

New insights on permafrost genesis and conservation in talus slopes based on observations at Flüelapass, Eastern Switzerland

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ABSTRACT

The talus slope at Flüelapass was the first mountain permafrost study site in Switzerland in the 1970s and the presence of ice-rich permafrost at the foot of the slope has been investigated in the context of several studies focusing on the role of snow cover distribution. We review previously developed hypotheses and present new ones using various data sources, such as temperature measurements in boreholes, a subaquatic DEM generated from unmanned aerial system (UAS) photogrammetry, terrestrial laser scan measurements of snow depth, geophysical ground investigations and automatic time-lapse photography. From this combination of data sources together with observations in the field, an interesting sequence of geomorphologic processes is established at Flüelapass. As a result we show how mass wasting processes can initiate the genesis and long-term conservation of ice-rich permafrost at the base of a talus slope.

1. Introduction

The lower fringe of mountain permafrost is often characterized by permafrost talus slopes or by rock glaciers with the root zone located in ice-rich permafrost talus slopes (Delaloye and Lambiel, 2005; Gruber and Haeberli, 2009; Lambiel and Pieracci, 2008). Permafrost in these landforms is, therefore, preferentially used to calibrate models of the local distribution of permafrost (Boeckli et al., 2012; Etzelmüller et al., 2001; Gruber and Hoelzle, 2001; Sattler et al., 2016) or to analyse the consequences of climate change on mountain permafrost (Monnier and Kinnard, 2016; Springman et al., 2012). The processes controlling the presence of permafrost in talus slopes, especially at elevations in the lower belt of the local permafrost environment are, thus, of particular interest. The talus slope at Flüelapass was the first site at which systematic research into mountain permafrost was carried out in the Swiss Alps and was first investigated by Haeberli (1975). Haeberli carried out extensive refraction surveys here and discovered the presence of ice-rich permafrost along the foot of the talus slope. This was later confirmed by vertical electrical soundings carried out by King et al. (1987). Furthermore, Haeberli (1975) showed a spatial correlation between thaw depth and perennial avalanche snow deposits: At the time of observation, the thaw depth was thinner at locations with

perennial avalanche snow. This observed spatial relation led to the hypothesis that permafrost at the foot of talus slopes is present because of the insulating effect of superimposed perennial snow fields against radiation and atmospheric warming (Haeberli, 1975). We henceforth refer to this as the “insulation theory”. This was adopted by other studies carried out at Flüelapass. Lerjen et al. (2003) supplemented the hypothesis by adding the effect of soil properties (organic material vs. rock and gravel) on the thermal regime of the ground. Luetschg et al. (2004) analysed ground temperature simulations, ground surface and borehole temperature measurements and found that a delay in snow melt influences the active layer temperatures. This was interpreted as a confirmation of the insulation theory. Lerjen et al. (2003) and Luetschg et al. (2004) cited the effect of snow erosion by wind as a ground cooling factor in the Flüela talus slope but did not specifically show a spatial correlation between the distribution of permafrost and the spatial pattern of wind erosion.

Ice-rich permafrost often occurs at the foot of talus slopes (e.g. Lambiel and Pieracci, 2008; Scapozza et al., 2011). The insulation theory is one of two general explanations for this spatial niche of permafrost. The second explanation refers to air ventilation in talus slopes. Several studies have shown that ventilation can lead to substantial ground cooling in talus slopes and might contribute to

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permafrost conservation or development (Delaloye and Lambiel, 2005; Gądek, 2012; Morard et al., 2010; Niu et al., 2016; Schneider et al., 2012; Wicky and Hauck, 2016; Zacharda et al., 2007). On the basis of borehole temperature measurements Phillips et al. (2009) also demonstrated the occurrence of a ventilation effect underneath the perennially frozen part in the Flüela talus slope, but showed that it mostly causes positive temperatures in the voids in winter, thus contradicting a development of permafrost by ventilation at this site.

Snow coverage has changed at the Flüela site in recent decades: whereas perennial avalanche deposits at the base of the slope were the normal case in the 1970s according to Haeberli (1975), no perennial snow has occurred for the last 14 years at least, according to time-lapse images taken by an automatic camera. Data availability has significantly improved since the 1970s; e.g. borehole temperatures, geophysical soundings or remote sensing data and the length of observation periods have increased, allowing a critical verification of the hypotheses made in the past. It is still unclear whether a substantial effect of avalanche snow or wind driven snow redistribution occurs on the presence of ice-rich permafrost. Based on the improved dataset presented here, we will discuss whether the insulation theory is indeed the most relevant explanation for permafrost in the Flüelapass talus slope and present an alternative hypothesis which may be relevant for other sites with ice-bearing talus slopes. A key question here: what is the origin of the excess ice in the Flüela talus slope?

