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The Dösen Rock Glacier in Central Austria: A key site for multidisciplinary long-term rock glacier monitoring in the Eastern Alps

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Abstract

Rock glaciers are distinct landforms in high mountain environments indicating present or past permafrost conditions. Active rock glaciers contain permafrost and creep slowly downslope often forming typical flow structures with ridges and furrows related to compressional forces. Rock glaciers are widespread landforms in the Austrian Alps (c. 4600). Despite the high number of rock glaciers in Austria, only few of them have been studied in detail in the past. One of the best studied ones is the 950 m long Dösen Rock Glacier located in the Hohe Tauern Range. This rock glacier has been investigated since 1993 using a whole suite of field-based and remote sensing-based methods. Research focused on permafrost conditions and distribution, surface kinematics, internal structure and possible age of the landform. Results indicate significant ground surface warming of the rock glacier body during the period 2007-2015 accompanied by a general acceleration of the rock glacier surface flow velocity (max. 0.66 m/a) over the last two decades. This speed-up is possibly related to higher ice temperature and water content. As judged from various geophysical measurements, the maximum thickness of the rock glacier is about 30-40 m with an active layer of several meters depending on the location. The permafrost thickness beneath the active layer was quantified to be between 10 m (at the margins) and 40 m (at the central and upper parts). Massive sedimentary ice has not been observed or detected by geophysics so far at the central and lower part but might exist to in the rooting zone of the rock glacier as indicated from field evidences. The Dösen Rock Glacier is primarily a talus-derived rock glacier although a small glacier might have existed some times in the past in the eastern part of the rooting zone. Age estimations of the rock glacier by using the Schmidt-hammer exposure-age dating method indicate a formation period of several thousand years with alternating periods of faster and slower evolution. Research findings at this typical alpine rock glacier in the Austrian Alps clearly point out that the morphogenesis, the internal structure as well as the climate-rock glacier relationship is complex but typical for such peculiar alpine landforms.

1. Introduction

Mountain permafrost is a widespread phenomenon in the Austrian Alps and relevant for geomorphic processes and landforms in alpine areas. Present climate change and its impacts on the cryosphere are omnipresent in high mountain areas. Impressive expressions of cryospheric changes in Austria are for instance massive rockfalls released from rock faces affected by permafrost degradation (Kellerer-Pirklbauer et al., 2012a) or multi-temporal, nation-wide glacier inventories (Fischer et al., 2015). Interference with human beings or infrastructure might turn these natural processes to natural hazard and are therefore also of socioeconomic interest and also relevance.

Permafrost is defined as ground material (i.e. soil and rock unrelated to ice content) that remains at or below 0°C for at least two years (van Everdingen, 1998). A recent permafrost modelling approach considering the entire European Alps is the Alpine Permafrost Index Map (APIM) (Boeckli et al., 2012). According to APIM permafrost in Austria covers between 484 (index ≥ 0.9) and 2907 km² (index ≥ 0.1) of the national territory depending on the permafrost index chosen as a threshold. This index describes semi-quantitatively the occurrence of permafrost and varies from 'permafrost nearly in all conditions' to 'permafrost only in very favorable conditions'. Permafrost areas in Austria are more extended compared to glaciated areas which cover currently some 415 km² (Fischer et al., 2015).

Active rock glaciers are creeping landforms occurring in continuous or discontinuous permafrost areas with high-relief and suitable topoclimatic conditions. Such landforms move slowly downvalley or downslope and evolve over a period of several centuries to millennia (Barsch, 1996; Haeberli et al., 2006; Berthling, 2011; Krainer et al., 2015). Rock glaciers are commonly characterized by distinct flow structures with longitudinal and concave-downward bended transversal furrows and ridges at the surface. In steeper terrain the rock glacier body might start to disintegrate (Avian et al., 2009) or even completely tear-apart and collapse (Schoeneich et al., 2015). Active rock glaciers that are influenced by permafrost degradation might change first to inactive rock glaciers (no movement, widespread permafrost ice), second to pseudo-relict rock glacier (no movement, sporadic permafrost ice) and third to relict rock glaciers (no movement) (Barsch, 1996;

Kellerer-Pirklbauer, 2016a). Inactive and active rock glaciers are sometimes jointly termed as 'intact' in particular when movement data are missing (Barsch, 1996). The ice component within a rock glacier may have formed by freezing in a continuous body of water (congelation ice) or by a transformation of snow to ice (sedimentary ice). The latter is typical for glaciers (Haeberli and Vonder Mühll, 1996).

Several rock glacier inventories were elaborated during the last years in Austria. A first point-based rock glacier inventory for Central and Eastern Austria was published by Lieb (1996). This inventory was later revised and updated (Kellerer-Pirklbauer et al., 2012b; polygon shapefiles can be downloaded via the Pangaea database; see Lieb et al., 2012). Recently, airborne laser scanning (ALS) data were used to elaborate a third generation of a rock glacier inventory for a 2440 km² large area in central Austria (Kellerer-Pirklbauer et al., 2016). This ALS-based inventory-update process is currently carried out also for other regions in Austria within the framework of a project named RGHeavyMetal. By using ALS data it is feasible to detect also relict rock glaciers in forested areas which previously had remained undetected (Kellerer-Pirklbauer et al., 2016). For the federal province of Tyrol, Krainer and Ribis (2012) published a rock glacier inventory listing 3145 rock glaciers. 45.5% of them (n=1713) were classified as relict and 54.5% (n=1432) as intact, respectively. For the federal province of Vorarlberg – located in the very west of Austria – a rock glacier inventory was elaborated by Stocker (2012) mapping 145 relict and 57 intact rock glaciers. Combined results from the three inventories by Lieb et al. (2012), Krainer and Ribis (2012), and Stocker (2012) list 2859 relict and 1691 intact rock glaciers for Austria.

In contrast to the very high number of rock glaciers in Austria only few of the active rock glaciers have been studied in detail applying jointly field work and remote sensing approaches. A combination of methods might be successfully used to understand movement, internal structure, climate, ground

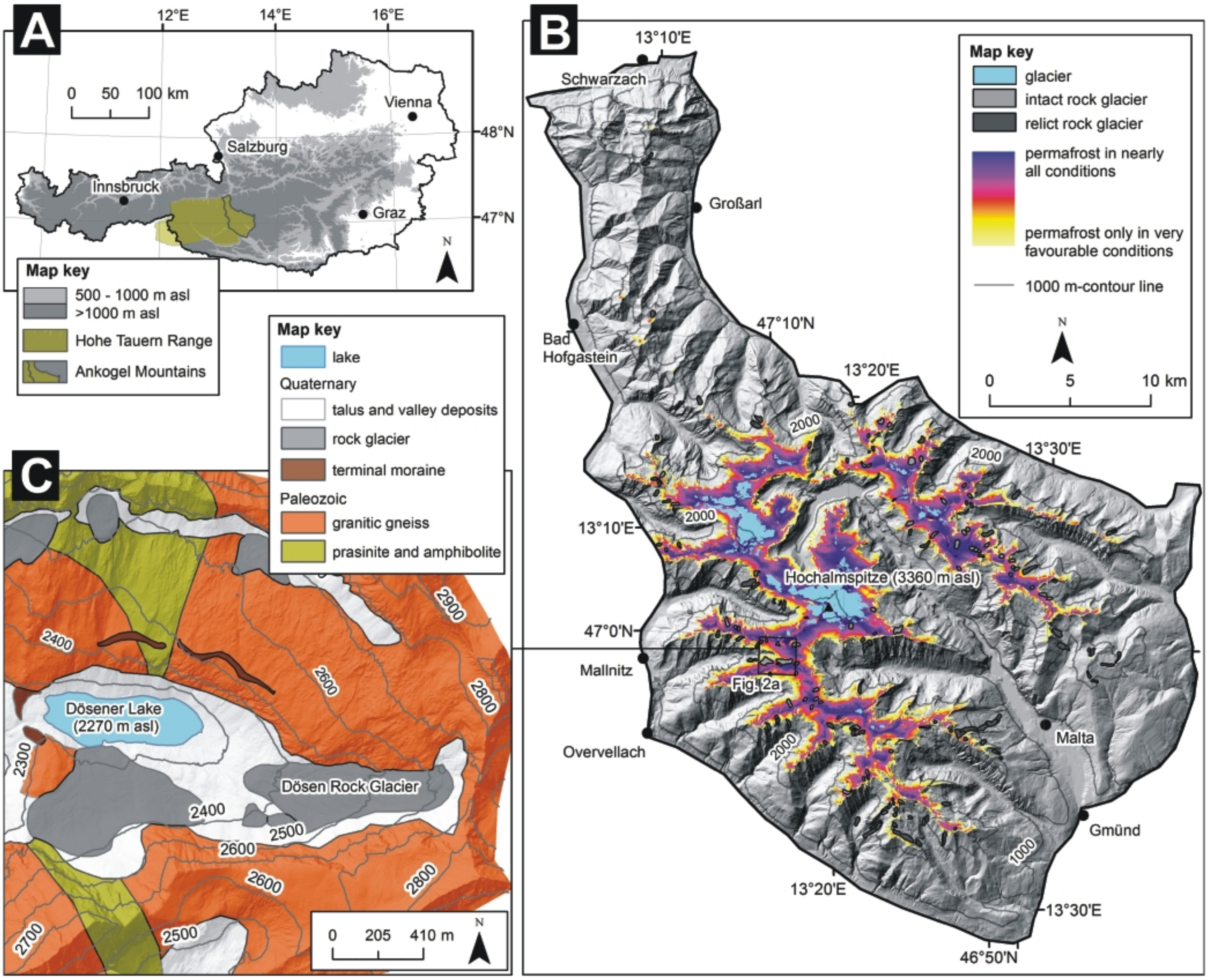

Figure 1: Study area: (A) Location of the Hohe Tauern Range, the Ankogel Mountains and the study area in Austria. (B) Relative position of the study area within the Ankogel Mountains depicting the spatial distribution of glaciers (Fischer et al., 2015), rock glaciers (Kellerer-Pirklbauer et al., 2012), and modelled permafrost (Boeckli et al., 2012). (C) Geological overview map of the study area based on Braunstingl (2005) (for bedrock) and own mapping (for Quaternary sediments), respectively.

