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Short Communication

Permafrost Creep within a Recently Deglaciated Glacier Forefield: Muragl, Swiss Alps

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ABSTRACT

Photogrammetric measurements of surface movement, 1981–94, on the Muragl glacier forefield (Swiss Alps) are compared to direct current resistivity surveys for the same area. At three locations isolated patches of frozen sediments were inferred, each about 10,000–20,000 m^2 in area. These were deforming at surface velocities of up to 50 cm per year. The locations where creep was observed coincide well with areas where two-dimensional (2D) resistivity surveys suggest ice is present within the ground. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: permafrost creep; photogrammetry; 2D resistivity surveys; Swiss Alps

INTRODUCTION

The massive glacier retreat since the Little Ice Age (LIA) has uncovered forefields, some of which are located within the mountain permafrost belt and contain thick deposits of glacier sediments—both favourable prerequisites for creep formation (Haeberli, 1983, 1992; Barsch, 1996; Humlum, 1998; Kneisel, 1998, 2003; Ribolini, 1999; Kneisel *et al*., 2000; Maisch *et al*., 2003; Reynard *et al*., 2003; Lugon *et al*., 2004). Questions arise concerning the extent to which potentially pre-existing permafrost was influenced by overriding during the LIA glacier advances, and the extent and rate to which permafrost and ground ice can build up, or recover, after ground exposure to the atmosphere due to glacier retreat.

This note presents digital photogrammetric measurements of surface displacement made upon the Muragl glacier forefield, Swiss Alps, Upper Engadine (9°56′30″ E, 46°30′15″ N; Figures 1 and 2). In this application, a coherent surface velocity field is viewed as a proxy for frozen ground material with a high ice content and which is sufficiently long-lasting for significant creep deformation to occur (e.g. Savigny and Morgenstern, 1986; Bennett and French, 1990, 1991; Wang and French, 1995; Dallimore *et al*., 1996; Arenson, 2002). The results of the surface displacement rates are compared to results from two-dimensional (2D) resistivity surveys and allow inferences to be made as to the present-day permafrost occurrence at the site.

The combination of measured surface displacement fields with geophysical surveys of sub-surface conditions has been shown to be a successful concept for investigating creeping mountain permafrost (e.g. Berthling *et al*., 1998; Haeberli *et al*., 1998; Hoelzle *et al*., 1998; Potter *et al*., 1998; Konrad *et al*., 1999; Isaksen *et al*., 2000; Ikeda *et al*., 2003; Bucki and Echelmeyer, 2004; Bucki *et al*., 2004; Lambiel and Delaloye, 2004; Ødegård *et al*., 2004).

STUDY SITE

The site is close to the well-investigated and currently-active Muragl rock glacier (Figures 1 and 2) (e.g. Kääb and Vollmer, 2000; Arenson *et al*., 2002; Vonder Mühll *et al*., 2003). The glacier forefield extends in elevation from 2650 m to 2880 m a.s.l.. In the upper part of the cirque from 2880 m to 3080 m a.s.l., a

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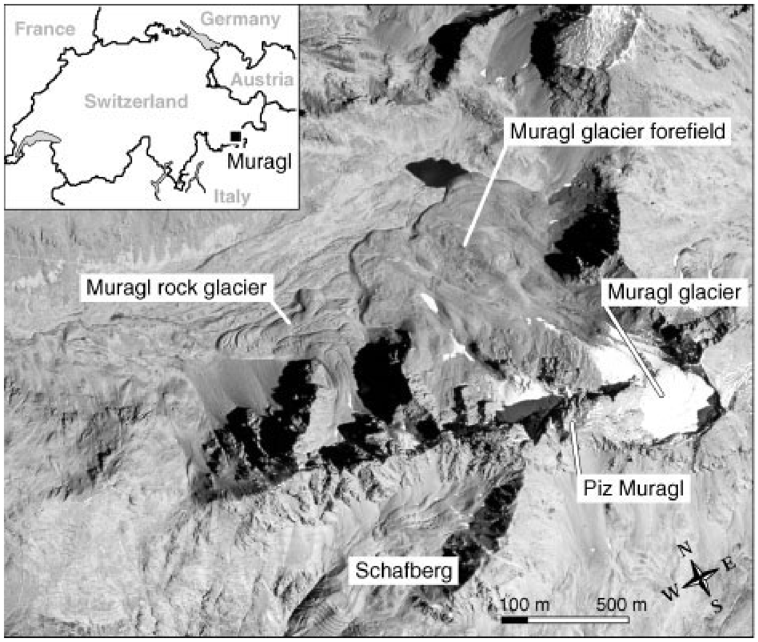

Figure 1 Airphoto of the Muragl valley with the glacier forefield under study. Inset: location of the study site within Switzerland. Airphoto taken by the swisstopo/flightservice on 7 September 1988.

