A new rock glacier inventory of the eastern European Alps

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Abstract

Rock glaciers are striking features in high mountain environments indicating permafrost conditions during the period of formation and activity. Within the framework of the Alpine-Space-Project PermaNET, a new polygon-based inventory of rock glaciers has been elaborated comprising the alpine areas of central and eastern Austria as part of an inventory covering the entire European Alps. The establishment of the new inventory was primarily based on an existing point-based inventory which was re-evaluated and amplified using currently available orthophotos, different digital elevation models and derivatives thereof. Further topographic information such as for instance elevation of lower and upper limits, maximum length and width, area and activity degree were gathered in an attribute table. All different parameters were analysed regarding the entire investigation area, differences between the relevant federal provinces of Austria and between the single mountain regions. These regions were distinguished by differences of mainly climate, topography and present glacier extent. As a result, data on altogether 1647 rock glacier polygons or units were gathered in the inventory comprising 1430 monomorphic rock glaciers (rock glacier with one unit/generation) and 98 polymorphic rock glaciers (with two to five distinct units). 1300 rock glacier units have been classified as relict (no permafrost anymore) covering 97.7 km² in total, whereas 347 units with a total area of 21.3 km² as intact (containing permafrost) ones. The mean lower limit of relict rock glacier units with a mean size of 0.075 km2 is situated at 2102 m a.s.l.. For the intact ones the respective values are 0.061 km² and 2515 m a.s.l.. Interpreting the results leads to the conclusion that the dominance of relict rock glaciers is due to fact that the summit elevations decrease towards the east thus restricting current permafrost occurrence to limited areas. Furthermore, “normal glaciers” still occupy rock glacier favourable sites particularly in central Austria. Intact rock glaciers usually developed over millennia primarily during the Holocene. In contrast, relict rock glaciers began to form during and after the Lateglacial deglaciation of cirques which generally occurred earlier in the east compared to the west of the investigated area. However, slope orientation was relevant for the deglaciation pattern causing formation of older rock glaciers on „warm“ slopes whereas on “cold” slopes rock glaciers are possibly of younger age. Although a comprehensive overview on rock glacier distribution can be given by our study, drawbacks of this study are the varying quality of information sources, the absence of data on surface motion (except for single rock glaciers) and missing absolute dating of rock glacier surfaces.

Blockgletscher sind herausragende Elemente der Hochgebirgslandschaft und zeigen Permafrostbedingungen während ihrer Bildungs- und Aktivitätszeit an. Im Rahmen des Alpine-Space-Projektes PermaNET wurde ein neues polygon-basiertes Inventar der Blockgletscher für die österreichischen Alpen östlich von Nordtirol als Beitrag zu einem gesamtalpinen Inventar erarbeitet. Die Methodik umfasste die Reevaluierung und Erweiterung eines schon bestehenden punkt-basierten Inventars mit aktuell erhältlichen Orthophotos, neueren digitalen Geländemodellen sowie numerischen Ableitungen daraus. Daneben wurde eine Reihe von topographischen Informationen in einer Attributtabelle gesammelt wie beispielsweise Höhe der Unter- und Obergrenze, maximale Länge und Breite, Fläche sowie Aktivitätsgrad. Die verschiedenen Parameter wurden für das gesamte Untersuchungsgebiet sowie bezüglich der Unterschiede zwischen den betreffenden österreichischen Bundesländern und zwischen einzelnen Gebirgsgruppen getrennt analysiert. Dabei unterscheiden sich die einzelnen Gebirgsgruppen voneinander vor allem durch Klima, Topographie und rezente Vergletscherung. Als Ergebnis konnten Daten von 1647 Blockgletscherpolygonen in das Inventar eingebracht werden. Diese bilden 1430 einfach aufgebaute monomorphe Blockgletscher sowie 98 komplexe, aus zwei oder mehreren Polygonen bestehende polymorphe Blockgletscher. 1300 der Blockgletscherpolygone mit einer Gesamtfläche von 97,7 km² wurden als reliktisch (Permafrost bereits abgetaut), 347 mit einer Gesamtfläche von 21,3 km² als intakt (gegenwärtig noch Permafrostbedingungen) klassifiziert. Die mittlere Untergrenze der reliktischen Blockgletscher, welche durchschnittlich eine Fläche von 0,075 km² bedecken, liegt in 2102 m ü.A., für die intakten Blockgletscher lauten diese Werte 0,061 km2 und 2515 m ü.A.. Die Interpretation der Ergebnisse führt zum Schluss, dass die Dominanz der reliktischen Blockgletscher mit den nach Osten abnehmenden Gipfelhöhen erklärt werden kann, welche rezenten Permafrost nur auf kleinen Flächen ermöglichen. Intakte Blockgletscher entwickelten sich gewöhnlich über Jahrtausende während des Holozäns, reliktische schon in früheren Phasen seit dem Eisfreiwerden der Kare im Spätglazial, was im Osten generell früher als im Westen geschah. Dieses regionale Muster wird aber durch lokale Gegebenheiten wesentlich verändert, wobei warme, eher in südlicher Richtung ausgerichtete Hangbereiche früher eine Blockgletschergenese zuließen als kalte nordex-

ponierte Bereiche. Obwohl die Arbeit einen guten Überblick über die Blockgletscher-Verbreitung gibt, bleiben als Nachteile die unterschiedliche Qualität der Quellenlage sowie das Fehlen von Daten zur Kriechbewegung (mit Ausnahme einzelner Blockgletscher) und von absoluten Datierungen der Blockgletscher-Oberflächen bestehen.

1. Introduction

Active rock glaciers are lobate or tongue-shaped large-scale creep features in permafrost environments consisting of perennially frozen debris material (talus and/or till) often supersaturated with interstitial ice and ice lenses. This material moves slowly downslope by creep thereby forming often bended transversal ridges and furrows on its lower part and parallel ridges on its upper part. The movement is a consequence of the deformation of the ice contained in them. Therefore, active rock glaciers are features of cohesive flow that are in motion over long periods, i.e. >10^2 to >10^3 a (Barsch, 1996). Spatial extent, internal structure, shape and surface geomorphology of rock glaciers are the cumulative result of their entire evolution period. When creeping stops active rock glaciers turn into inactive ones, which is either due to climate warming (climatic inactive) or due to topographical and/or reduced debris-supply reasons (dynamic inactive). Both active and inactive rock glaciers contain permafrost and are therefore considered as intact rock glaciers. Relict rock glaciers are permafrost free at present and are characterised by collapse structures at their surface. A fourth type is a pseudo-relict rock glacier which is an intermediate type between a relict and a climatic inactive rock glacier with locally isolated patches of permafrost (Barsch, 1996; Kellerer-Pirklbauer, 2008a). Rock glaciers are common landforms in the Austrian Alps with relict rock glaciers at lower elevations and still active ones in higher areas related to different formation periods during the Quaternary.

Little information is available about the possible occurrence of rock glaciers at very low elevations possibly of Last Glacial Maximum (LGM) or earliest Lateglacial age except for few evidences as for instance the valley Hauergraben near Grünau/Almtal (Upper Austria, 48°52’N, 13°56’E) described by van Husen (1996) with a lower limit at 520 m a.s.l.. However, the rock glacier character of these features remains uncertain: Besides the surface topography untypical of rock glaciers the sediments might also be the remnants of mass movement events which would better explain their distance from the root zone which is situated some 1.5-2 km upvalley without any visible connection. This is a morphological situation which could not be found at any rock glacier of the entire inventory.