thermal conditions, nourishment processes, landform genesis or landform age. The few intensively studied rock glaciers in Austria are the Reichenkar (Krainer and Mostler, 2000; Hausmann et al., 2007), the Ölgrube, the Kaiserberg (Berger et al., 2004; Hausmann et al., 2012) and the Outer Hochebenkar (Schneider and Schneider, 2001; Hartl et al., 2016) rock glaciers in western Austria. Furthermore, the Hinteres Langtalkar (Avian et al., 2005; Kellerer-Pirklbauer and Kaufmann, 2017), the Weissenkar (Kellerer-Pirklbauer and Kaufmann, 2012) and the Dösen Rock Glacier (e.g. Lieb, 1996) have been studied in

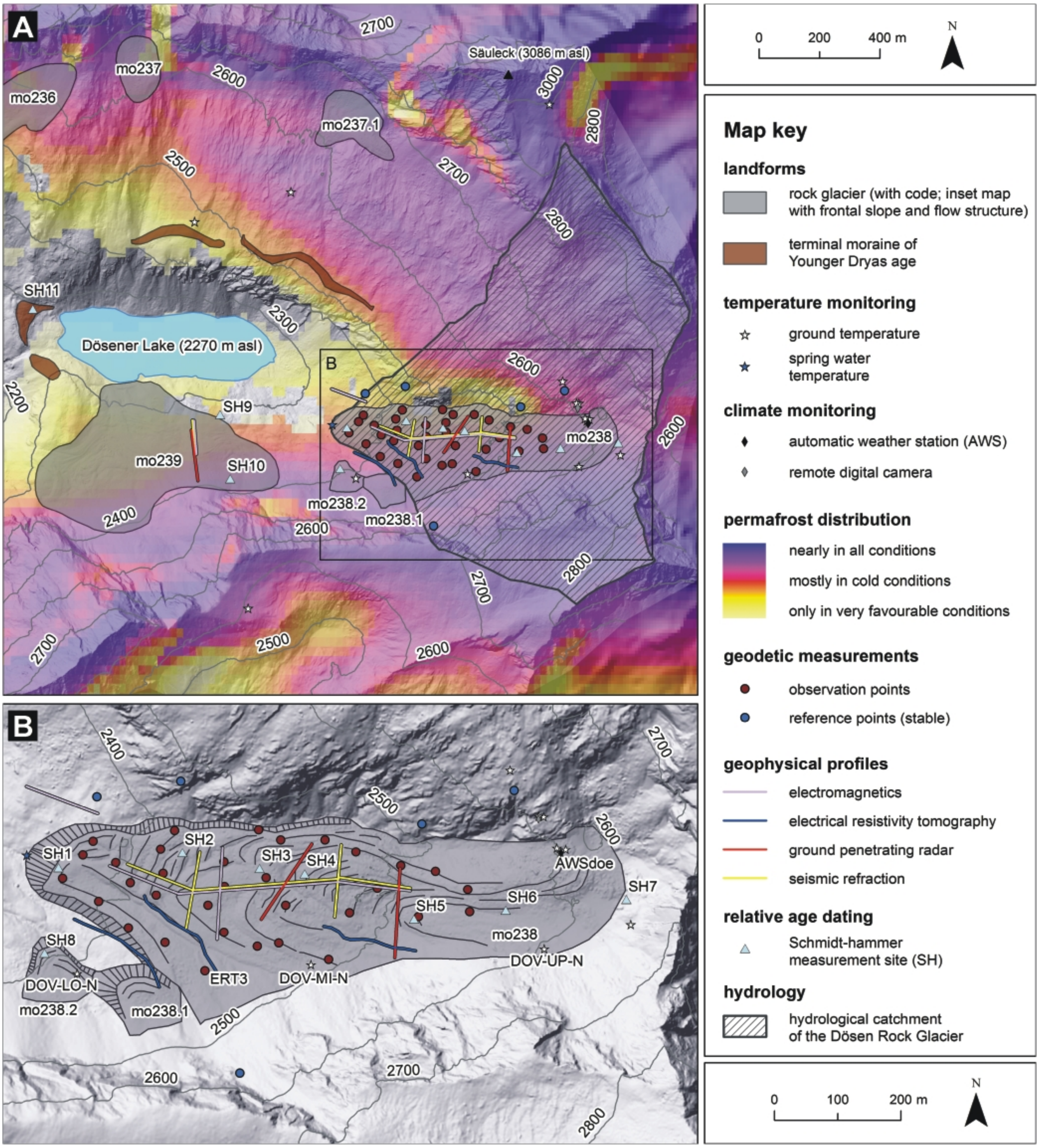

Figure 2: The Dösen Rock Glacier and its surroundings with measurement sites and geophysical profiles: (A) overview with the valley head of the Dösen Valley including the summit of Säuleck as its highest location and the hydrological catchment of the rock glacier. (B) detailed map of the rock glacier and its close vicinity. Measurement locations explicitly mentioned in the text are indicated and labeled. Rock glacier codes according to the inventory by Lieb et al. (2012). Permafrost distribution according to Boeckli et al. (2012). Hillshade based on an ALS-derived digital elevation model/DEM (acquisition year 2010) with a 1 x 1m grid (apart from some marginal areas outside the study area with a 10 x 10 m grid). DEMs kindly provided by Land Kärnten/KAGIS.

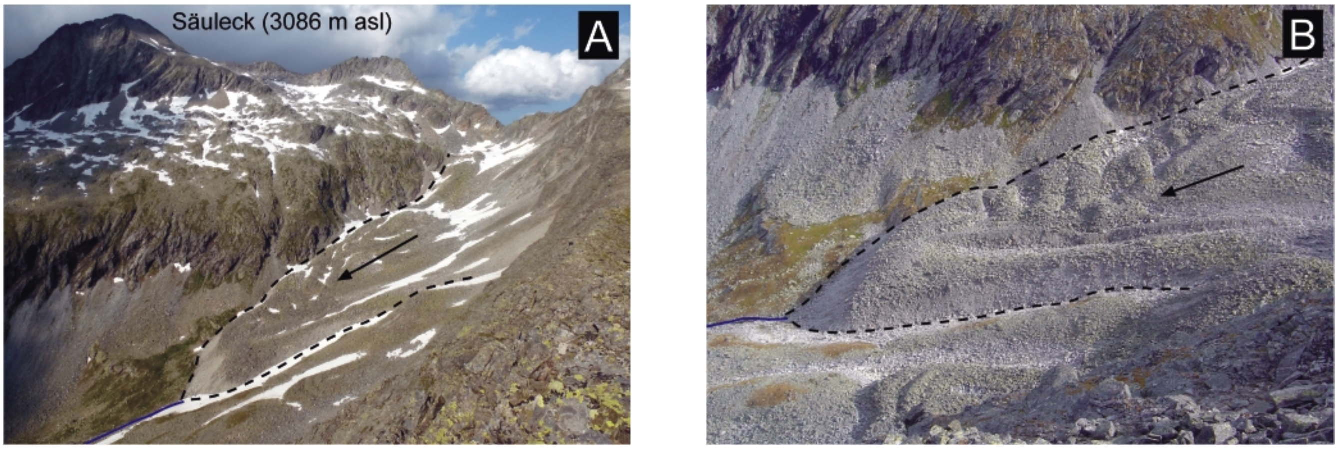

Figure 3: Terrestrial photographs of the active Dösen Rock Glacier. Black arrows indicate creep direction, dashed lines the margin of the rock glacier at its central and lower parts, and the blue line the creek emanating at the rock glacier terminus. Note the typical flow structure for rock glaciers, the snow patches in the depressions, the widespread lichen cover of the blocks (greenish color), and the lack of vegetation at the rock glacier surface. (A) view towards NE with the mountain Säuleck in the background. (B) View towards N.

