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Mountain permafrost — research frontiers and a special long-term challenge

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ABSTRACT

Advanced methodologies such as core drilling, borehole logging/monitoring, geophysical tomography, high-precision photogrammetry, laser altimetry, GPS/SAR surveying, miniature temperature data logging, geotechnical laboratory analyses, numerical modelling, or GIS-based simulation of spatial distribution patterns in complex topography at regional to global scales have created a rapidly increasing knowledge basis concerning permafrost in cold mountain ranges. Based on a keynote presentation about mountain permafrost at CFG8 in Obergurgl 2012, a brief summary is provided concerning primary research frontiers and the long-term challenge related to the increasing probability of far-reaching flood waves in high-mountain regions originating at newly forming lakes as a consequence of large rock falls and landslides from destabilising steep rock walls with conditions of warming and degrading permafrost often in combination with de-buttressing by vanishing glaciers. Research is especially intense in the densely populated European Alps.

1. Introduction

Research on permafrost in cold mountain regions is a still relatively young but rapidly evolving field of science. Increasing pressure on high altitudes from human activities and concern about adverse impacts from climate change are strongly increasing the awareness about the importance of perennially frozen ground on steep slopes (UNEP, 2007). A recent overview report as an invited contribution to the special issue of No. 200 of the Journal of Glaciology briefly describes the historical evolution, discusses primary focuses and provides numerous references concerning this part of cryosphere science (Haeberli et al., 2010). The following reflection is based on this state-of-the-art report and relates to the corresponding keynote on mountain permafrost presented at the opening of CFG8 in Obergurgl, Austria 2012. It briefly summarises primary research frontiers and hints to a special long-term challenge — the destabilisation of deeply frozen rock walls and the systematically increasing probability of far-reaching flood hazards from impact waves caused by high-magnitude rock falls and landslides into new lakes forming in de-glaciating high-mountain ranges.

2. Present-day research frontiers and examples of latest developments

Beyond a few precursory observations, systematic research on permafrost in cold mountains essentially started around 1970. Nearly half a century later, current research activities primarily concern the following topics (Haeberli et al., 2010):

- occurrence and distribution patterns
- near-surface effects and microclimate
- subsurface thermal conditions
- geotechnical properties
- geophysical prospection
- long-term creep and rock glaciers
- slope stability
- infrastructure
- climate-related monitoring.

Progress continues to be rapid (cf. Krainer et al., 2012 and the collection of papers about recent permafrost research in the Austrian Alps as contained in the same volume). Prominent examples of latest developments concern, for instance, the spatial modelling of permafrost distribution at regional to global scale and multidisciplinary research about the stability of warming permafrost on ice-rich frozen slopes and in steep rock walls.

Statistically calibrated high-resolution simulations of the permafrost distribution were prepared for the entire European Alps (Boeckli et al., 2012, Fig. 1) and for the mountains in northwest Canada (Lewkowicz et al., 2012). A model calculation was also completed of worldwide permafrost distribution including both hemispheres and mountains with rugged topography, using global elevation data and air-temperature information from reanalysis data (Gruber, 2012). Simulation of possible future developments based on climate scenarios use spatial models in a time-dependent mode (Bonnaventure and Lewkowicz, 2012 for

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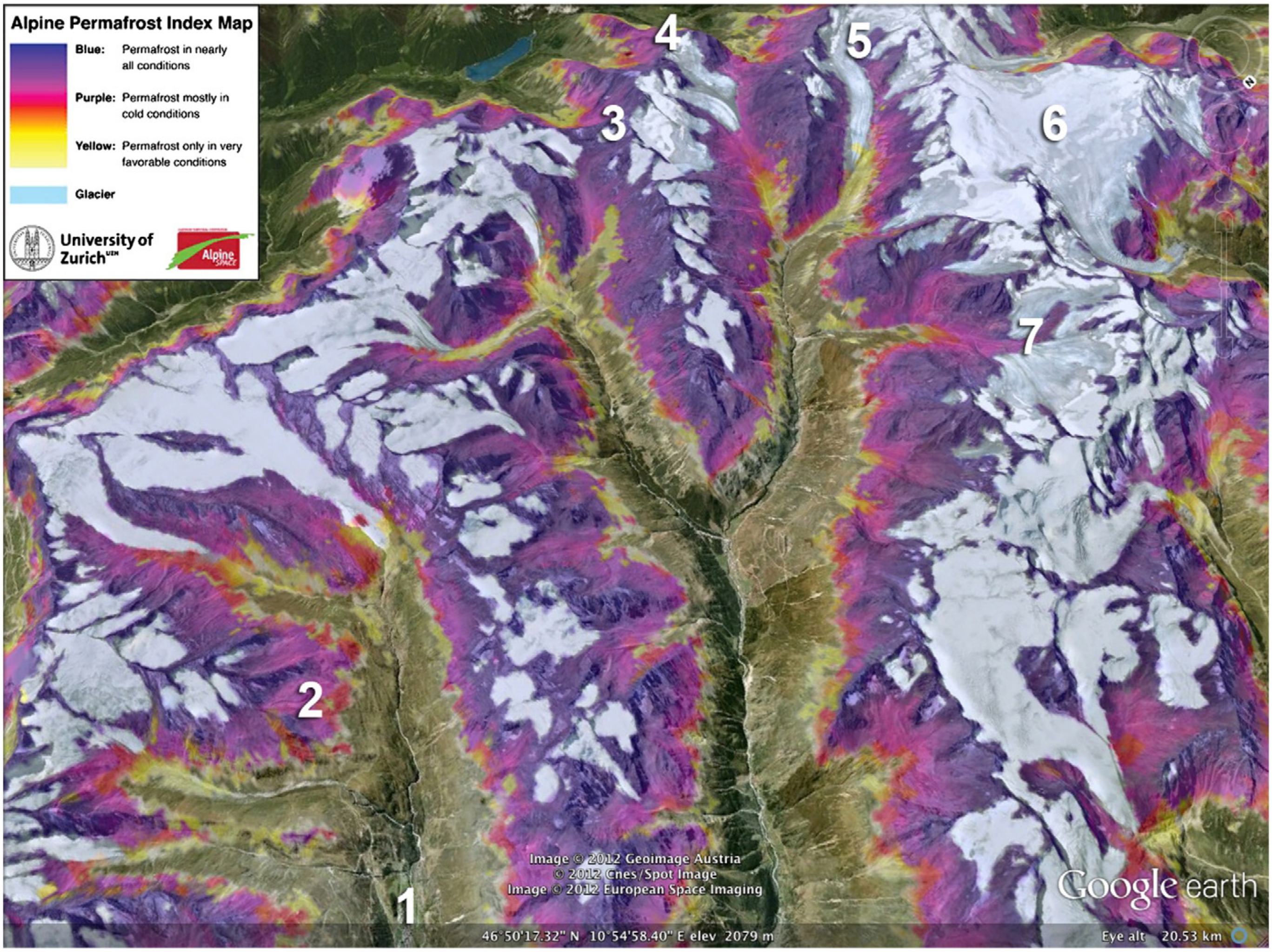

