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PERMAFROST RESEARCH IN AUSTRIA: HISTORY AND RECENT ADVANCES

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ABSTRACT

In the Austrian Alps the study of alpine permafrost started during the 1920ies and until about 1980 was mainly concentrated on rock glaciers. Since 1980 the number of publications related to permafrost increased and since the late 1990ies investigation of permafrost has been intensified. This introductory article provides an overview on the history of permafrost research in the Austrian Alps, on current activities including new results and a short outlook for the next years.

Current research includes the distribution of rock glaciers and modelling of the distribution of permafrost in the Austrian Alps, the study of internal structures and the dynamics of active rock glaciers, permafrost monitoring, the response of permafrost to climate change and natural hazards related to permafrost.

Core drilling on active rock glaciers including a detailed analysis of the frozen core and instrumentation of the bore holes for long-term monitoring of permafrost is one of the main issues for the future.

In den österreichischen Alpen begann die Erforschung des alpinen Permafrostes in den 1920er Jahren und konzentrierte sich bis 1980 hauptsächlich auf Blockgletscher. Seit 1980 stieg die Anzahl der Publikationen über alpinen Permafrost und in den späten 1990er Jahren wurde die Forschungsaktivität intensiviert. Dieser einleitende Artikel bietet einen Überblick über die Geschichte der Permafrostforschung in den österreichischen Alpen, über gegenwärtige Forschungsaktivitäten und neue Ergebnisse sowie einen kurzen Ausblick auf geplante Aktivitäten für die nächsten Jahre.

Gegenwärtige Forschungsarbeiten umfassen die Untersuchung der Verteilung der Blockgletscher und die Modellierung der Verbreitung des alpinen Permafrostes in den österreichischen Alpen, Untersuchung der internen Strukturen und Dynamik aktiver Blockgletscher, Permafrost-Monitoring, das Verhalten des Permafrostes in Hinblick auf Kimaänderungen sowie Naturgefahren in Zusammenhang mit alpinem Permafrost. Kernbohrungen auf aktiven Blockgletschern einschließlich einer detaillierten Analyse der gefrorenen Kerne und Instrumentierung der Bohrlöcher für ein langfristiges Permafrost-Monitoring zählen zu den wichtigsten Zielen für die nahe Zukunft.

1. INTRODUCTION

Understanding the distribution and dynamics of mountain permafrost and their relationships to climate are increasingly important considering the effects of the ongoing climate change on mountain environments and its cryosphere (Barry and Gan, 2011). Research of mountain permafrost is still a rather young and dynamic field of research with still many open questions to be solved (Haeberli et al., 2006, 2011). An improvement of the understanding of permafrost environments in mountain regions has also a significant impact on the people living in these mountain regions considering for example mountain slope hazards due to warming and degradation of the stabilizing permafrost (Huggel et al., 2010).

2. HISTORICAL OVERVIEW ON PERMAFROST RESEARCH IN AUSTRIA

Permafrost research in the Austrian Alps started as early as the 1920ies. Investigations during that time and during the following decades focused particularly on rock glaciers and concentrated on their areal distribution, flow velocity, and paleoclimatic interpretation. The study of rock glaciers started in the Ötztal Alps in 1928 when Finsterwalder first described the active rock glacier at Innere Ölgrube, Kaunertal (Finsterwalder, 1928). In 1938, 1939, and 1953 Pillewizer measured the flow velocity of this rock glacier (Pillewizer, 1938, 1957). In 1938 he further began to measure flow velocities on the Hochebenkar rock glacier near Obergurgl which is one of the largest and most active rock glaciers in the Austrian Alps. This rock glacier shows the worldwide longest record of flow velocity and has been measured by terrestrial photogrammetry, since 1951 by terrestrial geodetic methods (theodolite) and since 2008 by differential GPS (Vietoris, 1958, 1972; Haeberli and Patzelt, 1982; Kaufmann, 1996; Schneider and Schneider, 2001; Kaufmann and Ladstädter, 2002, 2003; Ladstädter and Kaufmann, 2005).

