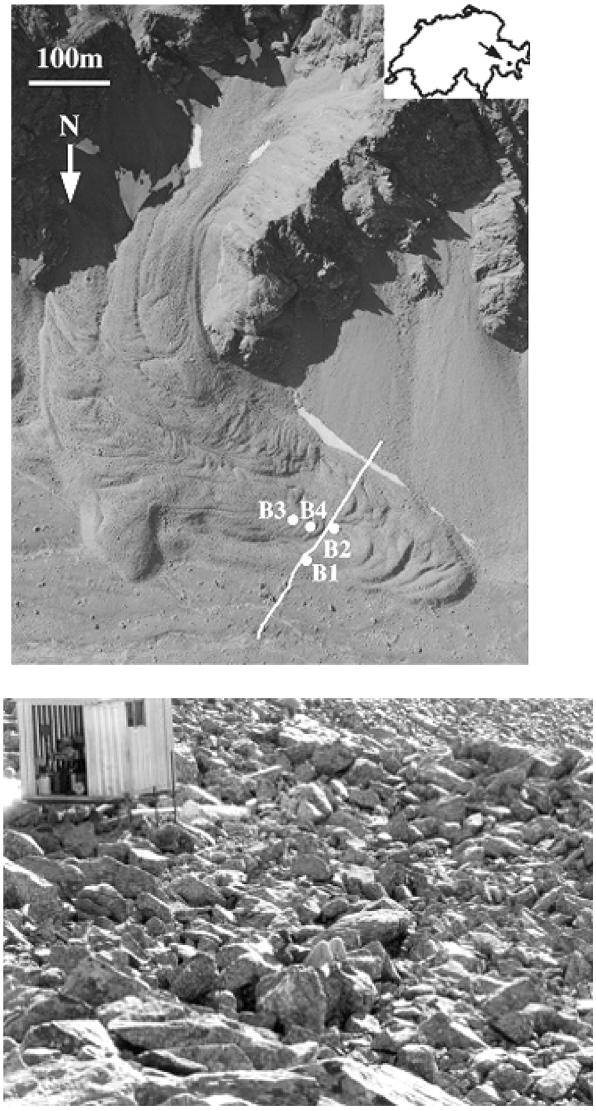

Figure 1. a) Air photograph of the Muragl rock glacier. Solid white line delineates a seismic profile and B1–B4 mark positions of the boreholes. b) Rock glacier surface.

flown in by helicopter. Furthermore, the extremely rugged terrain (Fig. 1b) complicated the investigations.

3 SURFACE-BASED INVESTIGATIONS

Lateral and vertical extensions of the rock glacier, as well as its gross internal features, had to be determined as a first step. Lateral boundaries could be delineated reliably using air photographs (Fig. 1a). Encouraged by excellent results from the nearby Murtèl-Corvatsch rock glacier (Lehmann & Green 2000), several georadar profiles were recorded across this rock glacier. Unfortunately, strong scattering effects from the heterogeneous near-surface structure (Fig. 1b) did not allow depth information to be extracted from the georadar data. Therefore, high-resolution seismic reflection profiles were recorded.