Figure 2 Photograph of the Muragl glacier forefield. Piz Muragl and Muragl glacier are in the background to the top middle. Muragl rock glacier is to the lower right. Photo taken on 12 August 2003.

remnant of the former Muragl glacier exists (as of 2004; Figures 1 and 2).

The forefield is located at the lower regional boundary of discontinuous permafrost distribution, as inferred by modelling (e.g. Frauenfelder and Kääb, 2000) and measurements of the bottom temperature of the winter snow cover (BTS) (Haeberli, 1992; Kneisel, 1999). At boreholes in the nearby Muragl rock glacier at an elevation of about 2550 m a.s.l. (i.e. 100 m lower than the forefield investigated but with similar topographic setting) negative ground temperatures close to 0°C were measured (Vonder Mühll and

Schmid, 2003). For the Muragl glacier forefield no boreholes are available so far. The patchy permafrost distribution revealed in this study suggests that such boreholes would not be representative of large areas of the forefield.

The Muragl glacier forefield is believed to have been completely ice-covered at the LIA glacier maximum at around 1850 (Maisch *et al*., 2003). The occurrence of fluted moraines and a well-developed push moraine provide geomorphological evidence of a complex thermal regime of the former Muragl glacier with cold marginal parts frozen to the bed and warm-based ice in more central parts where fluted moraines could develop (Kneisel *et al*., 2000). The detection of permafrost within this glacier forefield has been inferred in recent years (1996–98) using one-dimensional (1D) geoelectrical soundings as well as BTS measurements and year-round near-surface temperature measurements. In summer 2002, 2D electrical resistivity tomography was applied (Kneisel, 2003, 2004).

METHODS

Surface displacements for the glacier forefield were measured on the basis of digitized aerial photography (approximately 1:6,000 scale) taken on 7 September 1981 and on 23 August 1994. Digital terrain models (DTMs) of 1981 and 1994 were computed from photogrammetric stereo models using standard procedures of digital photogrammetry (Kääb and Vollmer, 2000). Ortho-images of 1981 and 1994 (Figure 3) were derived using these DTMs, the original digitized imagery, and the image orientation calculated from precise ground control points available for the site. DTM-generation and ortho-image production were conducted within the software SOCET SET. Horizontal movements were measured with 10 m grid spacing using a digital cross-correlation technique between the multitemporal ortho-images (software CIAS; Kääb and Vollmer, 2000; Kääb, 2002).

The air photos are from the same flight strips which cover the nearby Muragl rock glacier. For the latter, an extensive accuracy assessment was performed by Kääb and Vollmer (2000) using the same flight parameters applied in this study. An accuracy for individual displacement measurements was estimated to be about 0.02–0.03 m a^{-1} root mean square. Due to the similar imaging and ground conditions, this finding can be assumed to apply to the Muragl glacier forefield.