the past (see Krainer et al., 2012 for a details). Field-based research was initiated in 1993 at Dösen Rock Glacier and is still ongoing. This paper aims to (1) give a comprehensive overview about the research history and selected research achievements at this rock glacier during the last decades thereby (2) highlighting the need for a multidisciplinary approach for

Research aim	Method	Initiated/carried out/period	Relevant publications
Morphology and vegetation	field mapping and mapping from remotely sensed data	1993	Kaufmann (1996); Lieb (1996); Nutz et al. (2009)
Thermal conditions and permafrost distribution	ground surface temperature and near-surface temperature monitoring using miniature temperature datalogger (MTD)	1995 (continuous since 2006)	Kellerer-Pirklbauer (2013); Kellerer-Pirklbauer and Kaufmann (2012); Kellerer-Pirklbauer et al. (2014); Lieb (1996, 1998)
	spring temperature monitoring (rock glacier spring) by manual measurements	1993 (irregularly until Aug. 2016, continuously since then)	
	basal temperature of the winter snow cover (BTS)	1994 and 1995	
Climate	climate monitoring using an automatic weather station	2006	Kellerer-Pirklbauer and Kaufmann (2012); Kellerer-Pirklbauer et al. (2014)
	optical monitoring of the rooting zone (snow, rock fall) with an automatic remote digital camera (RDC)	2006	
Kinematic	photogrammetric surveying - airborne	1954-ongoing (multi-annual)	Buck and Kaufmann (2010); Delaloye et al. (2008); Kaufmann (1996, 1998, 2016); Kaufmann et al. (2007); Kenyi and Kaufmann (2003); Kienast and Kaufmann (2004)
	geodetic surveying — theodolite	1995-2014 (annual)	
	geodetic surveying – RTK-GNSS	2014-ongoing (annual)	
	surveying with DinSAR – spaceborne	1992	
Internal structure	seismic refraction (SR)	1994 and 1995	Kellerer-Pirklbauer et al. (2014); Lieb (1998); Schmöller and Frühwirth (1996)
	ground penetration radar (GPR)	1995	
	electromagnetics (EM)	1995	
	electrical resistivity tomography (ERT)	2011	
	very low frequency electromagnetic measurements (VLF)	2011	
Age	relative dating of rock glacier surface using Schmidt-hammer exposure age dating (SHD)	2007	Kellerer-Pirklbauer (2008)

Table 1: Compilation of research aims, applied methods and resultant publications at the Dösen Rock Glacier and its close vicinity.

rock glacier process understanding as exemplified at this rock glacier.

2. Study area

The Dösen Rock Glacier is located at the valley head of Dösen Valley at N46°59´12" and E13°17´08". The Dösen Valley is part of the Ankogel Mountains, the eastern-most subunit of the Hohe Tauern Range (Fig. 1A) located near Mallnitz in the federal province of Carinthia. The Ankogel Mountains – including the two subunits Hafner and Reißeck Mountains – cover some 1080 km² (Fig. 1B). The highest summit of this mountain range reaches 3360 m asl (Hochalmspitze). Permafrost is widespread at elevations above c.2500 m asl as indicated by regional permafrost models (Boeckli et al., 2012). 44 glaciers cover 12 km² of the entire Ankogel Mountain Range (Fischer et al., 2015).

The Dösen Rock Glacier is tongue-shaped, ranges from 2620-2340 m asl, covers an area of 0.2 km², is 950 m long and 300 m wide. The active front is up to 40 m high and 40-45° steep. Surface features such as longitudinal and transverse furrows and ridges as well as the steep frontal slope are visual expressions of surface deformation and inherent creep (Figs. 1C, 2, 3). The creep direction of the rock glacier is from east to west. Several other smaller rock glaciers, a tarn (Dösener Lake) and distinct terminal moraines of presumable Younger Dryas age (Lieb, 1996) are located near the rock glacier (Figs. 1C, 2). The debris of the Dösen Rock Glacier consists of metamorphic rocks of Paleozoic age, primarily granitic gneiss forming large very angular and angular blocks at the surface. According to the combined geological map of Salzburg (Braunstingl, 2005), the bedrock geology in the study area consists furthermore of prasinite (a type of greenshist) and amphibolites (Fig. 1C).

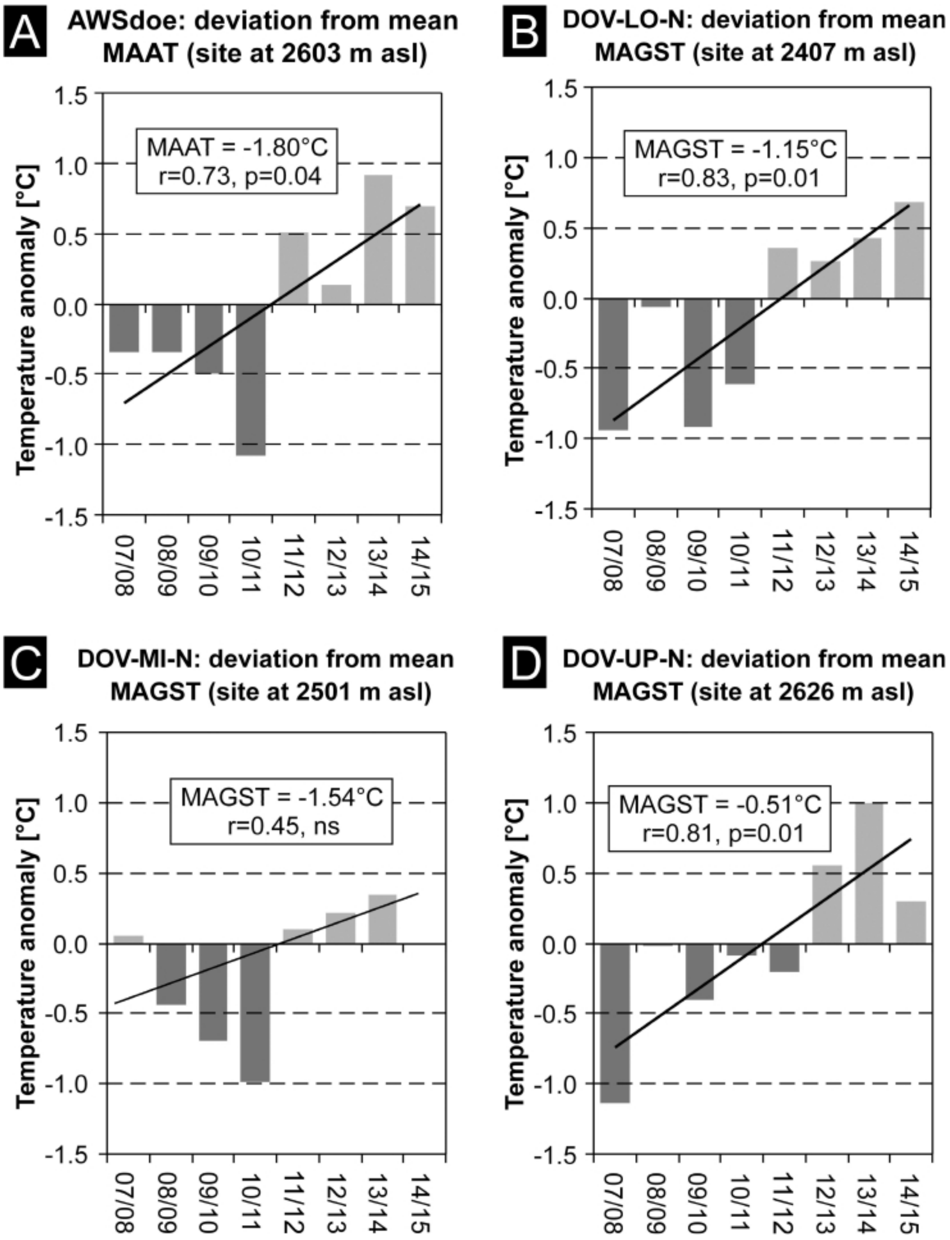

Figure 4: Air (A) and ground surface temperature deviations (B-D) from the mean value during the monitoring period (2007/08 – 2014/15) based on mean annual values (period Aug. 1. – d July 31.) at the automatic weather station located at the rock glacier (AWSdoe) and at three rock glacier sites (DOV-LO-N, DOV-MI-N, and DOV-UP-N). For locations see Fig. 2. Note the statistically significant warming at three sites (A, B, and D). MAAT=mean annual air temperature; MAGST=mean annual ground surface temperature; ns=not significant.

3. Methods

Field-based research activities at and near the Dösen Rock Glacier have been initiated in 1993 within a nationally funded project (Austrian Science Foundation/FWF project 'High Mountain Permafrost'; project no. P0 9565; 1993-1996). Since 2006 most of the research activities accomplished at this site have been carried out within the projects 'ALPCHANGE' (FWF-funded; project no. FWF P18304-N10), 'PermaNET' (European Regional Development Fund, Alpine Space Programme), and 'permAfrost' (Austrian Academy of Sciences). The study area itself is located in the Hohe Tauern National Park. The national park authority frequently supported research activities logistically and financially during the last two decades. Within the framework of the above mentioned projects different field-based and desktop-based methods have been used at Dösen Rock Glacier. Table 1 gives a brief overview of the applied techniques, relevant periods and specific readings. The following chapters present relevant research achievements.