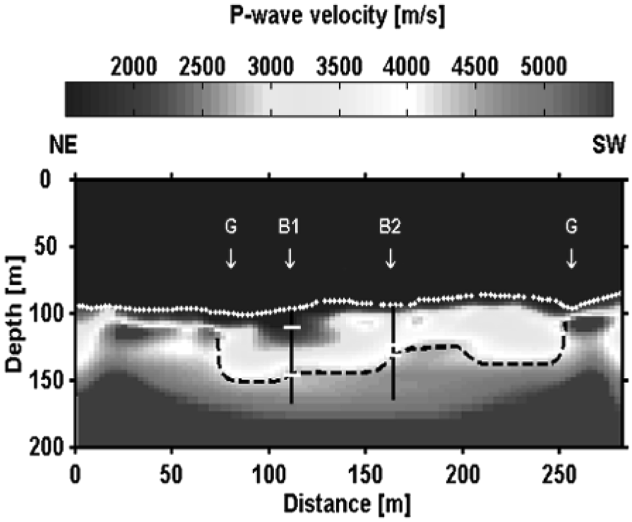

Figure 2. Refraction tomogram derived from seismic profile recorded across the Muragl rock glacier (Fig. 1a). Gs mark the lateral boundaries of the rock glacier as observed on the air photograph of Figure 2. B1 and B2 denote borehole locations. Small white lines indicate depths to bedrock and groundwater table observed in the boreholes. Dashed line outlines our interpretation of bedrock topography.

Extensive reflection processing of the data did not yield conclusive results, primarily due to the long-wavelength character of the returned signals and strong guided waves and scattering.

Since the quality of the first breaks was good, and the range of source-receiver offsets were up to 250 m, the signals could be analysed using a refraction tomography algorithm (Lanz et al. 1998). The tomogram corresponding to the seismic profile in Figure 1a is depicted in Figure 2. Bedrock topography was characterised by velocities of 4000–4200 m/s and depths to bedrock varied between 30 and 50 m below the surface, as indicated by the dashed line in Figure 2. Several distinct heterogeneities were observed within the rock glacier. The most conspicuous feature was a low-velocity block between 80 and 140 m horizontally along the traverse. It was interpreted as degraded permafrost, a region where the ice has melted completely, leaving large air voids.

4 IN-SITU BOREHOLE MEASUREMENTS

On the basis of the seismic refraction results, suitable locations were chosen for boreholes. Of particular interest was the zone of degraded permafrost (Fig. 2). Therefore, one borehole was located within this zone, and the others were placed in the nearby regions, where the annual surface velocity was about 0.2–0.3 m/y (Kääb & Vollmer 2000). The final choice of the borehole layout (Fig. 1a) was additionally constrained by accessibility for the drill rig and requirements imposed

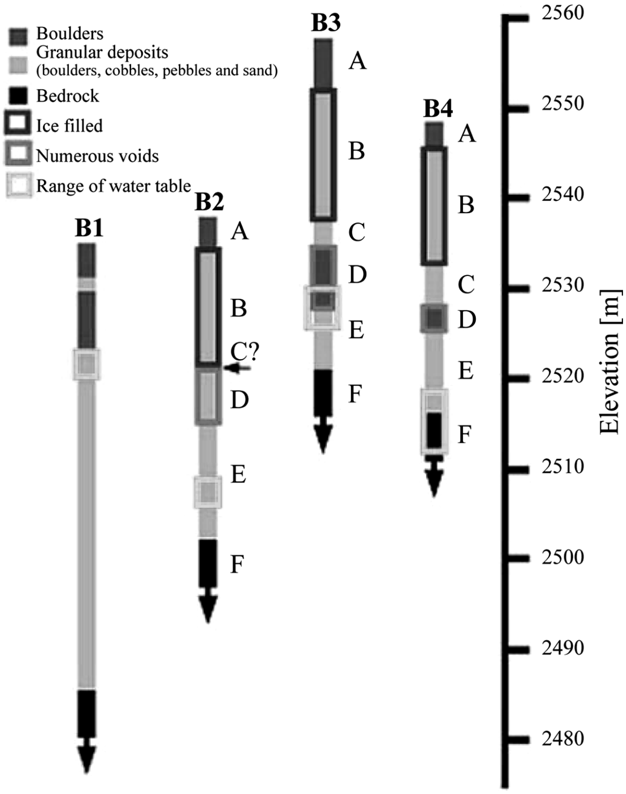

Figure 3. Geological logs obtained from drill cuttings and cores.