Rock glacier inventoring in Austria was started as early as 1988 by G. K. Lieb, first comprising the Austrian part of the Hohe Tauern Range (first publication in Lieb 1991) and subsequently expanded over the entire area shown in Fig. 1. Finally, this point-based inventory comprised a total of 1451 rock glaciers and was comprehensively published by Lieb (1996). Further statistical analysis was carried out by Lieb (1998a). The inventory was also presented on the CAPS Version 1.0 CD-ROM in June 1998 (Lieb 1998b) edited by the International Permafrost Association (IPA). Generally, the inventory was elaborated by visual interpretation of aerial photographs at different spatial scales and ages. Further sources were analogue drawings of rock glaciers in topographical maps at scales 1:25,000 or 1:50,000 and interpolating the relevant topographic metadata from these maps.

Within the Alpine Space project “PermaNET – Permafrost long-term monitoring network” it was aimed to create an alpine wide polygon-based rock glacier inventory which was widely successfully achieved (Cremonese et al., 2011). Within this PermaNET research activity, the authors of the present paper elaborated a new polygon-based inventory for Central and Eastern Austria published as Lieb et al. (2010) primarily based on the point-based inventory described above. The aim of this study is to present the methods, database and to summarize the results of the new inventory.

2. The investigated area and its climatic evolution

The investigated area is located in central and eastern Aus-

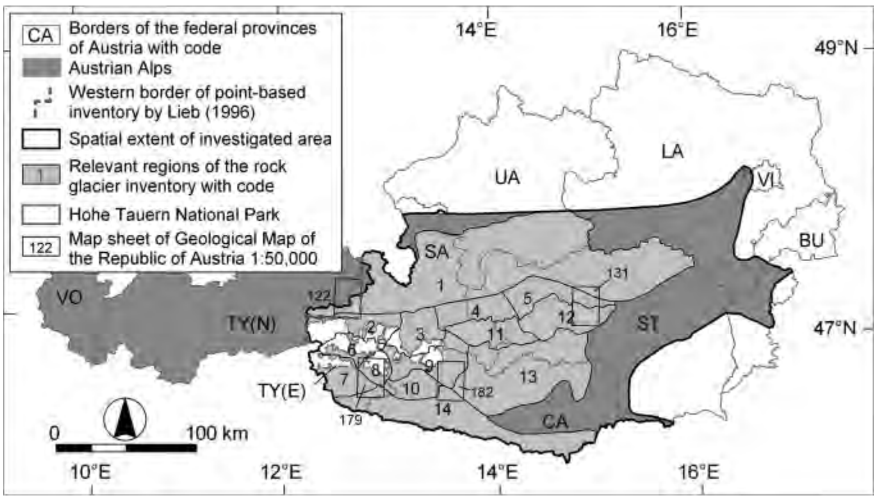

Figure 1: The spatial extent of the entire area considered in the compilation of the polygon-based rock glacier inventory and its relevant regions with rock glacier occurrence presented here. The western border of the point-based rock glacier inventory by Lieb (1996) as well as the spatial extent of relevant Geological Maps of the Republic of Austria at scale 1:50.000 and the Hohe Tauern National Park are indicated. For Abbreviations of relevant regions see Table 1. Abbreviations of federal provinces: VO=Vorarlberg, TY=Tyrol (N=North, E=East), SA=Salzburg, CA=Carinthia, UA=Upper Austria, LA=Lower Austria, ST=Styria, BU=Burgenland, VI=Vienna.

tria between about latitude 46°23'N and 48°17'N as well as longitude 12°06'E and 16°31'E and covers a total area of about 40,000 km². The highest peak in this region is Mt. Großglockner with 3798 m a.s.l. located at 47°04'30''N and 12°41'40''E, the lower elevation boundary of the mountain area considered in this study was 1000 m a.s.l. as described in the methods chapter.

At the LGM about 25-18 ka BP and hence during the Wuermian glaciation occurring during Oxygen Isotope Stage (OIS) 2, a large interconnected glacier system consisting of ice domes, ice streams and piedmont glaciers covered a substantial part of the Austrian Alps. The terminal moraines of these LGM glaciers in the European Alps stabilised at about 20 ka BP (Ivy-Ochs et al., 2004). Longitude 15°E marked approximately the easternmost limit of this interconnected LGM-glacier system within Austria (Fig. 2). Only rather small local glaciers existed further to the east and large areas in higher elevations experienced periglacial and permafrost conditions even during the LGM. For comparison, the earlier Riss glaciation (maximum at OIS6) was more extensive in Austria and the interconnected glacier system reached further to the east (van Husen, 2000). This general glaciation pattern of the Austrian Alps was caused by the combined effect of lower mountains and less precipitation/higher continentality from central Austria towards the east.

In the Lateglacial period following the LGM, the system of ice domes, ice streams and piedmont glaciers collapsed to a dendritic glacier system, then finally to valley and cirque glaciers. The general deglaciation was interrupted by a number of successively smaller re-advance periods ("stadials") which were usually not single-phased (e.g. Egesen I to III substages; Sailer and Kerschner, 1999). According to Kerschner and Ivy-Ochs (2007) as well as Kerschner (2009), major Alpine Lateglacial readvances relevant for the Eastern Alps were Gschnitz (>15.4 ka BP; during the Heinrich 1 ice rafting event/Greenland Stadial 2a according to the GRIP/Greenland Ice Core Project timescale), Senders/Clavadel, Daun, and Egesen (maximum advance at ca. 12.3-12.4 ka BP; during the Early Younger Dryas/Greenland Stadial 1). According to the same authors, further notable stadials which substantially exceeded the glacier size during the Little Ice Age maximum (about 1850 AD) were Kartell (ca. 10.8 ka BP; during the Preboreal Oscillation) and Kromer (ca. 8.4 ka BP; during the Central European cold phase 3). Both occurred after 11.5 ka BP, hence already during the Holocene.

During the Lateglacial period, rock glaciers were able to form earlier in already deglaciated cirques and valley heads in the eastern part of Austria compared to the still glaciated cirques further west (e.g. Nagl, 1976). However, this general pattern is modified at each mountain range as follows: rock glaciers of older age often predominate on slopes exposed to the south because at the same time colder slopes in more radiation-sheltered locations were still covered by glaciers. In a later stage during the Lateglacial and/or Holocene periods, rock glaciers also formed on these colder slopes after deglaciation. Thus, rock glacier fronts at identical elevation but different slope aspects might be of different age (Kellerer-Pirklbauer, 2007). Further climate warming during the Holocene caused widespread permafrost degradation at lower elevations and turned many rock glaciers into relict ones.

3. Methods and database

3.1 Database

The point-based inventory of rock glaciers in Central and Eastern Austria (see Fig. 1 for spatial extent) published in Lieb (1996, 1998b) as well as the manuscript maps which were drawn between 1988 and 1996 showing the generalized shapes of the rock glaciers were used as a basis for setting up the new polygon-based inventory presented here. Furthermore, for some areas additional existing digital rock glacier mappings were provided by the Geological Survey of Austria (J. Reitner, Th. Untersweg). Particularly, rock glacier polygons of the map sheets Nr. 122, 131, 179 and 182 of the Geological Map of the Republic of Austria at scale 1:50.000 (see Fig. 1) were used. The source of the rock glacier polygons in these map sheets are largely based on the old inventory of Lieb (1996) or of Untersweg and Schwendt (1994, 1995) and Kellerer-Pirklbauer (2007).