Gerhold studied the glacial geology and mapped rock glaciers in the western Ötztal Alps. Based on morphologic observations he distinguished three main types of rock glaciers (Gerhold, 1965, 1967, 1969, 1970). The spatio-temporal distribution of relict rock glaciers in the Niedere Tauern Range located further to the east was studied by Nagl (1976). Van Husen (1976) studied block streams in southern Austria and discussed their relevance for periglacial landscape modification. Kerschner (1978) described relict (fossil) rock glaciers from two stages of the Lateglacial period (Daun and Egesen stages). He used the distribution of relict rock glaciers to provide a paleoclimatic interpretation for the Tyrolean Alps (Kerschner, 1978, 1983a-c, 1985).

However, until the 1980s relatively little had been published and only since then the number of publications related to permafrost in national and international journals increased substantially. Haeberli and Patzelt (1982) measured the basal temperatures of the winter snow cover on the Hochebenkar rock glacier in 1975, 1976 and 1977, as well as the water temperature of rock glacier springs. These authors further applied seismic refraction and detected ice below the debris layer, determined the depth of the active layer, and roughly estimated the ice content of the rock glacier.

Rolshoven (1982) presented information on the distribution of discontinuous permafrost in the Lasörling Mountain Group and discussed environmental factors which influenced the occurrence of permafrost in this area. Höllermann (1983) described the distribution of rock glaciers in the Austrian Alps in relation to climatic and biogeographic parameters. Later, the spatial distribution and evolution of permafrost was studied in the eastern Austrian Alps and led to the establishment of the first rock glacier inventory (Lieb, 1986, 1987, 1991, 1994, 1996, 1998; Lieb and Schopper, 1991; Lieb and Slupetzky, 1993). In the westernmost part of Austria, De Jong and Kwadijk (1988) discussed the origin and age of six relict rock glaciers located in central Vorarlberg. Fink (1989) investigated the temporal variation of temperatures at a low-elevation talus slope near Puchenstuben (Lower Austria) where ice was encountered during the road construction.

Since the late 1990s the study of mountain permafrost in Austria has been intensified by working groups at the Universities of Graz and Innsbruck. Buchenauer (1990) studied glaciers and rock glaciers of the Schober Mountain Group and presented a paleoclimatic interpretation for the late- and postglacial period. Schmöller and Fruhwirth (1996) investigated the internal structure of Dösen rock glacier (Ankogel Mountains) by using seismic refraction with blasts as energy source and slingram electromagnetic mapping. Wakonigg (1996, 2001) studied ventilated and undercooled talus slopes at low elevations and explained the formation of permafrost by the 'chimney effect' which was first mentioned by Balch (1900). Similar studies followed (Punz et al., 2005). In 1995 a geomorphometric monitoring using geodetic and photogrammetric methods was started at the Dösen rock glacier and enabled to study its creep behaviour (Kaufmann, 1996a, b). This monitoring was expanded in 1997 to the Weissenkar rock glacier and in 1998 to the Hinteres Langtalkar rock glacier, all located in the Schober Mountain (Kaufmann and Ladstädter, 2002, 2003, 2004; Kaufmann et al., 2006, 2007; Avian et al., 2005; Ladstädter and Kaufmann, 2005). In the Niedere Tauern Range further to the east springs and related relict rock glaciers were investigated extensively by Untersweg and Schwendt (1995, 1996) and Untersweg and Proske (1996).

Since the end of the 20th century permafrost activities in Austria have increased substantially at the Universities of Innsbruck, Vienna and Salzburg as well as at the Central Institute for Meteorology and Geodynamics (ZAMG). These institutions started and/or intensified their permafrost research in western and central Austria (Ötztal Alps, Stubai Alps and Hohe Tauern Range). Several rock glaciers (Ölgrube, Kaiserberg, Reichenkar) were studied in detail in western Austria by Krainer and co-workers and included geomorphologic mapping, sediment analyses, hydrologic and geodetic monitoring, GPS measurements and ground penetrating radar (GPR) surveys (Krainer and Mostler, 2000, 2001, 2002, 2004, 2006; Krainer et al., 2002, 2007; Berger et al., 2004; Krainer and Ribis, 2009). The hazard potential of degrading permafrost was first assessed by Hirschmugl (2003) for debris flows in the Hohe Tauern Range and was elaborated in subsequent studies (Lieb et al. 2007; Kellerer-Pirklbauer et al., 2012). Recent advances in terrestrial and airborne laser scanning (TLS and ALS) as well as synthetic aperture radar (SAR) interferometry were applied to monitor rock glaciers (Bauer et al., 2003; Avian et al., 2008; Kenyi and Kaufmann, 2003) and periglacial permafrost areas (Avian et al., 2009; Kellerer-Pirklbauer et al., 2012).