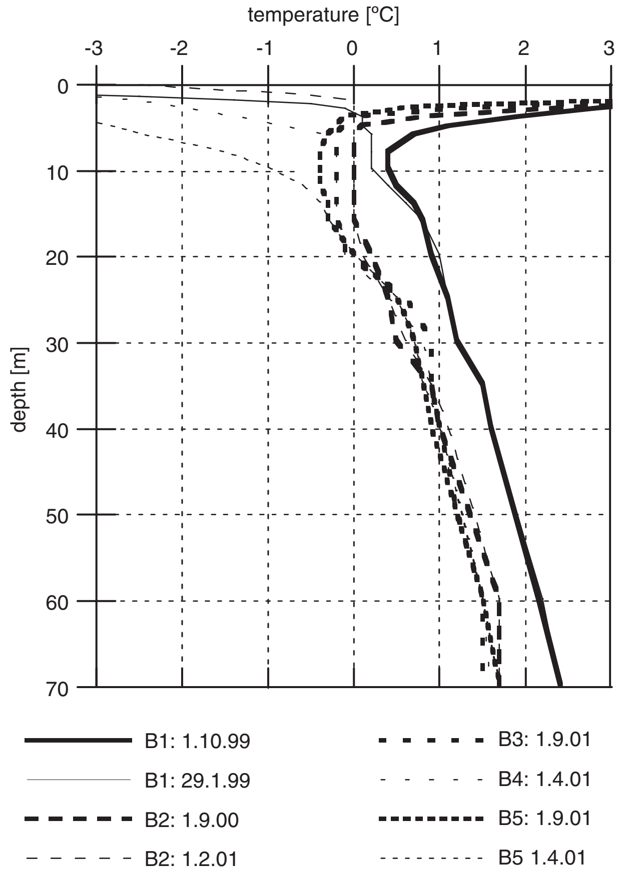

Figure 4. Temperature profiles of the four boreholes at different times of the year.

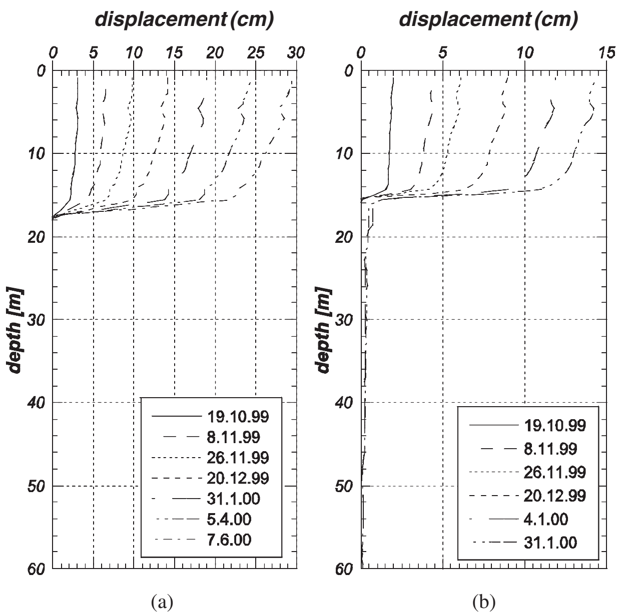

Figure 5. Deformation profiles of borehole B3 (a) and B4 (b) measured with a slope inclinometer (Arenson et al. 2002).

by the cross-hole experiments to be performed. In order to characterise the base of the rock glacier appropriately, all four boreholes were drilled at least 10 m into bedrock. Figure 3 shows simplified geological logs. Boulders were encountered in the upper few metres of all boreholes. These were underlain by a sequence of granular deposits. Ice was found in the upper 20 m of boreholes B2, B3 and B4. As expected from the refraction tomogram in Figure 2, no ice was observed in borehole B1, which is situated in the area of degraded permafrost.

Figure 4 shows temperature profiles collected at different times of the year. Seasonal variations seem to influence the data down to a depth of about 10 to 15 m. The temperatures drop slightly below 0° in the ice-rich zones of boreholes B2 to B4 and then increase continuously with depth. Temperatures measured in borehole B1 show significantly increased values, which provide further evidence for the absence of permafrost (Fig. 4).