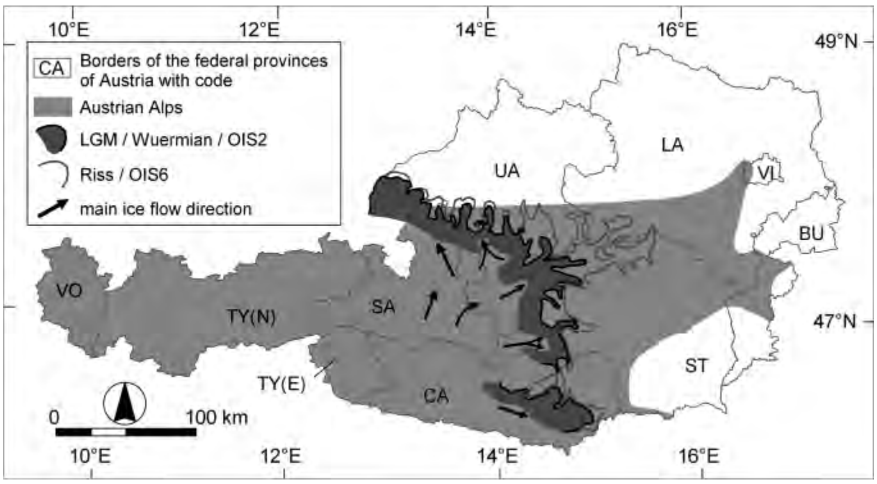

Figure 2: The Austrian Alps and its foreland depicting the maximum eastern extent of the main glacier systems and their general flow direction during the ultimate (LGM / Wuermian / Oxygen Isotopic Stage 2) and penultimate (Riss / OIS6) glaciations. Small local glaciers to the east of the main glacier systems are not indicated. For abbreviations of federal provinces see Fig. 1. Glacier extent based on van Husen (2000).

3.2 Study regions identification

The inventory covers the mountain areas situated above 1000 m a.s.l. of the entire Federal Provinces of Styria, Salzburg, Upper Austria and Carinthia. Of the Federal Pro-vince of Tyrol, the entire county of Lienz (=Eastern Tyrol) was mapped (Fig. 1). No rock glaciers were found in the Federal Province of Lower Austria. The Federal Provinces of Vienna and Burgenland do not reach altitudes of 1000 m a.s.l. On the one hand, this altitudinal constraint is due to the method of visual interpretation of orthophotos which does not allow recognizing rock glaciers under a dense forest cover at lower elevation. On the other hand, the focus in the analysis was laid on rock glaciers which evolved during the Lateglacial and Holocene period.

The western margin of the study area of the new polygon-based inventory differs slightly to the one of the point-based inventory published by Lieb (1996). In the new inventory, the border of the Federal Province of Salzburg was taken as the western limit. In contrast, in the old inventory borders were related to sheet lines of the official national topographical maps at scale 1:50,000 (Fig. 1).

In a further step, the investigated area was subdivided into 14 different regions where rock glaciers have been mapped widely following the previously used division by Lieb (1996). These 14 regions cover an area of 26,654 km² in total and range from 396 km² (R8) to 9860 km² (R1). This division is a compromise between the traditional division of the Eastern Alps (e.g. Grassler, 1984), different climatic regions (e.g. north of the main drainage divide versus south of it), and an attempt to equally distribute the number of rock glaciers to the individual regions. Table 1 lists all 14 regions with information about mountain ranges, related river catchments and surface area.

3.3 Rock glacier polygon delineation

A first step was to check every single rock glacier of the first inventory by Lieb (1996) and to map its outline as precisely as possible in ArcGIS 10 thereby digitising rock glacier polygons. This was done by analysing the available digital elevation models (DEM) and DEM-derived products such as slope and hillshade maps. The generation of up to four different hillshade maps per DEM (Table 2) was carried out by using multiple illumination azimuths (NE, SE, SW, NW). This allows better interpretation and delineation of relevant landforms (e. g. Bell et al., 2012). Orthophotos were used wherever available as well as complementary Google Earth satellite images (Table 2). In many cases field knowledge (based on numerous hiking trips and respective field notes and photographs in the investigated area during the last decades) aided a better delineation of rock glaciers. Furthermore, the entire areas covered by orthophotos were visually scanned in order to detect rock glaciers which might have been overlooked or misinterpreted in the old point-based inventory due to the lower quality and smaller scale of the aerial photographs used earlier. However, only in a small number of cases, the elimination or new consideration of rock glaciers in the inventory was necessary.

Generally only rock glaciers with both length and width exceeding 100 m were considered apart from a few very pronounced, but slightly smaller ones. For rock glaciers where it was possible to distinguish between different rock glacier generations or units, more than one rock glacier polygon was mapped. Such rock glaciers are termed as "multiunit" (Barsch,

Code	Region	Mountain range (drainage catchment)	Area (km²)
R1	Northern Alps	KB (sa), SS (sa), BA (sa), DS (en, tr)	9860
R2	Western Hohe Tauern Range, north	ZA (zi), VE (sa), GR (sa), GG (sa)	1104
R3	Eastern Hohe Tauern Range, north	SO (sa), AH (sa)	943
R4	Western Niedere Tauern Range, north	RT (sa, en), ST (en)	902
R5	Eastern Niedere Tauern Range, north	WT (en), SK (en)	985
R6	Western Hohe Tauern Range, south	VE (is), GR (is), GG (is, mo)	590
R7	Defereggen Mountains (wider sense)	DA (dr), RG	900
R8	Schober Mountains	SC (dr)	396
R9	Eastern Hohe Tauern Range, south	SO (mo), AH (mo,li,mu)	1253
R10	Kreuzeck Mountains	KR (dr)	605
R11	Western Niedere Tauern Range, south	RT (mu), ST (mu)	929
R12	Eastern Niedere Tauern Range, south	WT (mu), SK (mu), EA (mu)	1265
R13	Gurktaler and Seetaler Mountains	GU (gk), SE (la)	3927
R14	Southern Alps	KA (dr, ga), LD (dr)	2997

Table 1: Division of the investigated area into relevant regions with information about mountain ranges, related river catchments and surface area. For location and delineation of regions see Fig. 1. Mountain ranges: AH=Ankogel Mountains, BA=Berchtesgadener Alps, DA=Defereggen Alps, DS=Dachstein Mountains, GG=Glockner Mountains, GR=Granatspitz Mountains, GU=Gurktaler Mountains, KA=Carnic Alps, KB=Kitzbühler Alps, KR=Kreuzeck Mountains, LD=Lienzer Dolomiten, RG=Rieserferner Mountains, RT=Radstädter Tauern, SC=Schober Mountains, SE=Seetaler Alps, SK=Seckauer Tauern, SO=Goldberg Mountains, SS=Salzburger Schieferalpen, ST=Schladminger Tauern, VE=Venediger Mountains, WT=Wölzer Tauern, ZA=Zillertaler Alps; drainage catchments: dr=Drau, en=Enns, ga=Gail, gk=Gurk, is=Isel, la=Lavant, li=Lieser, mo=Möll, mu=Mur, sa=Salzach, tr=Traun, zi=Ziller.