2. Site description and geomorphological history

The talus slope at Flüelapass is located on the NE flank and at the base of the summital rock wall of “Chlein Schwarzhorn”, a 2986 m high peak in the eastern Swiss Alps (46°44′37.804″N 9°56′13.758″E). The foot of the talus slope at 2375 m a.s.l. forms the eastern shore of lake Schottensee, which has an area of 83,000m² (Fig. 1). Two 20 m vertical boreholes were drilled in the slope in 2001; the upper one (B1) is 125 m above the lake at 2501 m a.s.l., and the lower one (B2) is 20 m above the lake at 2394 m a.s.l. Around B1 the slope is covered with soil and grass and positive temperatures are registered throughout the borehole (no permafrost), whereas the foot of the slope around B2 is devoid of vegetation, covered in talus and has negative temperatures between 3 and 10 m depth (permafrost). The stratigraphies of both boreholes are presented in Phillips et al. (2009) and apart from the surface and the ice content they are very similar, with rocks and gravel and a very blocky

layer that is a few metres thick around 10 m (B1) and 15 m (B2) depth, respectively. The grain sizes of the talus at the surface of B2 range between 10 and 40 cm. The lower quarter of the slope is a snow avalanche deposit zone and avalanche snow often persists here for long periods of the summer.

A series of interesting landforms at Flüelapass reveal the history of the site and help to elucidate the genesis of permafrost ice at the bottom of the talus slope. These landforms are highlighted on the orthophoto in Fig. 2. There is a conspicuous shallow channel around B2, delimited by two sharply defined parallel escarpments. These escarpments are oriented parallel to the slope and reach from the lower third of the talus slope to the lake shore. We have observed similar channels with sharply defined escarpments in talus slopes at other sites. Fig. 3 shows a similar feature at a talus slope at Piz Corvatsch (Eastern Swiss Alps), close to the Murtèl rock glacier (Haerberli et al., 1998). A distinct lobe is evident directly below the shallow channel at Piz Corvatsch. Unpublished terrestrial laser scanning (TLS) and electric resistivity tomography (ERT) measurements we carried out indicate that the Corvatsch lobe is creeping downslope and contains ice. It is, therefore, very likely that the loose rock material forming the lobe originates from the shallow channel above and was displaced by permafrost creep.

At Flüelapass a similar lobate form is also evident below the shallow channel, at the lake bottom. The orthophoto in Fig. 4, acquired by UAS borne photogrammetry shows this lobe, which encloses a deep depression in the lake. Based on the morphology (Haerberli, 1985) we consider both lobate features at Piz Corvatsch and Flüelapass as being small rock glaciers.

Rock glaciers cannot form under water, as the water temperature would lead to ice melt (Haerberli et al., 2001). The only explanation for the underwater rock glacier at Flüelapass is, therefore, that the lake is younger than the rock glacier. This in turn explains the deep depression in the underwater lobe. After the lake flooded the rock glacier, the ground ice melted and a thermokarst depression developed. The rock glacier front and side walls which contained less or no ice now form the underwater lobe with 45° steep side walls (Fig. 5). Similar features are visible all along the SW lakeshore, indicating widespread permafrost creep at the base of the talus slope in the past (Figs. 2 and 4). The sizes and positions of the lobes correspond to the main deposition areas of snow avalanches.

At the NW end of the lake there is a field of large rocks and boulders with a distinctly rougher texture than the neighbouring talus slopes

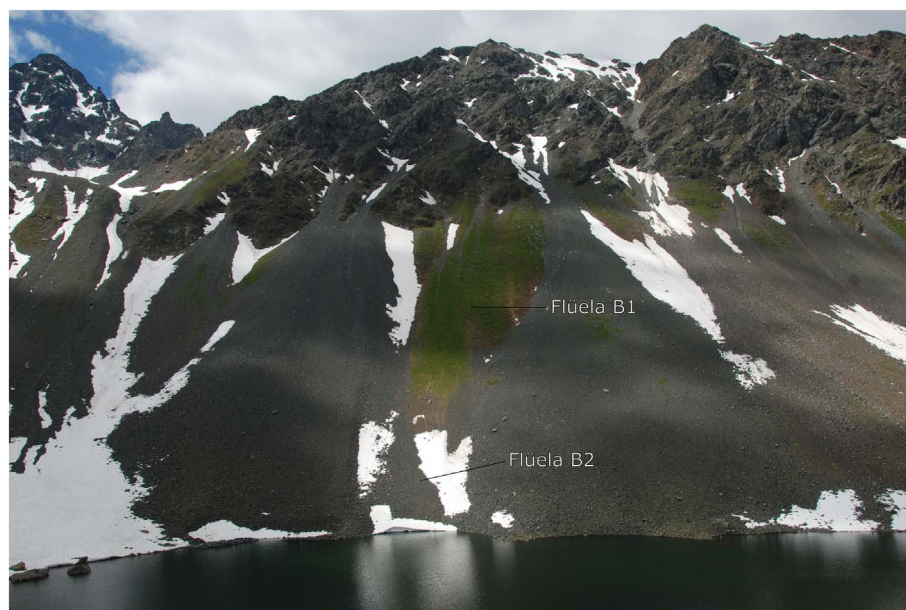


Fig. 1. Photograph showing the Flüela talus slope on 13.07.2009 with the positions of the two boreholes. The pattern of snow melt out is quite complex (Photograph: M. Phillips).

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