Boreholes B3 and B4 were equipped with inclinometer tubes to monitor horizontal deformations. Measurements were taken approximately once a month using a slope inclinometer. The results are summarised in Figure 5. Borehole B4 was sheared off after about 3 months, whereas 6 measurements were made in borehole B3. Both boreholes show pronounced displacements at about 18 m depth below surface including seasonal variations. Considering that the annual displacements observed at the surface are of the order of 0.2 m per year at this location, it must be concluded that virtually all movements are confined to a very narrow zone at about 18 m depth. More details on the deformation measurements can be found in Arenson et al. (2002).

5 CROSS-HOLE TOMOGRAPHY

Additional insights into the structure of the Muragl rock glacier were extracted from 22 MHz georadar cross-hole measurements. Both travel times and amplitudes to establish velocity and attenuation tomograms were inverted. Figure 6 shows velocity and attenuation tomograms for the planes spanned by boreholes B3–B4 and B4–B1. Smoothing constraints imposed during the inversion process forced the merged planes to be continuous across borehole B4.

The tomograms can be subdivided into several zones (Fig. 6). Zone A comprises the upper 3–10 m, which were largely unresolved in the tomograms, but can be expected from surface observations to contain mainly large boulders with numerous air voids. The underlying zone B is 7–11 m thick and is distinguished by high-velocities. The thickness of this layer decreases