1996) or "polymorphic" (Frauenfelder and Kääb, 2000) rock glaciers. This possibility was considered in the labelling and attribute table of the inventory (see Table 3 for details).

3.4 Rock glacier attribute table

For each polygon of the rock glacier inventory various additional parameters were collected and stored in an attribute table as it is common for such inventories (Cremonese et al., 2011). These parameters include information such as different topographical parameters (Fig. 3), type of rock glacier, location, person responsible for mapping, data source and coordinates (Table 3). For the topographical parameters different digital terrain models with a grid resolution of either 10 or 25 m formed the basis. In some cases only official topographical maps at scale 1:50,000 with 20 m equidistance between contour lines were available (Table 2).

The most striking methodological problem arises in determining the activity only by means of visual interpretation using rules of thumbs. Such a rule of thumb is for instance the reasonable assumption that frontal slopes of rock glaciers without vegetation are a sign of activity (Barsch, 1996). This of course is not state of the art, but except for single rock glaciers or limited areas where special permafrost studies have been carried out, no such information was available within the framework of PermaNET finances. In areas where permafrost knowledge existed – about a third of all rock glaciers mapped – this knowledge was used in elaborating the attribute table. For other areas, radar interferometry (e.g. Kenyi and Kaufmann, 2003) or multitemporal airborne laser scanning data (e.g. Abermann et al., 2010) would have been helpful detecting rock glacier

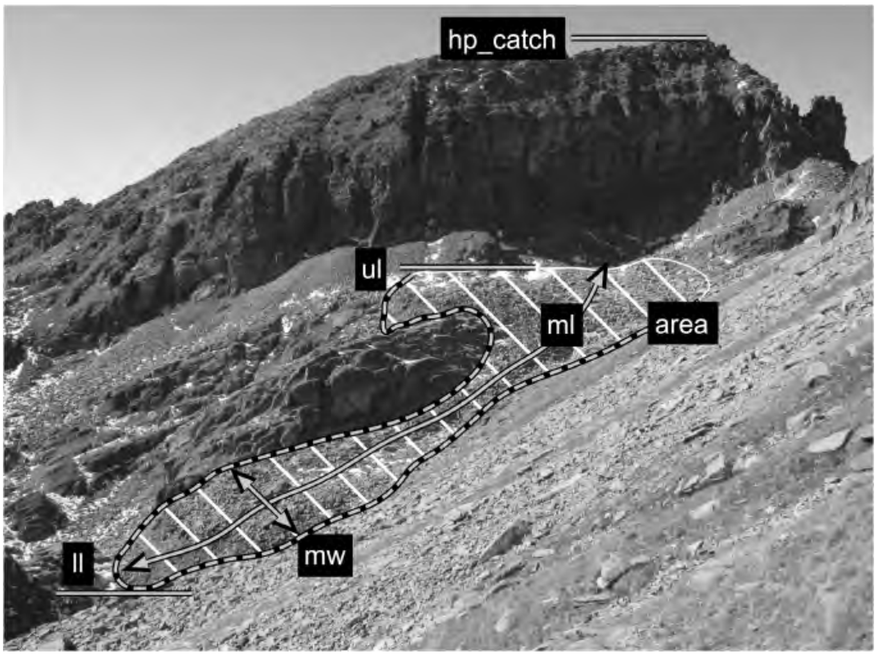

Figure 3: Different topographic attributes collected for each rock glacier exemplified for rock glacier "li5/se Rossalmscharte". Abbreviations of attributes: ll=lower limit of rock glacier; ul=upper limit of rock glacier; ml=maximum length; mw=maximum width; area=surface area of rock glacier; hp_catch= highest point of catchmen. See also Table 3. Photograph A. Kellerer-Pirklbauer.

Federal Province	Orthophotos/ satellite images	DEM/maps	Comments
Styria	Orthophotos fully available	10 m DEM available for entire province	complete re-evaluation of point-based inventory
Carinthia	Orthophotos available only for Hohe Tauern National Park; other areas by Google Earth images*	25 m DEM available for entire province	partial re-evaluation of point-based inventory
Salzburg	Orthophotos available only for Hohe Tauern National Park; other areas by Google Earth images*	25 m DEM available for entire province	partial re-evaluation of point-based inventory
Tyrol (Eastern)	Orthophotos available only for Hohe Tauern National Park; other areas by Google Earth images*	official topographical maps at scale 1:50,000	partial re-evaluation of point-based inventory
Upper Austria	Google Earth images	official topographical maps at scale 1:50,000	no relevant lack of information; only one rock glacier

Table 2: Availability of orthophotos and high-resolution digital elevation models (DEM) according to Federal Provinces. (*) Outside Hohe Tauern National Park Google Earth images were used in cases of uncertainties within the information of the old inventory. For spatial extent of Hohe Tauern National Park see Fig. 1.

Attribute	Explanation	Different classes/unit
rg_code	code of rock glacier polygon related to the drainage catchment and relative location. If a rock glacier consists of more than one distinct generation, the attributes "a", "b" and so on were added to the polygons	for codes of drainage catchments see Table 1; example for rock glacier with three generations:
		a=oldest/lower generation b=younger generation
		c=youngest generation
name	name of rock glacier is related to nearby topographical features such as for instance mountain summits. Partly further information as geographic direction form this feature	e.g. name "w Querlstein" means rock glacier to the west of the mountain Querlstein
mra	mountain range	for codes of mountain ranges see Table 1
asp	slope orientation	eight different aspect classes:
		N, NE, E, SE, S, SW, W, NW
ll	lower limit of rock glacier unit; elevation of lowest point of rock glacier unit at the terminus	m a.s.l. (accuracy - 5m)
ul	upper limit of rock glacier unit; elevation of highest point	m a.s.l. (accuracy - 5m)
ml	maximum length along the assumed (former) creeping direction	m (accuracy - 10m)
mw	maximum width perpendicular to length	m (accuracy - 10m)
rel_ml_mw	ratio between maximum length and maximum width	ratio
area	surface area of rock glacier unit	m² (accuracy - 100m²)
hp_catch	highest point of the catchment area of the rock glacier unit taken from official topographical maps	m a.s.l. (accuracy - 0m)
dif_ca_ll	difference between highest point of the catchment area and lower limit of the rock glacier unit	m (accuracy - 5m)
act	activity status of rock glacier unit	i=intact (active or inactive)
		r=relict
type	rock glacier with one or more generations; i.e. monomorph or polymorph sensu Frauenfelder and Kääb (2000); the attributes "a", "b" and so on were added as described under "rg_code"	m=monomorph
		p=polymorph
prov	federal province of Austria	CA=Carinthia
		SA=Salzburg
		ST=Styria
		TY-E=Tyrol (East)
		UA=Upper Austria
reg	different regions of the investigated area	See Table 1 and Fig. 1
delpers	person or institution who was involved in the rock glacier mapping	GKL=Gerhard Karl Lieb
		AKP=Andreas Kellerer-Pirklbauer
		HK=Harald Kleinferchner
		GBA=Austrian Geological Service
		or combination of above
delsour	base data for mapping the rock glacier and compiling topographical information for the attribute table	dem=digital elevation model
		map=official topographical map
		air=orthophoto/google earth
		or combination of above
x_coord	x-coordinate of central point of polygon	Bundesmeldenetz M34
y_coord	y-coordinate of central point of polygon	Bundesmeldenetz M34

Table 3: Inventory structure in the attribute table with explanation and information about different classes, units and accuracy. See also Fig. 3.

movement. As a consequence, we did not differentiate between active and inactive rock glaciers and used the class "intact" instead. This can also be justified by the fact that both types contain permafrost at present. In a final step different conventional statistical analyses were carried out using the elaborated rock glacier inventory.