4. Research activities and achievements

4.1 Permafrost conditions and climate

In the European Alps the lower limit of discontinuous (i.e. continuity of permafrost coverage 50-90% of an area) permafrost is related to a mean annual air temperature (MAAT) of -1°C (Barsch, 1978; Haeberli et al., 1993) or -2°C (Barsch, 1978; Humlum, 1998). The lower limit of sporadic (i.e. continuity of permafrost coverage 10-50%) permafrost may be expected at a MAAT of 0°C (Barsch, 1978; Humlum and Christiansen, 1998). The MAAT measured at the climate station at the rock glacier was -1.8°C (Fig. 4A) during the period 2007-2008 to 2014-2015 indicating discontinuous permafrost if using the above mentioned thresholds.

4.1.1 Ground temperature and climate monitoring

The basal (or bottom) temperature of the winter snow cover (BTS) is known to be a useful indicator of the occurrence or absence of permafrost. The scope of this method is to measure the stable winter temperature below a rather thick (c.1m), thermally insulating winter snow cover. Therefore, BTS campaigns are commonly carried out in March or early April. BTS temperatures of <-3°C suggest permafrost probable whereas temperatures >-2°C suggest permafrost unlikely with an uncertainty range in between (cf. Haeberli, 1973). The interpretation of measured BTS values should be made very carefully. BTS was measured in winter 1994 and 1995 and results supported permafrost existence at the rock glacier, at higher-elevated south-facing slopes and at shaded north facing slopes (Lieb, 1996). BTS data have been also used for area-wide permafrost existence estimates as shown further below.

Continuous ground temperature monitoring was initiated in 2006 with 12 monitoring sites (Fig. 2). Therein several miniature temperature dataloggers (MTD) at locations with different elevations, aspects, substrates and depths in the ground automatically log ground temperatures in 1h-intervalls. The (still) used MTDs are either 1-channel dataloggers (GeoPrecision, Model M-Log1) with one temperature sensor or 3-channel dataloggers (GeoPrecision, Model M-Log6) with three sensors at different depths (maximum 3 m below the ground surface). The MTDs have been installed at 2407-3002 m asl in near vertical rock walls, at debris slopes, at the rock glacier surface, and at vegetation-covered slopes (Kellerer-Pirklbauer, 2013). An automatic weather station (AWSdoe) was additionally installed at a large block at the upper part of the rock glacier (Fig. 2) measuring continuously air temperature, air humidity, wind speed, wind direction, and global radiation. Finally, a remote digital camera used for snow and rock fall monitoring has been installed in 2006 (Fig. 2).

Deviations of mean annual values (period August 1 to July 31) from the mean annual value of the ground surface temperature (MAGST) at the two MTD sites at the Dösen Rock Glacier (DOV-MI-N, DOV-UP-N) and at one site at an adjacent smaller rock glacier (DOV-LO-N; see Fig. 2) are presented in Fig. 4B-D. The deviations from the MAAT during the same period at the meteorological station AWSdoe are additional shown in Fig. 4A for comparison. Results indicate substantial interannual variations in both air and ground surface temperatures. Furthermore, in three out of the four cases in Fig. 4 a

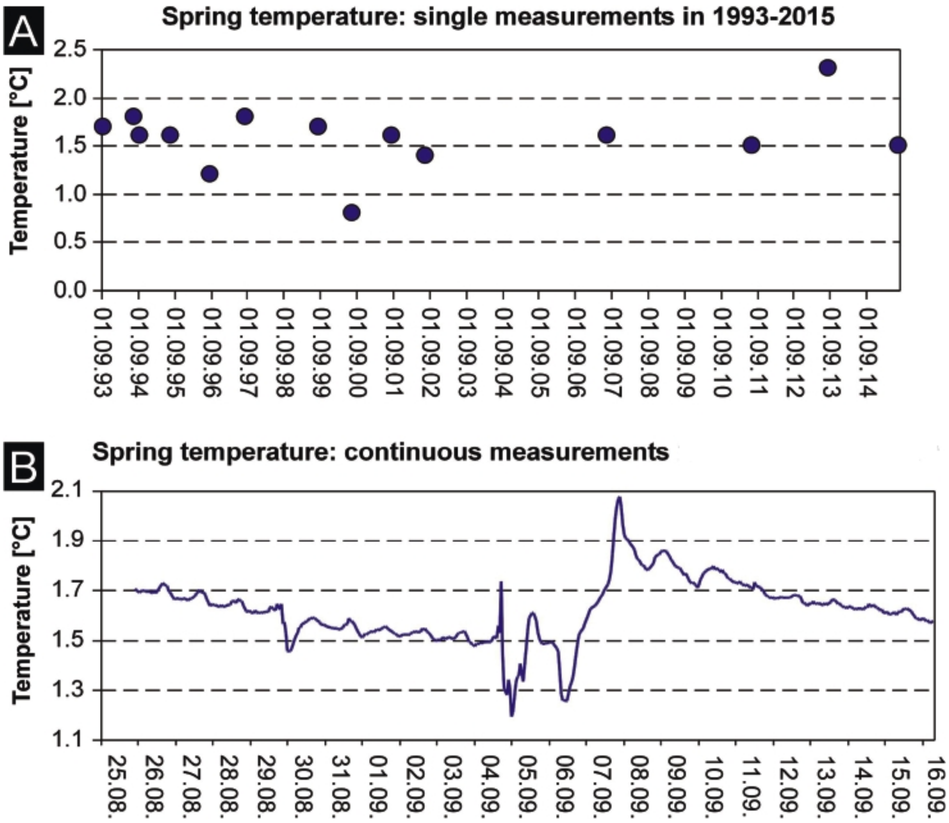

Figure 5: Spring temperature measurements at the front of the Dösen Rock Glacier (Fig. 2 for location of spring) carried out irregularly since 1993 (A) and continuously (with hourly resolution) during the period August 25, 2016 to September 16, 2016 (B). Note the general temperature trends (steady decrease in temperature) in (B) with superimposed distinct diurnal variations and substantial interruptions of this pattern between September 4 and 8, 2016.

statistical significant warming of the mean annual temperature was revealed. Only at the site DOV-MI-N this warming trend is not statistically significant. This 'outlier' can be explained by the fact that the site DOV-MI-N is severely influenced by a long lasting (~300 days) seasonal snow cover causing an effective de-coupling of the ground temperature from the air temperature during the autumn, winter, and spring seasons masking the atmospheric influence on the ground. Furthermore, there is no decrease of the MAGST with elevation at the rock glacier (i.e. warmest MAGST value at the highest site; Fig. 4D) related to the dominance of local topoclimatic conditions (including variable snow cover, shading, etc.) in relation to the common altitudinal decrease of air temperature. The results shown in Fig. 4 are in good agreement to the area-wide general warming trend of ground temperatures in central and eastern Austria (Kellerer-Pirklbauer, 2016b).

4.1.2 Water spring temperature monitoring

Water temperatures at springs reflect the thermal regime of the spring's catchment area. If measured without direct influence of a nearby snow patch spring temperatures can be used as indicators of permafrost. According to Haeberli (1975) temperatures below 1°C make the existence of permafrost probable, temperatures above 2°C improbable with a span of uncertainty in between. In the inner Dösen Valley occasional water temperature data from several springs are available since 1993 (Lieb, 1996) among them the large and only spring below the front of the Dösen Rock Glacier (Fig. 2 for location). Fig. 5A depicts spring temperature data measured manually between 1993 and 2015. Measurements were accomplished in most cases in July or August and values range from 0.8°C (measured during a cold weather period with no notable surface runoff above the spring hence potentially indicating sole permafrost-melt conditions) to 2.3°C (measured during a warm summer day) yielding a mean of 1.5°C.