The spatial distribution of permafrost in the Styrian part of the Niedere Tauern Range was modeled at a regional scale and monitored at a local scale by Kellerer-Pirklbauer (2005). In the same regional study area, Kellerer-Pirklbauer (2007) studied the relevance of geological conditions on the areal distribution of rock glaciers. The effect of a warming climate on alpine rockwalls and its effects on mountain permafrost in central Austria were studied by Kellerer-Pirklbauer et al. (2008). The relationship between glacier retreat and formation of permafrost-related landforms in the Schober Mountains was studied by Kellerer-Pirklbauer and Kaufmann (2007) and Kellerer-Pirklbauer (2008b).

Absolute and relative datings of rock glacier surfaces in Austria are rare so far. In the Larstig Valley of the Stubai Alps, Tyrol, two relict rock glaciers were dated by surface exposure age dating using cosmogenic ^{10}Be (Ivy-Ochs et al., 2009). Further to the east only relative dating was carried out so far. There, the Schmidt-hammer exposure-age dating (SHD) method was applied at nine rock glaciers, five of them are intact (i.e. active or inactive still containing permafrost) and four are considered as relict (Kellerer-Pirklbauer, 2008a, 2009; Rode and Kellerer-Pirklbauer, 2012). Rode and Kellerer-Pirklbauer (2009) carried out macrofabric analyses at several rock glaciers in the Niedere Tauern Range pointing out the importance of flow dynamics, the influence of topography, the size of the rock glaciers as well as the movement of blocks during permafrost thawing for clast orientation.

The chemical composition (ion and metal concentration) of high-mountain lakes and creeks situated in the catchment area of active rock glaciers were investigated by Thies et al. (2007) as well as their impact on drinking water quality. Combinations of several geophysical methods (GPR, seismic refraction, gravimetry) helped to improve structural models of rock glaciers (Hausmann et al., 2006; Hausmann et al., 2007) and to better understand their rheological behaviour using the derived ice content and permafrost thickness. The recent interannual creep variation of several rock glaciers in the European Alps was jointly analysed and discussed by Delaloye et al. (2008).

A first estimation of the permafrost distribution in Austria was published by Lieb (1996, 1998) using the lower limit of active rock glaciers in central and eastern Austria. A first approach to model the permafrost distribution of Austria was performed by Ebohon and Schrott (2008). Permafrost in ice caves was also studied and included the link between (speleo-) meteorology and ice formation, attempts to determine the age of the ice as well as the quantification of local ice volumes (Hausmann and Behm, 2011; Obleitner and Spötl, 2011; Schöner et al., 2011). Recently, Otto et al. (2012) investigated slopes using a combination of ground temperature measurements, TLS and geophysical methods in order to detect permafrost. The authors describe the occurrence of sporadic and discontinuous permafrost in the Glatzbach catchment (Hohe Tauern Range) with strong lateral variations controlled by the grain size of the regolith as well as solar radiation. Kellerer-Pirklbauer and Avian (2012) studied permafrost and ground temperatures in the Reisseck Mountains, Hohe Tauern Range, analysing five years of continuous ground temperature data also highlighting the need of long-term monitoring strategies. Winkler et al. (2010, 2012) recently revived research activities on the hydrogeological role of rock glaciers in the Styrian part of the Niedere Tauern Range thereby focussing on the hydraulic properties of relict rock glaciers applying hydrograph analyses and natural and artificial tracers. Finally, a complete seasonal cycle of continuous resistivity measurements was recorded at the Mölltal Glacier and the Magnetköpfle in the framework of a study on active layer processes (R. Supper, pers. comm.).

3. Current permafrost research activities in Austria

3.1 Modeling of mountain permafrost distribution and the distribution of rock glaciers and permafrost in the past and today

This special issue starts with a spatial modeling approach of permafrost distribution for the entire Hohe Tauern region using the new index-based PERMAKART 3.0 model (contribution by Schrott, Otto and Keller, 2012 [this volume]). A permafrost map was made on a calibrated topoclimatic key covering an area of 550 km^2 which is potentially underlain by permafrost.