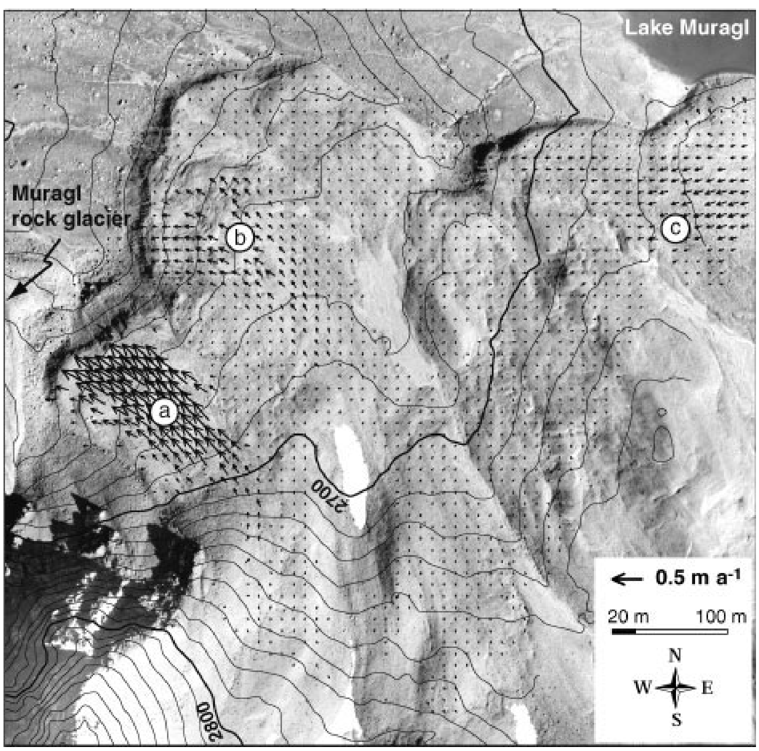

Figure 3 Horizontal surface displacements 1981–94 on a section of the Muragl glacier forefield as derived from digital photogrammetry. For letters a–c refer to the text.

Because geoelectrical methods are most suitable for investigating the subsurface with distinct contrasts in conductivity and resistivity, respectively, direct current resistivity soundings constitute one of the traditional geophysical methods which has been applied in permafrost research to confirm and characterize ground ice (e.g. Olhoeft, 1978; Seguin, 1978; King and Garg, 1980; for a review see Scott *et al.*, 1990). For heterogeneous mountain permafrost environments with complex spatial distribution of frozen ground, 2D geophysical methods, in particular 2D electrical resistivity imaging, have become increasingly important in recent years (e.g. Hauck, 2002; Hauck and Vonder Mühll, 2003; Kneisel and Hauck, 2003).

For this study, 2D electrical surveys were performed using the Wenner configuration and an IRIS SYSCAL Junior Switch resistivity meter. As many as 30 2D resistivity surveys were performed focusing on the outermost parts of the forefield, the orographic left side of the forefield close to the Muragl rock glacier and the push moraine on the orographic right side (Figure 4). Based on these results, the small-scale distribution and characteristics of ground ice were inferred.

RESULTS

By matching aerial photographs from 7 September 1981 with those from 23 August 1994, three zones of significant surface movement were distinguished. Zone (a) (Figure 3) showed surface speeds of up to $0.55\,m\,a^{-1}$. Speeds in the order of $0.50\,m\,a^{-1}$ are found above the creep front towards Muragl rock glacier. The front is advancing horizontally by approximately $0.17\,m\,a^{-1}$, even more in parts, as found by image and DTM comparison. No significant supply of frozen debris by creep from the upper parts of the glacier forefield can be detected.

The same applies for zone (b). There, horizontal surface movement amounts to $0.16\,m\,a^{-1}$. A potential advance of the corresponding front is within the measurement accuracy. Near Lake Muragl in zone (c), the location of a Holocene push moraine, movement in the order of $0.15\,m\,a^{-1}$ can be observed. In all zones described, the creep direction follows the direction of steepest slope. Adjacent to zones (a), (b) and (c), no significant movement during 1981 to 1994 was detected on the Muragl glacier forefield.

The permafrost distribution in parts of the Muragl glacier forefield, as delineated through the 2D elec-