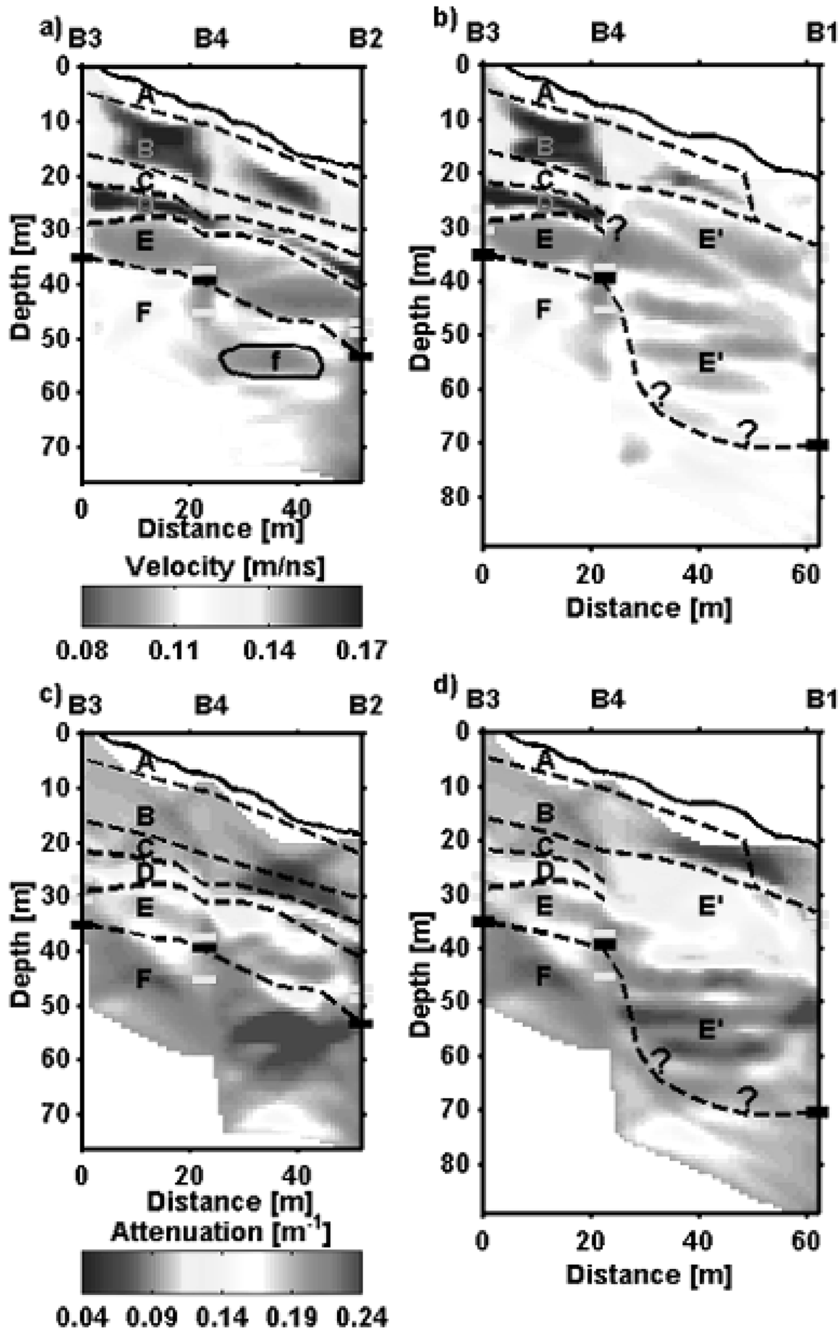

Figure 6. Tomographic inversion of Muragl cross-hole georadar data. a) and b) show the velocity and c) and d) the attenuation distributions, respectively. Small solid black lines indicate bedrock depth obtained from borehole logs and small light lines indicate the range of groundwater-table depths in the boreholes. See text for explanations of zones A to F.

towards borehole B1. Attenuations in zone B are uniformly low ($\sim$0.04–0.09 m^{-1}). Zone C is characterised by moderate velocities and low attenuations. Between 20 and 25 m depth, a conspicuous high-velocity zone is found between boreholes B3 and B4 (zone D). The deepest zone F indicates markedly higher velocities compared with zone E, whereas attenuations of these two deepest zones are similar.

6 INTERPRETATION

In-situ determinations of geological logs, temperatures and deformations as well as cross-hole tomography results provided critical information on the internal structure of the Muragl rock glacier. However, isolated interpretation of the individual data sets is difficult and most likely ambiguous. For example, georadar velocities are inversely proportional to the square root of dielectric permittivity. High velocities thus correspond to low dielectric numbers, which can be either due the presence of ice or air (e.g. Telford et al. 1990). Likewise, attenuation is largely controlled by electric conductivity, and there are various combinations of subsurface materials, which can be related to a particular conductivity value. By means of an integrated interpretation of all types of data, the Muragl rock glacier can be characterised in a unique fashion.

The high velocities and low attenuations found in zone B (Fig. 6) in the georadar tomograms indicate large amounts of ice. This interpretation is supported by the geological logs (Fig. 3) and the low temperatures measured (Fig. 4). The presence of ice is an important prerequisite for the flow of a rock glacier (e.g. Barsch 1996), so it is expected that displacements must be related to this ice layer. It is either possible that the entire layer is deforming or that the displacements are constrained to a shear horizon. The inclinometer data shown in Figure 5 demonstrate clearly that the latter applies to the Muragl rock glacier. Finally, the ice layer fades out towards borehole B1. This is consistent with (i) the decreased surface displacements in the area of borehole B1 (Kääb & Vollmer 2000), (ii) the interpretation of degraded permafrost in the refraction tomogram (Fig. 2), (iii) the geological logs (Fig. 3), and (iv) the temperatures observed (Fig. 4).

The decreased velocities and still relatively high attenuations in zone C (Fig. 6) were identified as a dry zone of sandy gravel, which is virtually ice-free. Temperatures and inclinometer data support such an interpretation. The thin zone D of high velocities in the georadar tomogram is more difficult to interpret. Temperatures, inclinometer data and geological logs preclude the high velocities from being interpreted as ice. A more consistent explanation would include the presence of large voids. Such an interpretation is further supported by the relatively high attenuations within zone D, which may be caused by strong scattering of the electromagnetic waves.