Current research shows that permafrost in Austria occurs in unconsolidated sediments (in rock glaciers and in low- and high-elevation talus slopes) and in bedrock. In the past field research was focused particularly on a few rock glaciers characterized by their large extension and impressive creep morphology. Quantitative information on the rock glacier distribution was provided only for some parts of Austria or involved only a few parameters. This special issue provides an overview of rock glacier distribution as well as new and detailed rock glacier inventories and related analyses for the Tyrolean Alps (contribution by Krainer and Ribis, this volume) and for the central and eastern part of the Austrian Alps (contribution by Kellerer-Pirklbauer, Lieb and Kleinferchner, 2012 [this volume]). In addition, the permafrost distribution during the Younger Dryas and the Little Ice Age was reconstructed for the Reisseck Mountains, Hohe Tauern Range (contribution by Avian and Kellerer-Pirklbauer, 2012 [this volume]).

3.2 Internal structure and dynamics of rock glaciers

Core drilling on rock glaciers showed that the internal structure and distribution of ice may change significantly both vertically and laterally. Layers composed of either massive ice, ice in pore space, ice lenses, or sandy-silty material occur below the active layer. Surface-based geophysical methods were applied and allowed to obtain information on structural and physical parameters such as ice content, permafrost thickness, depth to the permafrost table and depth to the bedrock. A study on the internal structure and ice content of the Ölgrube and Kaiserberg rock glaciers resulted in 4-layer models including a core of massive ice (contribution by Hausmann, Krainer, Brückl and Ullrich, 2012 [this volume]). The geophysical models enabled to explain the creep behaviour of these two rock glaciers as well as of the Reichenkar rock glacier. A multi-disciplinary investigation of an active rock glacier in the Sella Group (Dolomites) found fine-grained dolomite debris in the active layer, moderate flow velocities, and a massive ice core with banded ice of glacial origin. This rock glacier shows a high hazard potential as debris may be mobilized at its steep front causing debris flows (contribution by Krainer, Mussner, Behm and Hausmann, 2012, [this volume]).

3.3 Permafrost monitoring

Monitoring initially focused on measuring the displacement at individual markers in order to describe the kinematics of rock glaciers apart from aerial photogrammetric and/or SAR approaches (see above). New methods (TLS and ALS) allow to record high-sampled point clouds to describe the temporal variation of surfaces in high-mountain environments (e.g. rock glaciers, rock falls) and to detect changes in permafrost creep, sediment volume and/or terrain surface. Important parameters for the monitoring of the state of permafrost are ground temperature, seismic velocity, permittivity, electrical resistivity, snow height, solar radiation, and wind. The paper on rock glacier monitoring using terrestrial photogrammetry describes the evolution of this method and presents a case study from the

Äußeres Hochebenkar rock glacier (contribution by Kaufmann, 2012 [this volume]). The paper on intended long-term monitoring of the Kitzsteinhorn describes the monitoring concept of ground thermal conditions in steep rock faces as currently implemented in the MOREXPERT project. Based on a combination of deep/shallow boreholes and electrical resistivity tomography (ERT) measurements surface and subsurface thermal conditions are monitored at high resolution at this study site (contribution by Hartmeyer, Keuschnig and Schrott, 2012 [this volume]). The paper on the spatial structures of permafrost at Sonnblick describes the results of monitoring of temperature and seismic velocities in three boreholes, of ground surface temperature (GST) and of base temperature of the winter snow cover (BTS) in the Sonnblick region, and of TLS and GPR at the summit. Based on these data the ground temperatures were modelled at the summit and a permafrost distribution map was established for the Sonnblick area (contribution by Schöner, Boeckli, Hausmann, Otto, Reisenhofer, Riedl and Seren, 2012 [this volume]).

3.4 Climate Change and Natural Hazards

The paper on rock glacier velocity and its relationship to climate and climate change combines rock glacier movement data with different climatic parameters at three rock glaciers in the Hohe Tauern Range. Movement data are based on annual geodetic field campaigns and complementary data from aerial photogrammetric surveys covering up to 57 years of observation. These data were combined with ground surface and near ground-surface temperature data as well as air temperature data from two meteorological stations all measured at the three rock glaciers. Furthermore, complementary climate data from a meteorological observatory were used in the study. Results revealed complex relationships between movement and climate and highlight the need for long-time series in such types of analyses (contribution by Kellerer-Pirklbauer and Kaufmann, 2012 [this volume]).