At the rock glacier spring a temperature data logger has been installed in 2016 measuring water temperature hourly. So far data are available for the period Aug. 25, 2016 until Sept. 16, 2016. The mean value of this summer period (1.6°C) corresponds well with the previously occasional measurement values but surprisingly does not indicate 'permafrost probable'. Clear diurnal variations (amplitude of c.0.05°C) are superimposed on a general cooling trend in the late summer/early autumn season indicating a fast water temperature response to weather conditions. The trend during the monitoring period was, however, substantially influenced by a cooler and wetter period between September 4, 2016 and September 7, 2016 which caused a clear shift in the water tem-

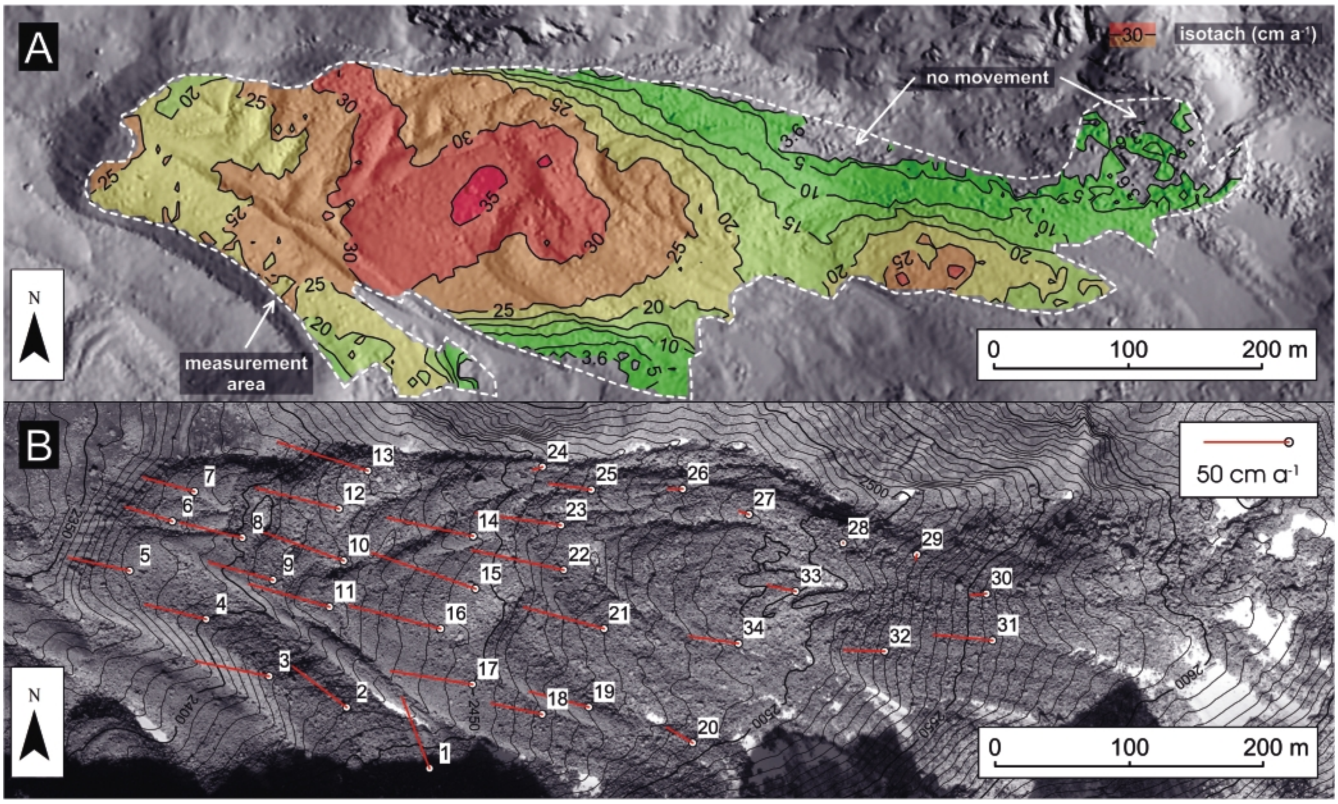

Figure 6: Horizontal flow velocities at Dösen Rock Glacier based on photogrammetric (A) and geodetic (B) measurements. (A) Mean annual horizontal flow velocity for the time period 1997-2010. Equidistance of isotachs is 5 cm/a. Maximum flow velocity amounts to 39.0 cm/a. The significance level of the velocities is at 3.6 cm/a. Computed velocities smaller than 3.6 cm/a are statistically non-significant, thus respective areas can be classified as non-moving. The shaded relief is based on an ALS-derived DEM (acquisition year 2010) with a grid spacing of 1m x 1m. DEM kindly provided by Land Kärnten/KAGIS. (B) Annual movement (2014-2015) of the 34 observation points at the rock glacier. The horizontal movement (displacement vectors shown in red color) is exaggerated by a factor of 150. The maximum flow velocity has been measured at point 15 and amounts to 65.9 cm/a. Aerial photograph (21 September 2010), BEV, Vienna.

perature towards the warmer side. The pattern of the spring water temperature evolution depicted in Figure 5B resembles a typical spring recession curve (in terms of discharge) and its interruption by a precipitation event. The measured water temperature suggests that the spring gets its water not only from permafrost-influenced areas but also from a sub-permafrost groundwater system and from parts of the drainage catchment that are not influenced by permafrost.

The hydrological drainage catchment of the rock glacier spring is depicted in Figure 2A. The catchment covers 0.94 km² and is not entirely in the modelled permafrost environment supporting the rock glacier spring observations. Therefore, the spring temperatures measured at this spring seem to represent a mixed temperature signal of a permafrost-affected and permafrost-free catchment. Only during cold or prolonged dry periods in summer with little superficial discharge one might expect to measure the sole permafrost-melt discharge component of the spring.

4.1.3 Permafrost modelling

Based on the previously described BTS and spring temperature data as well as geomorphic mapping, a first permafrost distribution map was compiled already in 1996 (Lieb, 1996). According to this approach probable permafrost exists at north-exposed, blocky sites at 2270 m asl. In contrast, at south-exposed slopes the lower limit of permafrost was predicted for elevations of 2950 m asl. More recently an Alpine wide regional permafrost modelling approach (APIM, see above) was accomplished using also ground temperature data from the studied Dösen Rock Glacier (Boeckli et al., 2012). According to this approach, permafrost does widely exist in the entire study area (Fig. 2A), although areas exposed to higher radiation values (the north-western part of the rock glacier) are in less permafrost-favorable areas. This general pattern is supported by the earlier BTS measurements (Lieb, 1996) although clear local lower limits of permafrost still cannot be drawn based on few field data.

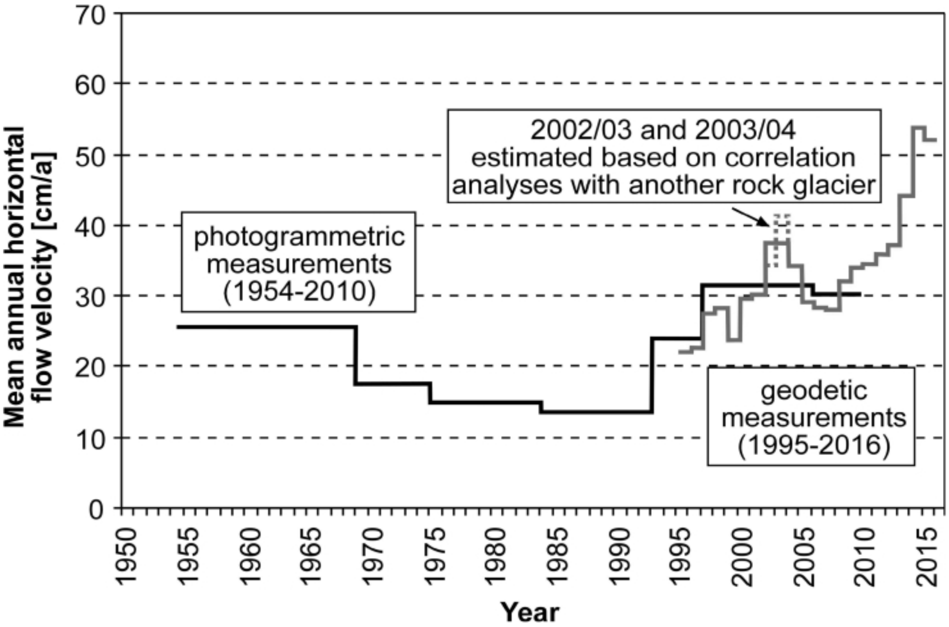

Figure 7: Mean annual horizontal flow velocity of Dösen Rock Glacier during the time period 1954-2016 based on photogrammetrically derived flow velocities (1954-2010) and annual geodetic measurements (1995-2016). The velocities shown are mean values derived from 11 representative observation points (10-17, 21-23; see Fig. 7A). Geodetic measurements were not carried out in 2003. Therefore, velocities for 2002/03 and 2003/04 were estimated based on correlation analyses with the Hinteres Langtalkar Rock Glacier located some 35 km to the west (cf. Kaufmann, 2016).

4.2 Rock glacier kinematics

The understanding of rock glacier kinematics and landform evolution is still in its infancy (Müller et al., 2016). Appropriate models for in-depth describing the dynamic behavior of rock glaciers do not exist at all. This is mainly because the natural processes involved are to complex and hard to understand. For the time being only rather simple models exist which try to model rock glacier geometry and flow velocity as a function of, e.g., ground surface temperature, ice temperature changes and/or sediment input (Kääb et al., 2007; Hausmann et al., 2007; Müller et al., 2016). For example, these models can help to better understand or even proof the obvious correlation of surface temperature change with flow velocity change.

4.2.1 Monitoring of geometric surface changes

A recent summary about different types of measurements of rock glacier flow velocities at several rock glaciers in Central Austria including Dösen Rock Glacier has been provided by Kaufmann and Kellerer-Pirklbauer (2015). According to these authors and Haeberli et al. (2006) the existing measurement techniques in rock glacier movement monitoring can be classified into three main groups: photogrammetric/image-based methods, geodetic methods (using a total station, Global Navigation Satellite System/GNSS-based), and laser scanning. In this paper we present results obtained from aerial photogrammetry and geodetic work.