4. Results

We elaborated a rock glacier inventory consisting of 1647 rock glacier polygons or rock glacier units (Fig. 4). Because of the better scale of the currently available orthophotos, the polygons of the rock glaciers were mapped in more detail than previously. The total number of rock glaciers differs only slightly compared to Lieb (1996): 1451 in the old inventory versus 1528 rock glaciers consisting of 1647 rock glacier units in the new one. About 79% of the rock glacier units are regarded as relict (n=1300) covering 97.7 km², whereas only 21% as intact (n=347) covering 21.3 km².

The most complex rock glacier is li13a-e (Tandlalm) located in the federal province of Carinthia in region R9 covering 0.9 km². This rock glacier has also the lowest lower limit (1240 m a.s.l.) of all mapped rock glacier units. The largest polymorphic rock glacier is mu275a-d (ne Hochreichart/Reichartkar) occupying a total area of 1.26 km², terminating at 1520 m a.s.l. The easternmost and concurrently northernmost alpine rock glacier is mz2 (n Heukuppe) located at N47°41'37" and E15°41' 37''. This relict monomorphic rock glacier terminates at 1630 m a.s.l. and covers an area of 29,000 m².

4.1 Rock glaciers complexity and activity

By far most of the rock glacier units (94%) form monomorphic rock glaciers, hence consisting of only one polygon (Fig. 5). In contrasts, 98 polymorphic rock glaciers (6%) with two or more different distinct units were mapped. Some of these rock glaciers consist of intact (higher elevation with permafrost) and relict (lower elevation without permafrost) rock glacier units. 59 polymorphic rock glaciers consist of two distinct polygons, 37 of three different polygons, one of four, and finally one of five different units. About 80% of all intact rock glacier units occur in Carinthia and Eastern Tyrol. Contrary, by far most of the relict rock glacier units (31%) were

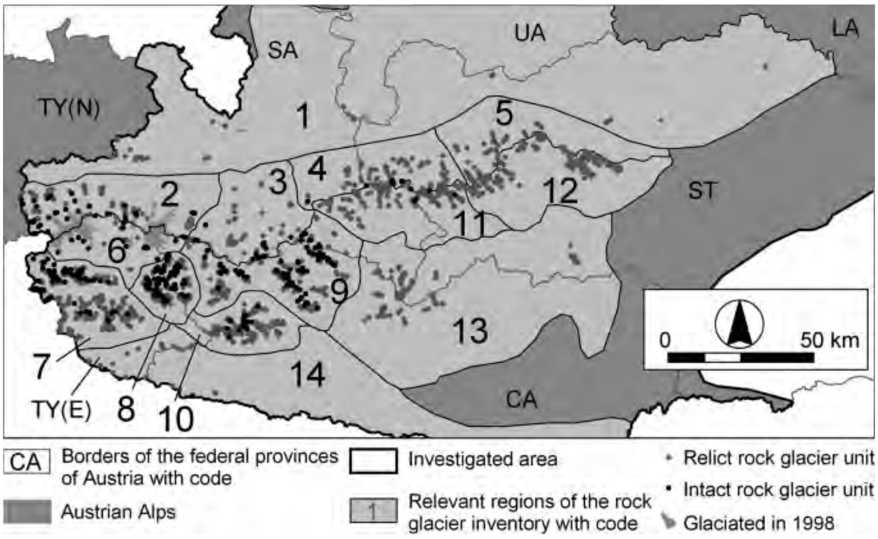

Figure 4: The new polygon-based rock glacier inventory of central and eastern Austria comprising 1647 rock glacier polygons or units, thereof 347 units are intact and 1300 are relict. The spatial extent of the glaciated areas in 1998 is based on the latest glacier inventory of Austria (Lambrecht and Kuhn, 2007).

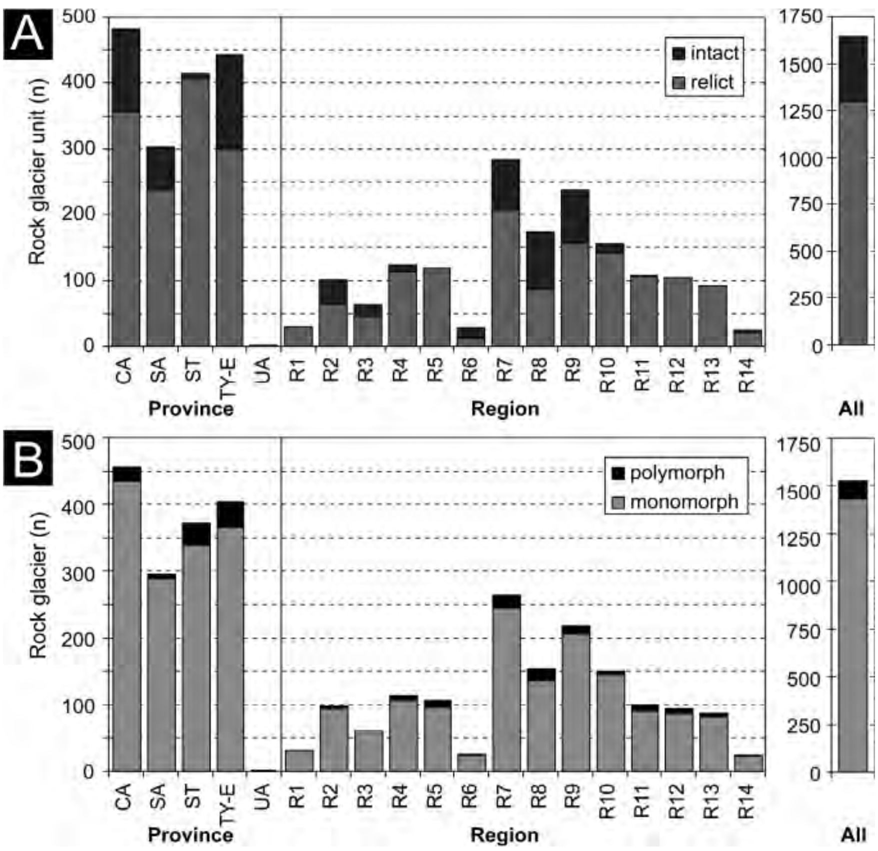

Figure 5: Geographic distribution of relict and intact rock glacier units (A) as well as of monomorphic and polymorphic rock glaciers (B) in the entire investigated area, the five relevant Austrian Federal Provinces (or parts of it for Tyrol) and, respectively, in the 14 different study regions.

mapped in Styria followed by Carinthia (27%) and Eastern Tyrol (23%). Focusing on the complexity of the mapped rock glaciers in the different provinces, most polymorphic rock glaciers are found in Eastern Tyrol (38%) and Styria (35%).

Comparing the 14 different investigated regions, most rock glacier units were mapped in region R7 (17% of all rock glacier units) followed by region R9 (14%). Of very little importance regarding rock glacier occurrence are the three regions R1, R6 and R14 (Fig. 5). Furthermore, no intact rock glacier units were mapped in the three regions R5, R12 and R13 due to low elevations. Monomorphic rock glaciers dominate in all 14 regions. In region R8, however, 11% of all mapped rock glaciers are polymorphic hinting a more complex evolution of the rock glaciers in this region. Complex polymorphic rock glaciers are absent in R1 and rare in R2, R3 and R10 (Fig. 5).