Relatively low velocities and high attenuations within zone E indicate the presence of water. This is consistent with repeated measurements of the groundwater table in boreholes B1 and B3, but seems to disagree with B2 and B4. Possibly, boreholes B2 and B4 created new hydraulic connections to deeper-seated permeable zones and thus may have altered the groundwater table locally.

Neither temperatures nor inclinometer data, nor georadar tomograms exhibit sharp discontinuities at the bedrock interface. Only the velocity tomograms show somewhat increased values (zone F in Fig. 6). This is not surprising since the rock glacier material and bedrock are of the same origin, although the absence of voids in massive bedrock will alter the physical properties somewhat. This is also observed in the refraction tomogram in Figure 6, which shows a rather gradual velocity increase at the bedrock interface, perhaps due to weathering of the bedrock surface.

7 CONCLUSIONS

Combined interpretation of geophysical, geotechnical and glaciological data allowed internal features of the Muragl rock glacier to be resolved reliably. The findings provide several important insights into the ongoing thawing processes related to Alpine permafrost and the associated natural hazards. It is likely that voids found at depths between 20 and 25 m (Fig. 6) were filled with ice, which was melted only recently. Accordingly, the low velocities (presence of voids) observed in the refraction tomogram (Fig. 2) indicate that permafrost thawing seems to progress quite rapidly.

The results not only document the presence of permafrost degradation, but also indicate that the thawing front moves from the bottom of the permafrost body to the top. This has important consequences with regard to the stability of the rock glacier. The most critical factor that may initiate failure includes pore pressure. Upward degradation allows the water to drain, which precludes developments of high pore pressures. Therefore, the risk of failure of the Muragl rock glacier is judged to be low.

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REFERENCES

Arenson, L., Hoelzle, M. & Springman, S. 2002. Borehole deformation measurements and internal structure of some rock glaciers in Switzerland. *Permafrost and Periglacial Processes* 13: 117–135.

Barsch, D. 1996. Rockglaciers: indicators for the present and former geoecology in high mountain environments. *Springer Series in Physical Environment* 16.

Cheng, G. & Dramis, F. 1992. Distribution of mountain permafrost and climate. *Permafrost and Periglacial Processes* 3: 83–91.

Haeberli, W., Cheng, G., Gorbunov, A.P. & Harris, S.A. 1993. Mountain permafrost and climate change. *Permafrost and Periglacial Processes* 4: 165–174.

Haeberli, W., Wegmann, M. & Vonder Mühll, D. 1997. Slope stability problems related to glacier shrinkage and permafrost degradation in the Alps. *Eclogea Geologicae Helveticae* 90: 407–414.

Haeberli, W., Kääb, A., Hoelzle, M., Bösch, H., Funk, M., Vonder Mühl, D. & Keller, F. 1999. Eisschwund und Naturkatastrophen im Hochgebirge. Vdf Hochschulverlag, ETH Zürich.

Kääb, A. & Vollmer, M. 2000. Surface geometry, thickness changes and flow fields on creeping mountain permafrost: automatic extraction by digital image analysis. *Permafrost and Periglacial Processes* 11: 315–326.

Keller, F., Frauenfelder, R., Gardaz, J.M., Hoelzle, M., Kneisel, C., Lugon, R., Phillips, M., Reynard, E. & Wenker, L. 1998. Permafrost map of Switzerland. *Proceedings of the 7th International Conference on Permafrost, Yellowknife*: 557–562.

Lanz, E., Maurer, H.R. & Green, A.G. 1998, Refraction tomography over a buried waste disposal site. *Geophysics* 63: 1414–1433.

Lehmann, F. & Green, A.G. 2000. Topographic migration of georadar data: implications for acquisition and processing. *Geophysics* 65: 836–848.

Telford, W.M., Geldhart, L.P. & Sheriff, R.E. 1990. Applied geophysics. 2nd edition, *Cambridge University Press*.