4.2.2 Photogrammetry

Aerial photogrammetry is a powerful technique for obtaining area-wide three-dimensional information on rock glacier movement. Aerial photographs of Dösen Rock Glacier dating from 1954, 1969, 1975, 1983, 1993, 2006, and 2010 were evaluated so far. The computation of horizontal displacement vectors is based on 2D image matching of multi-temporal orthophotos. The three-sigma rule of thumb (for 99.7% probability) was applied as a threshold for detection of significant change/movement. Figure 6A shows exemplarily the mean annual horizontal movement of the rock glacier in 1997-2010. Surface elevation change was computed by subtracting the multi-temporal DEMs which were obtained either by manual mapping (older epochs) or automatic mapping procedures. However, limited elevation accuracy and other objections, such as seasonal snow cover and shadows, made successful mass balance analyses for the entire landform difficult. Surface lowering due to permafrost degradation (melting of interstitial or even sedimentary ice) was roughly estimated to be a few centimeters (up to max. 10 cm) per year. Additionally, satellite-based differential Synthetic Aperture Radar/SAR interferometry has been applied in past supporting the photogrammetrically derived flow pattern of this rock glacier (Kenyi and Kaufmann, 2003).

4.2.3 Geodetic measurements

Common for geodetic rock glacier monitoring is the usage of a geodetic network consisting of a few stable reference points located outside the rock glacier and a set of well-distributed observation points on the rock glacier itself. At Dösen Rock Glacier a geodetic network consisting of observation points (in total 107) on boulders of the rock glacier surface and stable reference points (in total 11) positioned in the surrounding was set up in 1995 (Kaufmann, 1996). Since back then geodetic measurements have been carried out on an annual basis except for 2003 due to financial reasons. In 2006 and 2013 the network of stable reference points was expanded. The set of observation points on the rock glacier consists of 34 points stabilized with brass bolts (Fig. 2B) and 73 supplemental points marked with red color forming two longitudinal and two transversal profiles. Measuring the 73 supplemental points has been stopped in 2014. In the same year the traditional surveying method was replaced by GNSS-based surveying (Kaufmann, 2016).

Fig. 6B depicts exemplarily the annual movement of the 34 observation points at the rock glacier surface for the time period 2014-2015. This observation is in accordance to the photogrammetrically-derived flow field of the rock glacier (Fig. 6A). Figure 7 summarizes the velocity measurements carried out at this rock glacier so far depicting mean annual horizontal flow velocity rates for the period 1954–2016. This mean velocity is based on 11 selected geodetic observation points (no. 10-17 and 21-23) and the appropriate locations at the aerial photographs, respectively. As shown in this graph, the horizontal flow velocity of Dösen Rock Glacier has changed significantly over time with distinct periods of acceleration and deceleration. A possible explanation for this change in flow velocity is given in Delaloye et al. (2008) and Kellerer-

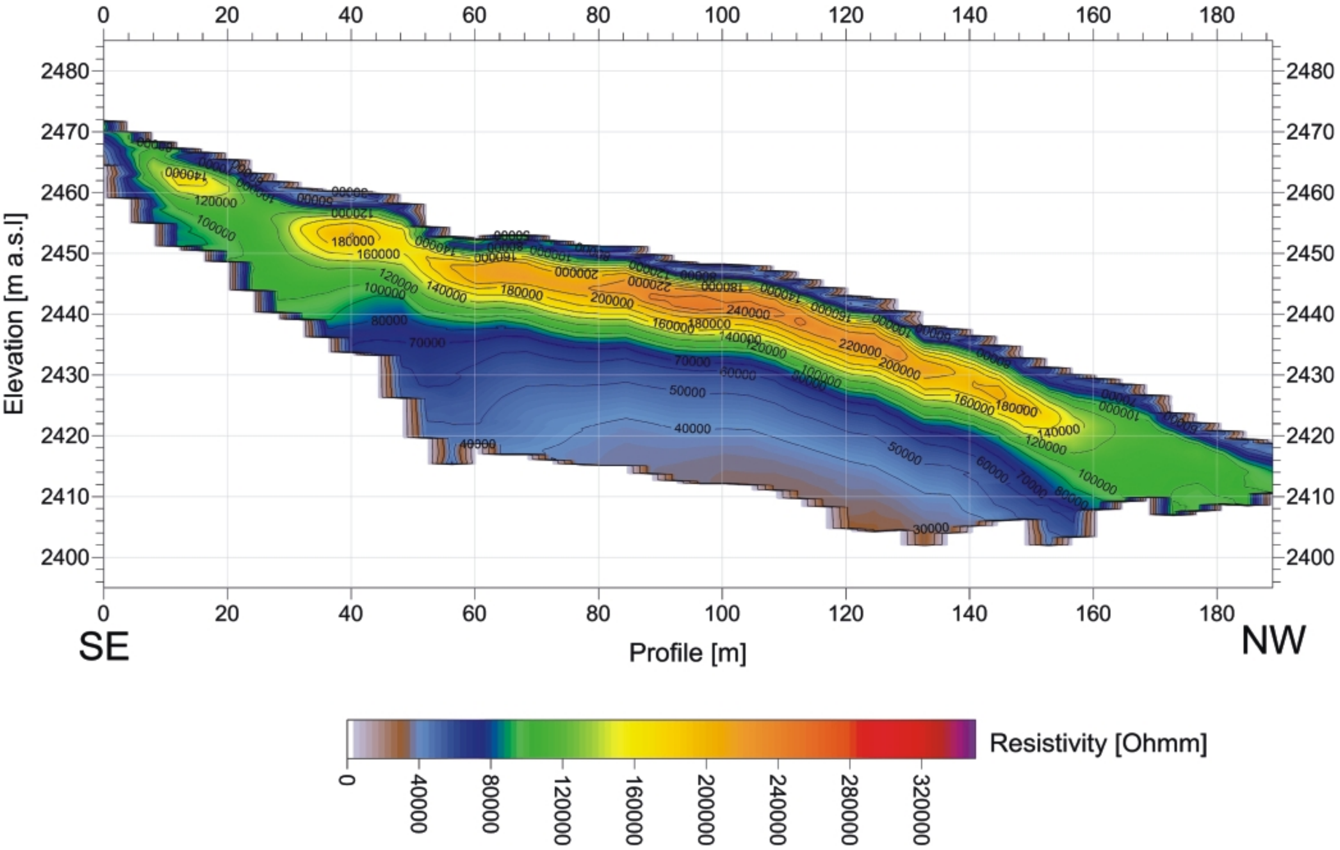

Figure 8: Example of a geophysical profile measured at Dösen Rock Glacier. Results of a geoelectric resistivity tomography profile (ERT3 in Fig. 2) measured at the central part of the rock glacier. In this case evidences of an ice-rich permafrost body are below a depth of c.4 m (active layer) with high values (100-240 kOhmm) in a 10-15 m thick zone overlying a lower resistivity zone (20-100 kOhmm) with a total thickness of about 25-30 m (modified after Kellerer-Pirklbauer et al., 2014).

Pirklbauer and Kaufmann (2012) revealing synchronous velocity changes for several rock glaciers in the European Alps.

The synchronicity is clearly attributed to climatic forcing. The measurements made in 2014 and 2015 at Dösen Rock Glacier showed by far the highest flow velocities (mean 53.6 cm/a; maximum 65.9 cm/a at point 15) ever measured at this rock glacier. In 2015-2016 the surface flow velocity decreased only slightly (mean 52.0 cm/a; maximum 64.7 cm/a at point 15). These values are about four times higher than the mean annual velocities measured between the 1970s and the early 1990s. Regarding velocity changes, a time lag of one to more years for acceleration can be expected when a rock glacier reacts to warm air temperatures whereas strong cooling seems to cause a faster deceleration (Kellerer-Pirklbauer and Kaufmann, 2012). This is in accordance to earlier findings by Schneider and Schneider (2001) from Western Austria, or Kääb et al. (2007) from Switzerland. Both groups found out that higher air temperatures correlate with higher velocity rates (attributed to higher ice temperature and higher water content). In contrast, lower temperatures correlate with lower velocity rates. The general low velocity rates at this rock glacier point towards a dominance of internal deformation, permafrost ice poor conditions, and no distinct sliding processes (e.g. Hausmann et al., 2007, 2012; Avian et al., 2009).