Two regions in the central, more continental part are of particular interest regarding the ratio between relict and intact rock glacier units. In only one region (R6) the number of intact rock glacier units exceeds the number of relict ones although large areas suitable for intact rock glaciers are covered by glaciers. Furthermore, in R8 the number of intact rock glacier units equals that of relict ones. In all other regions relict rock glacier units clearly dominate, in particular in the northern, eastern und south-eastern part of the investigated area (R1, R5, R11-R14). Intact rock glacier units are of similar mean size in Carinthia, Salzburg and Eastern Tyrol. Only those in Styria are substantially smaller which can be explained by unsuitable topographic conditions for the formation of larger

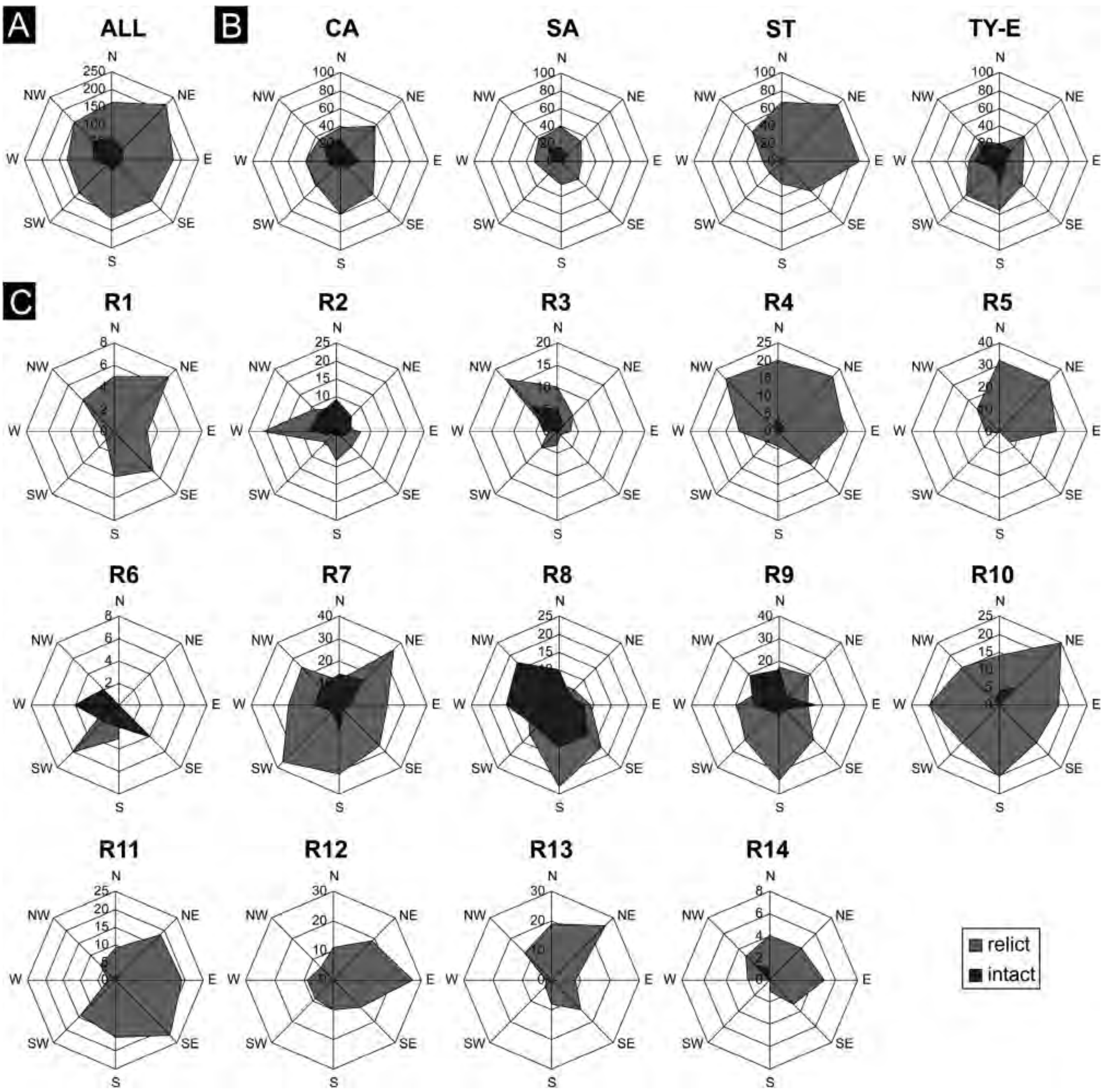

Figure 6: Rock glacier units and their relationship to slope orientation for the entire investigated area (A), the four federal provinces (B), and the 14 different study regions. Note the different scale for A, B and C. Furthermore, for better visibility the scale varies also between the regions in C.

Province/ Region (n)	asp	ll (m asl)	ul (m asl)	ml (m)	mw (m)	rel_ml_mw (ratio)	area (m²)	hp_catch (m asl)	dif_ca_ll (m)
	Parameter of relict rock glacier units (n=1300)								
CA (357)	S	2176	2323	385	230	1.82	70,720	2511	334
SA (237)	N	2047	2183	382	247	1.68	75,662	2401	354
ST (406)	NE	1900	2028	383	249	1.70	77,475	2264	364
TY-E (299)	S	2331	2476	399	248	1.82	76,847	2682	351
UA (1)	NE	1680	1800	340	215	1.58	56,852	2415	735
R1 (30)	NE	1798	1948	419	249	1.81	82,648	2182	384
R2 (63)	W	2160	2298	384	239	1.75	71,932	2525	365
R3 (46)	NW	2108	2244	341	238	1.57	64,828	2412	305
R4 (114)	NE	1973	2091	297	215	1.59	50,793	2325	352
R5 (118)	N+NE	1823	1955	407	263	1.74	86,805	2188	365
R6 (12)	SW	2310	2471	451	258	1.79	87,305	2754	444
R7 (208)	SW	2354	2496	394	243	1.85	72,978	2673	319
R8 (87)	S	2292	2444	418	243	1.92	80,639	2702	409
R9 (156)	S	2208	2367	423	238	1.93	80,171	2606	398
R10 (141)	NE	2182	2315	340	220	1.71	59,736	2464	283
R11 (106)	SE	2009	2142	426	243	1.89	81,334	2422	413
R12 (104)	E	1850	1978	429	267	1.72	95,335	2226	376
R13 (93)	NE	1985	2121	364	270	1.45	78,143	2254	269
R14 (22)	E	2123	2246	354	271	1.48	75,717	2466	344
mean	NE	2102	2240	387	243	1.76	75,129	2453	351