Fig. 1. Permafrost distribution modelled for the upper Oetztal, Austrian Alps, from the new permafrost distribution model for the entire European Alps; view is to the south (cf. Boeckli et al., 2012 and http://www.geo.uzh.ch/microsite/cryodata/PF_map_explanation.html). Permafrost in the Alps is widespread above timberline. 1 = Obergurgl, 2 = Hochebenkar with long surveyed rock glacier and detailed in-situ permafrost mapping, 3 = site where the Oetztal ice man was found, 4 = Grawand peak with horizontal borehole through permafrost ridge, 5 = Hintereisferner, 6 = Gepatschferner, 7 = Vernagtferner.

mountains in Canada) or heat diffusion models calibrated with borehole temperatures (Hipp et al., 2012 for southern Norway). The high variability of ground surface temperatures at even small spatial scales (Gubler et al., 2011) still constitutes a fundamental challenge for calibrating/validating spatial models of permafrost occurrence but can now be investigated by large numbers of iButtons for temperature recording.

Slope stability problems in mountain permafrost involve two distinct situations: the accelerating creep of perennially frozen talus/debris with high ice contents on moderately steep slopes of up to about 30° and the decreasing stability of steep (>40°) deeply frozen rock walls. In both cases, "warm" permafrost with temperatures rather close to melting conditions appears to be critical. Rock glaciers as striking expressions of cumulative deformation of perennially frozen, ice-rich surface sediments keep their fascination as the most striking and widespread permafrost phenomenon and landform in cold/dry mountains (Fig. 2). Comprehensive data sets from a multitude of advanced high-precision measurements on slow to fast rock glaciers help to establish complex numerical models for a better understanding of the strong flow acceleration (Springman et al., 2012; Wirz et al., in press) observed with warm creeping permafrost — now also beyond the Alps (cf. Daanen et al., 2012 in a case related to the Trans Alaska Pipeline). The relation between flow velocity and temperature may involve two segments with strong effects from meltwater penetration into frozen materials at near melting temperatures (Fig. 3; cf. Ikeda et al., 2008; Kääb et al., 2007). Evidence exists that slope failures and erosion rates in icy/frozen rock walls massively increased during recent decades (Fischer et al., 2012a). Investigation of the related processes is difficult and requires special efforts to develop and use highly sophisticated monitoring techniques such as sensor networks (Amitrano et al., 2012; Girard et al., 2012; Hasler et al., 2011, 2012) or repeat geophysical tomography, especially electrical resistivity and seismic refraction (cf. corresponding laboratory studies by Draebing and Krautblatter (2012)).

Other fields remain under-researched or still need pioneering investigations. An example is glacier/permafrost interactions in high-mountain regions (Dobinski et al., 2011; Etzelmüller and Hagen, 2005; Haeberli, 2005; cf. the extensive review by Waller et al. (2012) for cold lowlands, especially under ice-age conditions). Another still wide open question concerns the origin, age and characteristics of ice in perennially frozen mountain slopes. As documented by radiocarbon datings of permafrost cores, the ice in creeping frozen talus is mainly of Holocene age (Haeberli et al., 1999). Latest information from radiocarbon dating of drill cores from the Lazaun rock glacier in the Schnals valley, South Tyrol, Italian Alps, confirm that now degrading and melting mountain permafrost had survived the climatic variations of the past about 9000 years — a most important paleoclimatic evidence (written communication by K. Krainer, Innsbruck University). The ice filling cracks in cold bedrock of high summits may even have survived