The paper on modeling geomorphological hazards to assess the vulnerability of alpine infrastructure is based on a comprehensive evaluation of the processes which are caused by glacier retreat and permafrost degradation and which both are expected to accelerate in the near future. In the Austrian Alps, resulting geomorphological hazards like rock falls or debris flows only locally affect settlements or traffic routes, but widely endanger hiking trails and routes in high mountain areas. The study shows that changing permafrost environments are among the most prominent challenges in maintaining this infrastructure which is of crucial importance for Austria's summer tourism (contribution by Kern, Lieb, Seier and Kellerer-Pirklbauer, 2012 [this volume]).

3.5 Organization and networking

During the 7th International Conference on Permafrost held in Yellowknife, Canada, in 1998 Austria joined the International Permafrost Association (IPA) as a full member thanks to the efforts by Gerhard Karl Lieb and Viktor Kaufmann (both Graz). For many years Gerhard Karl Lieb was the Austrian representative to the IPA later followed by Andreas Kellerer-Pirklbauer (Graz). In October 2010, an Austrian national committee of the International Permafrost Association was founded. Since then, Andreas Kellerer-Pirklbauer has been supported by Gerhard Karl Lieb, Karl Krainer (Innsbruck), Lothar Schrott (Salzburg) and Helmut Hausmann (Vienna) in promoting joint research activities as well as raising permafrost awareness of the public in Austria. Lothar Schrott is a member of the executive committee of the IPA for the period 2012-2016.

The idea for this special issue on permafrost in Austria and South Tyrol was born during the permafrost workshop held in Obergurgl (Tyrol) in October 2010. At this workshop a working group "Permafrost in Austria" was founded and the following goals were defined: a) improving the coordination of permafrost research in Austria and South Tyrol (Italy), b) improving the cooperation of the various groups working on permafrost in Austria and South Tyrol, and c) selecting well-suited key sites for long-term permafrost monitoring in the Austrian Alps.

4. Outlook and open questions

Although in recent years several groups have been working intensively on the study of alpine permafrost in the Austrian Alps and the state of knowledge has expanded tremendously, many research questions still remain open.

One of the main goals is the distribution of permafrost in the Austrian Alps including its thickness and ice content. Whereas the distribution of rock glaciers is well known (rock glacier inventories by Kellerer-Pirklbauer et al. and Krainer and Ribis, 2012 [this volume]), still little is known on the distribution of permafrost in talus slopes and bedrock. The response of alpine permafrost on climate change is also poorly understood due to the lack of long-term monitoring in the Austrian Alps. Continuous data series on ground temperature in permafrost environments in Austria are only available since a few years making it difficult to analyse relationships between ground temperature evolution and climate change relevant for modeling future scenarios. Therefore existing monitoring systems – in terms of ground temperature monitoring (at the surface and in different substrates as well as different depths) or rock glacier movement monitoring – must continue. Additionally, high-resolution and multi-temporal ALS and TLS elevation data will help to improve existing rock glacier inventories (for central and eastern Autria) but also allow areal-wide rock glacier movement monitoring (Bollmann et al., 2012).

Another issue is the significance of alpine permafrost on the hydrology and water quality in high alpine regions. Natural hazards such as rockfall activity related to increased melting of permafrost in bedrock gained during the last years and need to be studied in detail.

During the next years a project on core drilling on one or two active rock glaciers including a detailed analysis of the frozen core (ice content, pH, electrical conductivity, anions, cations, heavy metals, stable isotopes, palynology, radiometric dating...) and instrumentation of the boreholes with temperature loggers for long-term monitoring should be achieved, in which all permafrost working groups in Austria are incorporated.

Furthermore, such an activity should be augmented by a geodetic monitoring system using Real-time Kinematic (RTK) low-cost Global Navigation Satellite System (GNSS) receivers embedded in a wireless network (of sensors) with remote control. The final goal is the implementation of a real-time rock glacier monitoring system where all permafrost working groups in Austria can participate in and benefit from.

In the future it will be important to continue and intensify research on alpine permafrost in the Austrian Alps under the use of new technologies. Collaboration with other research areas such as biology will play an important role in order to better understand the effects of global warming on permafrost and the environment in high alpine areas.

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