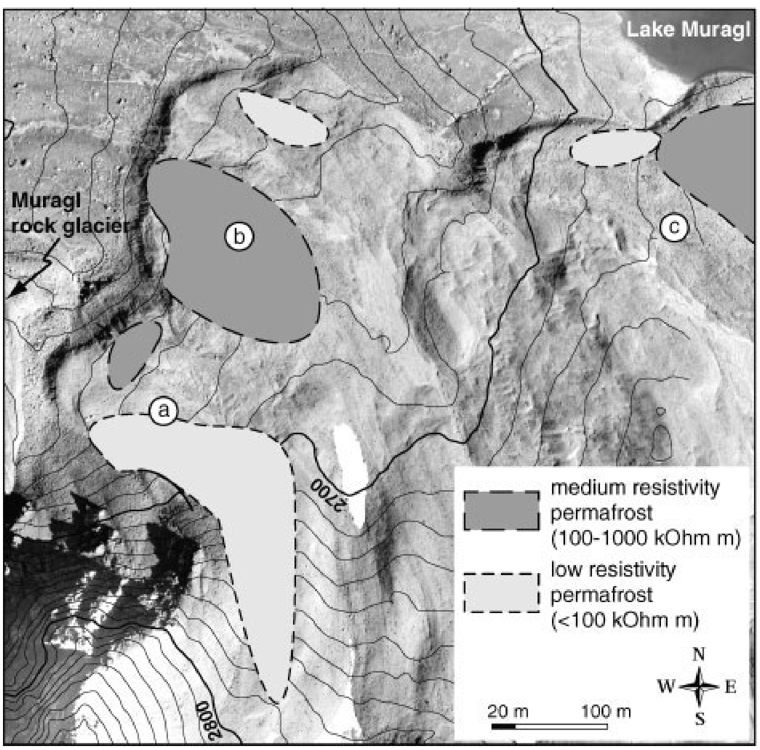

Figure 4 Ground ice/permafrost occurrence in the marginal parts of the Muragl glacier forefield as delineated from 2D electrical resistivity surveys. For letters a–c refer to the text.

trical resistivity surveys, has been classified in three classes: low resistivity permafrost ($<100\,\mathrm{k}\Omega\,\mathrm{m}$), medium resistivity permafrost ($>100\,\mathrm{k}\Omega\,\mathrm{m}$) and high resistivity permafrost ($>1\,\mathrm{M}\Omega\,\mathrm{m}$). The first two classes are depicted as grey areas in Figure 4. The third class is not present in the terrain section depicted. These shaded areas are represented through several 2D resistivity surveys, some of which were arranged as crossing surveys in order to obtain more reliable results. The terrain sections between the shaded areas are either not represented to a sufficient level in the geophysical surveys or are considered as permafrost-free according to the results of the 2D geoelectric measurements.

DISCUSSION

The horizontal surface displacement rates correspond well with the inferences made from the geoelectrical surveys performed in the area. While the earlier 1D geoelectrical soundings for zone (b) gave indications of thin and/or melting permafrost with an active layer of 2–5 m thickness (Kneisel, 1999), the more recent 2D surveys indicate medium resistivity permafrost of more considerable horizontal extent. Furthermore, BTS measurements in 1985 (Haeberli, 1992) and 1996 (Kneisel, 1999) suggest that zones (a), (b) and (c) are the only areas of the forefield sector investigated, where frozen ground occurrence is likely.

The comparatively large ratio between advance rate and surface velocity at the front of zone (a) points to little volume loss by ice melt-out and, thus, to a relatively small overall ice content of the body (see Kääb, 2005; Kääb and Reichmuth, 2005). Strong oversteepening of the front, as observed in the field, indicates that the movement is restricted, for the most part, to an approximately 10–15 m deep surface layer (see Kääb and Reichmuth, 2005). This interpretation compares well with the findings of the 2D resistivity surveys, which indicate low-resistivity permafrost in most parts of zone (a) (Figure 4). Low resistivities can be interpreted in terms of warm permafrost, i.e. close to 0°C. The associated high unfrozen water content could result in such low resistivities even in the presence of permafrost lenses with high ice contents. Warm permafrost temperatures might explain the movement rates which are comparably high for the low surface slope angles which for most zones do not exceed 15° (Kääb *et al*., 2002).

Zone (c) is interpreted as part of a push moraine complex (Haeberli, 1979, 1983). The indication of permafrost in that zone from BTS is also supported by the 2D resistivity surveys, which show a large area of higher resistivity ground within the main body of the moraine complex.

CONCLUSION

The agreement between the photogrammetric measurements and geophysical surveys confirms that the combination of photogrammetry and geophysical sounding can lead to a better understanding of the distribution of permafrost in periglacial mountain environments and of the interplay between ice content and slope deformation. Here, such a method combination was applied for the first time to investigate the dynamics and distribution of ice-rich permafrost within a recently deglaciated glacier forefield. The study opens a new perspective towards better understanding how permafrost and ground ice aggrades, after exposure of the ground to the atmosphere due to glacier retreat.

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