Province/ Region (n)	asp	ll (m asl)	ul (m asl)	ml (m)	mw (m)	rel_ml_mw (ratio)	area (m²)	hp_catch (m asl)	dif_ca_ll (m)
	Parameter of intact rock glacier units (n=347)								
CA (126)	N+NW	2492	2638	342	213	1.73	58,233	2837	345
SA (67)	NW	2412	2570	363	228	1.69	66,751	2766	354
ST (9)	N	2357	2448	194	174	1.22	27,488	2602	245
TY-E (145)	W	2592	2737	362	231	1.73	63,542	2940	348
UA (0)	-	-	-	-	-	-	-	-	-
R1 (1)	SE	2420	2500	330	265	1.25	61,662	2579	159
R2 (38)	N	2429	2612	394	218	1.89	70,535	2830	401
R3 (18)	NW	2400	2544	342	243	1.51	64,854	2675	275
R4 (10)	N	2336	2424	186	177	1.16	27,576	2593	258
R5 (0)	-	-	-	-	-	-	-	-	-
R6 (16)	W+SE	2640	2808	460	237	1.93	85,171	3027	388
R7 (76)	NE	2600	2737	323	227	1.62	55,586	2912	312
R8 (86)	NW	2582	2739	386	220	1.95	64,588	2973	390
R9 (81)	NW	2465	2608	345	234	1.57	64,122	2812	346
R10 (15)	NE	2392	2511	272	175	1.64	40,122	2605	213
R11 (3)	N	2333	2408	197	147	1.34	20,868	2656	323
R12 (0)	-	-	-	-	-	-	-	-	-
R13 (0)	-	-	-	-	-	-	-	-	-
R14 (3)	NW	2287	2370	203	155	1.25	28,469	2693	407
mean	NW	2515	2661	351	222	1.71	61,299	2860	345

rock glacier units in this province.

4.2 Rock glaciers aspect

Regarding slope aspect and rock glacier occurrence, most relict rock glaciers units are found in the NE aspect (n=220), whereas most intact rock glaciers are facing NW (n=72) (Fig. 6A, Table 4). If the four different federal provinces are analysed separately, the results are more heterogeneous (Fig. 6B). Most relict rock glacier units in Styria are found on NE- (n=91) and E-facing (n=88) slopes, in Carinthia and Eastern Tyrol on S-facing slopes and in Salzburg on N-facing slopes. Most intact rock glacier units in Styria are located on N-facing slopes, in Carinthia equally on N and NW-facing slopes, in Salzburg on NW-facing slopes and in Eastern Tyrol on W-facing slopes.

The slope orientation pattern is more diverse when considering the 14 different investigated regions separately (Fig. 6C, Table 4). In six of the 14 regions the highest number of relict rock glacier units is facing generally towards north (NW, N, NE). On the opposite, in five regions the dominant aspect is generally south (SE, S, SW). The three remaining regions mainly face either towards W (R2) or E (R12, R14).

4.3 Lower and upper limits of rock glaciers

The lower limits of rock glacier units are listed in Table 4. Furthermore, Fig. 7A depicts box plot diagrams showing the sample minimum, lower quartile, median, upper quartile, sample maximum as well as outliers. The mean (in Table 4) and median (in Fig. 7A) of the lower limit clearly differentiate between relict and intact rock glacier units in all analysed areas as expected. The mean for relict rock glacier units is located at 2102 m a.s.l., hence 413 m lower than the mean lower limit of the intact ones.

In general, the lowest relict rock glacier fronts are found in Styria and Salzburg (apart from Upper Austria with only one rock glacier unit terminating at 1680 m a.s.l.). The highest relict rock glacier fronts are found in Eastern Tyrol at a mean elevation of 2331 m a.s.l.. Interestingly this elevation is very similar to the mean lower limits of intact rock glaciers in Styria (2357 m a.s.l.) and Salzburg (2412 m a.s.l.). Likewise, the highest mean intact rock glacier fronts are also found in Eastern Tyrol, only 261 m higher compared to the relict ones.

On a regional scale, the mean lower limit of relict rock glaciers units varies between 1798 m a.s.l. in R1 to 2354 m a.s.l. in R7, hence spanning an elevation range of 556 m. In contrast, the mean lower limit of intact rock glacier units in the 14 different regions spans only 353 m ranging from 2287 m a.s.l. at R14 to 2640 m a.s.l. in R6. The mean lower limit of the intact rock glacier units in the regions R4, R10, R11, R14 (2287-2392 m a.s.l.) is very similar to the mean lower limit of the relict rock glacier units in the regions R6, R7 and R8 (2292-2354 m a.s.l) indicating that other factors than elevation are relevant for present and past rock glacier evolution.

Results on the analysis on the upper limit of rock glacier units are presented in Table 4 and Fig. 7B. Generally, the pattern shown in Fig. 7B is very similar to that described for lower limits. The lowest mean upper limits for relict and intact rock glacier units are found in Styria, whereas the highest ones were computed for Eastern Tyrol. The upper limit of relict rock glacier units in the different federal provinces as well as regions is generally 75 to 183 m higher compared to the lower limit. For intact rock glacier units, this difference is 118 to 161 m. The lowest mean upper limits for relict rock glacier units on a regional scale are found in R1, R5 and R12 (1948-1978 m a.s.l.), that of intact rock glacier units in R4, R11 and R14 (2370-2424 m a.s.l.).

4.4 Rock glaciers morphometry

Mean values regarding maximum length, maximum width perpendicular to length, and ratio between maximum length and maximum width are listed in Table 4. Generally, relict rock glacier units are slightly longer (387 m) compared to intact ones (351 m) if looking at all rock glacier units. However, at a federal-province scale in Styria the mean value of the maximum length of relict rock glacier units is twice as much as the mean value of intact ones. The major problem in this comparison is, however, the small sample size of intact rock glaciers. At a regional scale, the biggest differences in terms of longer relict rock glaciers are in R1 (although only one intact rock glacier unit), R4, R9, and in particular R11 and R14.

The mean value of the maximum width is quite the same for relict as well as intact rock glacier units. At a regional scale, the widest relict rock glaciers units are found in the E and SE of the investigated area (R12,

Table 4: Summarising results of the rock glacier inventory analyses presenting mean values of different topographic parameters thereby distinguishing between relict (upper table) and intact rock glacier units (lower table). For the parameter slope orientation (asp), the dominant slope orientation is indicated. For explanation of parameters see Table 3.

	ul	ml	mw	area	hp_catch	dif_ca_ll
ll	0.97**	-0.20**	-0.14**	-0.23**	0.83**	-0.23**
ul	1	-0.05*	-0.09**	-0.12**	0.87**	-0.13**
ml		1	0.28**	0.79**	0.08**	0.48**
mw			1	0.69**	0.00(ns)	0.25**
area				1	0.03(ns)	0.45**
hp_catch					1	0.34**

Table 5: Correlation matrix of selected parameters considered in the rock glacier inventory (n=1647). Correlations are not significant (ns) or significant at the 0.01 (**) and, respectively, 0.05 (*) levels.

R13 and R14). The most narrow ones in R4 and R10. In most regions, intact rock glacier units are narrower compared to relict ones, particularly in R11 (by 96 m) and R14 (by 116 m).

The mean ratio values between maximum length and maximum width presented in Table 4 show that in all federal provinces and in all 14 regions the rock glacier units are generally longer than wide. Maximum length and maximum width can also be used to analyse rock glacier shape (Fig. 8). Tongue-shaped rock glaciers are features where length exceeds width. In contrast, lobate-shaped rock glaciers are landforms where width exceeds length (Wahrhaftig and Cox, 1959). 292 rock glacier units are lobate-shaped, 1343 are tongue-shaped and 12 are equal in length and width. Interestingly, all 347 intact rock glacier units are tongue-shaped. Consequently, all 292 rock glacier units of lobate-shape are relict. Most of them are located in Eastern Tyrol (n=125). Almost all rock glacier units of equal length and width are in Salzburg. At a regional scale, 83% of the lobate-shaped rock glacier units are in the regions R4, R7 and R10. Only tongue-shaped rock glacier units were mapped in the regions R1-R3, R6, R9, and R11-13.