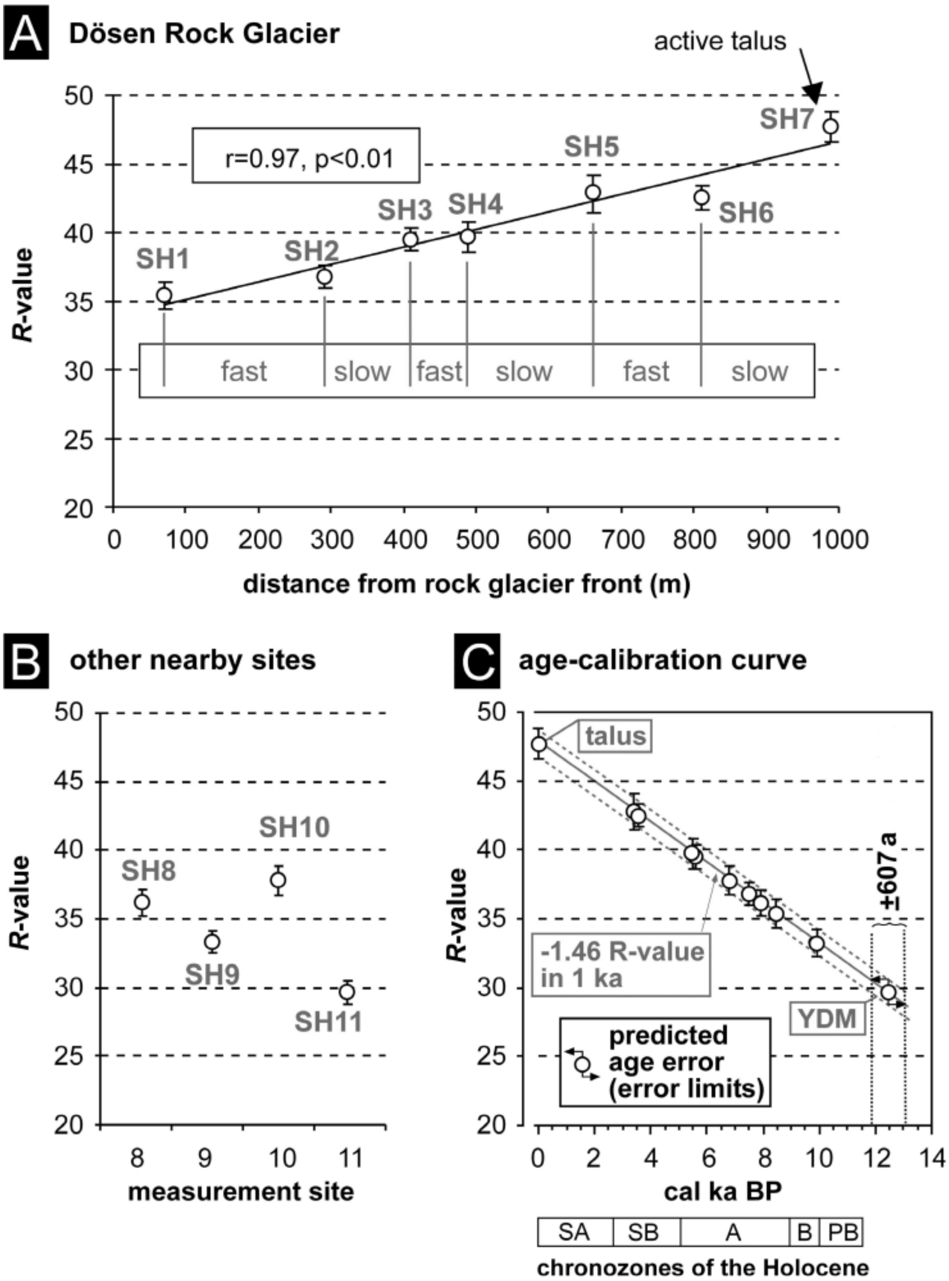

Figure 9: Relative age dating applying the Schmidt-hammer expose age dating (SHD) method at Dösen Rock Glacier (A) and its vicinity (B). The code numbers in the graph refer to the measurement sites depicted in Fig. 2. (C) Tentative age-calibration curve for the R-values measured at the Dösen Rock Glacier based on two surfaces of known age (i.e. an active talus slope and a terminal moraine of Younger Dryas age/YDM; c.12.5 ka). The calculation of predicted age error including error limits is illustrated for the YDM location. Holocene chronozones: SA=Subatlantic, SB=Suboreal, A=Atlantic, B=Boreal and PB=Preboreal (after Haas et al., 1998).

4.3 Rock glacier internal structure

Permafrost content and thickness as well as the internal structure of Dösen Rock Glacier were studied by applying so far five geophysical methods (Table 1). Figure 2B depicts the different sites and profiles were seismic refraction (SR), ground penetrating radar (GPR), electromagnetics (EM), and electrical resistivity tomography (ERT) was previously accomplished. In addition, very low frequency electromagnetic measurements (VLF) were carried out at 122 observation points at the rock glacier (not shown in Fig. 3B). The sections 4.3.1 to 4.3.3 are primarily based on Schmöller and Fruhwirth (1996) for SR, GPR and EM and Kellerer-Pirklbauer et al. (2014) for VLF and ERT.

4.3.1 Geophysics in the mid-1990s

Seismic refraction was accomplished during that time at six profiles, with profile lengths of 120 and 240 m using 5 and 10 m spacing between the geophons. Both sledgehammer and explosives have been used as seismic sources. Results show that at the rock glacier the active layer consists of an upper layer with coarse debris with open pore space (P-wave velocities 250-700 m/s; 1-3.5 m thickness; mean 2 m) and a lower layer with meltwater-saturated fine material and a thawing permafrost transition zone (P-wave velocities 1050-2500 m/s; up to a depth of 9 m below the surface; mean thickness 4.6 m). P-wave velocities of the underlying permafrost and bedrock are in the range of 3600-3900 m/s. According to this approach, the permafrost thickness was not detectable due to the low contrast between the permafrost body and the unfrozen basement underneath. A minimum permafrost thickness of 30-40 m was quantified.

Electromagnetic mapping was carried out along four profiles at the rock glacier and its vicinity (115-480 m long). This method was accomplished with various two-coil configurations with coils vertical and horizontal. The results permitted only qualitative interpretation concerning the conductivity distribution. According to electromagnetic mapping a low conductivity layer with dry boulders with open pore space is underlain by a non-conductive permafrost layer with wet rock material at the base. In agreement with the seismic results the permafrost thickness was estimated to be in the range of 30 m. However, permafrost might even be 50 to 60 m thick depending on the analytical approach.

Ground penetrating radar was applied at two profiles at Dösen Rock Glacier (140 and 150 m in length) and at one profile (180 m) at an adjacent rock glacier with the inventory code mo239 (Kellerer-Pirklbauer et al., 2012b) (Fig. 2). At all three profiles a 100 MHz antenna (GSSI, SIR-8) was used. GPR results are not in contradiction to the seismic and electromagnetic results. However, the poor reflectivity at the two profiles at Dösen Rock Glacier might lead to some ambiguous interpretation highlighting the importance of the combination of different geophysical methods (Schrott and Sass, 2008).

4.3.2 Geophysics in 2011

Very low frequency electromagnetic measurements use the components of the magnetic field of an electromagnetic wave. This electromagnetic wave is transmitted in the majority by military transmitters. The low frequencies of 15-20 kHz have been chosen to get a larger skin depth of the waves. Therefore the depth of penetration of these waves is, compared to waves with higher frequency, deeper. For the field measurements at Dösen Rock Glacier the VLF-receiver type EM16 (Geonics) had been applied. Although results of the very low frequency electromagnetic measurements are coarse in terms of spatial resolution, areas without permafrost can be distinguished from ice rich areas. Results from this method are in accordance to electrical resistivity measurements (see below) in terms of high and low resistivity value areas.

Electrical resistivity tomography was carried out at four profiles at the rock glacier although one without success due to electrode connection problems. The three successfully accomplished profiles were 145-198 m long (Fig. 2B) with 5-6 m electrode spacing and by using 30-40 electrodes. At Dösen Rock Glacier a lower permafrost resistivity threshold value of >100 kOhmm was chosen for ice-rich permafrost. Furthermore, resistivity values of around 20-100 kOhmm suggest permafrost with less ice. The uppermost of the three ERT profiles yields an active layer thickness of about 2 m overlying a solid permafrost body which is at least 15-20 m thick with maximum resistivity values around 300 kOhmm. The middle profile (labelled as ERT3 in Fig. 2B and depicted in Fig. 8) follows a ridge at the orographic left side of the rock glacier. At this profile evidences of a permafrost body are below c.4 m with high values (100-240 kOhmm) in a 10-15 m thick zone overlying a lower resistivity zone (20-100 kOhmm). This suggests an ice-rich upper permafrost layer and a lower permafrost layer with less ice and a total thickness in the order of 25-30 m. The lowest-elevated ERT profile follows the margin of the rock glacier body showing marginal permafrost occurrence at its upper part with a maximum permafrost thickness of ca. 8 m and maximum resistivities of around 160 kOhmm.

4.3.3 Findings based on geophysics

Summarising the results based on geophysics one can conclude that permafrost exists at Dösen Rock Glacier below an active layer of several meters. The active layer itself consists of an upper blocky surface layer with open voids and a lower layer with meltwater and finer material covering the permafrost body. The permafrost thickness is in the range of 10-40 m (or even more) depending on the considered location at the rock glacier. One must note here, however, that sometimes the interpretation is difficult particularly regarding the base of the permafrost. The maximum total thickness of the rock glacier is in the order of 30-40 m.

Massive sedimentary ice does not seem to exist at Dösen Rock Glacier; at least at its central and lower part where geophysical measurements were accomplished so far. Such buried lenses of massive ice in rock glaciers have been detected by geophysical measurements in the past particularly at higher-elevated areas of different rock glaciers (e.g. Lugon et al., 2004; Ribolini et al., 2010; Hausmann et al., 2012). Geophysical profile measurements have not been carried out so far at the rooting zone and the upper part of the rock glacier (cf. Fig. 2C). In this higher-elevated part or the rock glacier massive sedimentary ice might occur as indicated by a distinct rooting zone depression (Fig. 2B; note the surface depression at c.2600 m asl.), debris-buried massive ice observations during field work and high rates of surface subsidence particularly at the upper third of the rock glacier (cf. Fig. 10 in Kaufmann et al. 2007) causing unstable ground surface conditions (e.g. around the monitoring site DOV-UP-N in Fig. 2B). Therefore, this rock glacier seems to be primarily a talus-derived rock glacier although a small glacier might have existed some times in the past in the eastern part of the rooting zone. At the Hinteres Langtalkar Rock Glacier west of the study area it was shown that massive ice is widely absent at the lower and central part of this rock glaciers whereas massive sedimentary exists at its upper part (Kellerer-Pirklbauer and

Kaufmann, 2017). Similarly, two cores drilled in an active rock glacier in northern Italy (Krainer et al., 2015) reveal a higher average ice content at the higher-elevated drilling site (43 vol. %) compared to the lower one (22 vol. %) indicating a tendency of increasing ice content at higher elevations of a rock glacier.

4.4 Rock glacier age estimation

4.4.1 The Schmidt-hammer exposure-age dating method and its application at Dösen Rock Glacier

A Schmidt-hammer is a light and portable instrument traditionally used for concrete stability testing by recording a rebound value (R-value) of a spring-loaded bolt impacting a surface. This method has been increasingly applied in glacial and periglacial studies for relative rock surface dating since the 1980s (Matthews and Shakesby, 1984; McCarroll, 1989). The obtained R-value gives a relative measure of the surface hardness and therefore provides information on the time since surface exposure and weathering. High values are indicative of a lower age and vice-versa.

At seven locations close to the central flow line of the rock glacier (SH1-SH7 in Fig 2B) measurements were carried out with an L-type Schmidt-hammer at the Dösen Rock Glacier. This measurement setup was selected because of the common assumption that blocks at the surface of a rock glacier are passively transported in a rather stable position from the talus slope at its rooting zone towards the rock glacier terminus. Therefore, the age of the blocks should be progressively older from the rooting zone towards the rock glacier front. Furthermore, one has to keep in mind that rock material at the front of an advancing rock glacier tumbles down and gets overridden by the advancing rock glacier. The surface of the rock glacier is therefore generally younger compared to the entire landform (Haeberli et al., 2003). Hence, surface ages of a rock glacier should be regarded as minimum ages of the landform. Additional measurements were carried out at three sites on two smaller rock glaciers and at one site on a terminal moraine of presumed Younger Dryas/YD age (Fig. 2A). 50 individual Schmidt-hammer measurements were carried out at each site calculating arithmetic means and 95% confidence intervals. The 95% confidence limits are indicative for statistically significant age differences (Shakesby et al., 2006). For detail regarding the Schmidt-hammer approach at this rock glacier see Kellerer-Pirklbauer (2008).

Results at Dösen Rock Glacier yielded mean R-values ranging from 29.7 at the Younger Dryas moraine (YDM) site (SH11) to 47.7 at the active talus (SH7) in the rooting zone of the rock glacier covering a R-value range of 18.0 (Fig. 9A,B). The 95% confidence limits are generally below ±1.00 R-value. A relatively steady decrease in R-values between the rooting zone of the rock glacier and its front has been revealed with statistically different R-values along the flow line and a total R-value difference of 12.3 (35.4 at SH1 vs. 47.7 at SH7). A step-like R-value pattern can be observed with similar values at adjacent sites (SH1 and SH2; SH3 and SH4; SH5 and SH6) contrasting to different values in between these pairs. This suggests alternating (step-wise) periods of rapid and slow rock glacier movement (Fig. 9A). This step-wise movement behavior is to some extent confirmed by findings by Krainer et al. (2015) who point out that intact rock glaciers do not move necessarily with constant flow velocities, but periods with higher and lower activity seem to alternate with periods of relatively inactivity.

4.4.2 Estimated age of Dösen Rock Glacier

The initiation of the Dösen Rock Glacier occurred after the Egesen advance in the early YD period as suggested by the existence of YD moraines downvalley of the Dösen Rock Glacier. The stabilization age of the early YD moraines is 10Be-dated to around 12.3-12.4 ka for western Austria (Kerschner and Ivy-Ochs, 2007), to 12.8 ka for the Schober Mountains (Reitner et al. 2016) located 30 km W of the Dösen Valley, and to 12.6 for the Hoher Sonnblick area (Bichler et al., 2016) located 25 km WNW of our study area. Thus, the maximum and the minimum R-values in this study area can be absolute dated to sometimes around 12.5 ka at the YDM site and ~0 a at the active talus site in the rooting zone of the rock glacier, respectively. By using a linear relationship between R-value and time considering the YD moraine- and talus-ages, a tentative age-calibration curve with a mean decrease of 1.46 R-value per 1 ka can be inferred (Fig. 9C). This method (Skakesby et al., 2006) allows investigating the size of error of the absolute age estimates as derived by the linear relationship. Error limits for the predicted ages are determined separately for the YD and the talus site using the corresponding 95% confidence intervals. This approach yields error limits of ±607 years for YD site and ±774 years for the talus site. Thus a predicted age error of ca. ±0.7 ka for all sites should be considered.

The regression line calculated for Dösen Rock Glacier depicted in Figure 9C indicates that this rock glacier started to form sometimes before 8.4 ka BP (estimated age of the lowest Schmidt-hammer at the rock glacier surface SH1). During the entire evolution period of the rock glacier phases with lower and higher velocity rates seem to have alternated as indicated by the results depicted in Figure 9A. Recent velocity data from the rock glacier show mean annual velocity rates of between 13.4 cm/a and 53.6 cm/a during the period 1954–2016 (Fig. 7). If these velocities are taken as constant (which is questionable) over time and combined with the length of the rock glacier (950m), rough age estimates of 1.8-7.1 ka can be calculated. These estimated ages are between substantially lower to similar if compared with the age estimate based on the Schmidt-hammer approach. The results presented here are well in general accordance to absolute dating results of active rock glacier as for instance shown by Krainer et al. (2015) who dated 10,300-year old ice near the base of the Lazaun Rock Glacier.

5. Conclusions

The research activities and achievements accomplished at the Dösen Rock Glacier during the last decades can be summarized as follows:

- Field-based research activities at Dösen Rock Glacier have been initiated within a project running in 1993-1996 that focused on geomorphological description, internal structure and permafrost content, rock glacier movement, and permafrost distribution. Annual geodetic measurements initiated during that time are still ongoing providing valuable long-term rock glacier velocity data.
- A network of automatic devices was installed in 2006 which is still operating. This network automatically collects data relevant for understanding the rock glacier system and climate change-impacts.
- Geodetic and photogrammetric measurements regarding rock glacier velocity and surface changes have been successfully continued over the years. The utility of the Synthetic Aperture Radar interferometry method for rock glacier monitoring was tested. Additional geophysical studies have been performed since then allowing an improved characterization of the internal structure of the rock glacier.
- Ground temperature and air temperature monitoring clearly reveals a statistically significant warming during the period 2007-2015 at the rock glacier. High interannual variations are common for both air and ground temperature. In particular the seasonal snow cover strongly influences the ground thermal regime.
- Horizontal flow velocities at the rock glacier surface varied substantially during the last six decades with lowest values around the 1970s until the early 1990s. This lower velocity values are related to cooler climatic conditions. The highest values are related to a warmer permafrost conditions and a higher content of liquid water in the rock glacier body lubricating the rock glacier system.
- Five different types of geophysical methods (seismic refraction, ground penetrating radar, electromagnetics, electrical resistivity tomography, and very low frequency electromagnetic measurements) were applied so far. Results indicate that permafrost exists below a several meter thick active layer. The active layer consists of an upper blocky surface layer with open pore space and a lower layer with meltwater and finer-grained material covering the permafrost body. The permafrost thickness is in the range of 10-40 m whereas the total thickness of the rock glacier is in the order of 30-40 m. The existence of massive sedimentary ice – as known from other sites – has not been proven so far. However, field and remote sensing-based evidences suggest the existence of such massive sedimentary ice bodies.
- The application of the Schmidt-hammer exposure-age dating method revealed that rock glacier initiation occurred in the early Holocene and the evolution lasted over a period of several thousand years with apparent periods of slower and faster movement. Present movement rates seem to be rather high compared to the mean velocities during the Holocene.
- Research activities at Dösen Rock Glacier achieved a series of new or at least deeper insights (e.g. kinematics, temperature, climate, possible age) in rock glacier science. However, research at this rock glacier should be continued focusing on, e.g. more detailed analyses of the internal structure, on short-term velocity changes, on the interaction between climate, hydrology and such short-term velocity changes, on modelling of the rock glacier creep, and finally on the potential future evolution of such landforms in a warming climate.

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