The mean surface area of intact rock glacier units is slightly smaller (by 18% or 0.014 km²) compared to relict landforms (Table 4). The mean size of relict rock glacier units is relatively homogenous in Carinthia, Salzburg, Styria and Eastern Tyrol. However, if looking on the box plot diagrams in Fig. 9, it is revealed that the largest relict rock glacier units are located in Styria. Intact rock glacier units are of comparable mean size as well as interquartile range in Carinthia, Salzburg and Eastern Tyrol. Only those in Styria are substantially smaller. At a regional scale, the highest mean values for relict rock glacier units were generally found in R12 (0.095 km²), R5 and R6 (both 0.087 km²), whereas the lowest values were computed for R4 (0.051 km²) and R10 (0.060 km²). By far the largest intact rock glaciers are located in R6 with a mean area of 0.085 km² followed by R2 with 0.071 km². Likewise the interquartile range for relict and intact rock glacier units varies substantially between the 14 regions. The size of relict rock glacier units is quite heterogeneous with a large interquartile range in particular in the regions R5, R6, R8 and R12-R14. Intact rock glacier units vary substantially in size in R2 and R6-R8.

4.5 Catchment of rock glaciers

Table 4 lists the mean values for the highest point of the catchment area of the rock glacier and the difference between

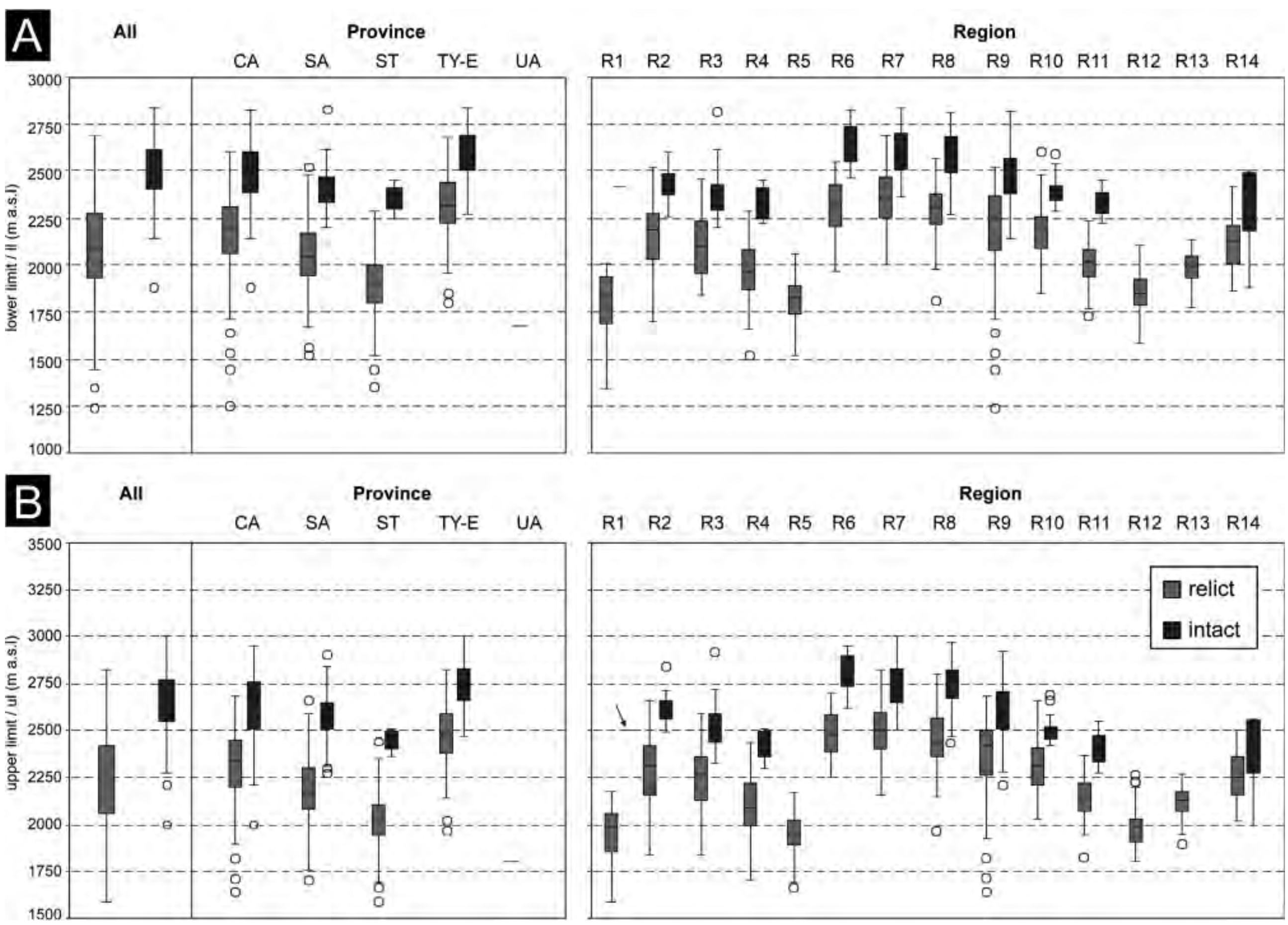

Figure 7: Box plot diagrams of the variations in the lower (A) and upper limits (B) of all rock glacier units in the entire investigated area, the five federal provinces, and the 14 different study regions. The diagrams show the sample minimum, lower quartile, median, upper quartile, sample maximum as well as outliers (indicated as circles). For mean values refer to Table 4. One outlier in (B) with an upper limit value of 1440 m a.s.l. is not indicated. This outlier is the lowest lobe of the polymorph rock glacier li13/Tandlalm in the province CA/R9. The arrow at R1 in (B) indicates the one intact rock glacier in R1.

highest point of the catchment area and the lower limit of the rock glacier unit. The mean value for the highest point of the catchment area of relict rock glacier units is 407 m lower compared to the catchment area of intact ones clearly pointing out the fact that many relict rock glaciers are located away from intact ones in generally lower mountain ranges. This is confirmed by looking on the results from the different federal provinces (lowest in Styria, highest in Eastern Tyrol for both relict and intact rock glacier units) and different analysed regions (lowest in R1, highest in R6 again for both relict and intact rock glacier units).

The difference between the highest point of the catchment area and the lower limit of the rock glacier unit is more or less identical for relict and intact rock glacier units, if looking on the entire sample size. However, if looking on a federal-province scale a big difference is revealed for Styria with a difference of 119 m, i.e. less extended catchment areas of intact rock glaciers compared to relict ones. At a regional scale, in all but one region (R2) the catchment areas of intact rock glacier are substantially to slightly smaller in elevation range compared to relict ones.

5. Discussion

5.1 Intact rock glaciers

The 347 intact rock glacier units are all tongue-shaped, occur in a smaller elevation range, are shorter, narrower and smaller compared to relict ones, terminate ca. 410 m higher, and are predominantly exposed towards NW and N. The noticeably low amount of intact rock glacier units (21 %) in relation to the relict ones is mainly because the eastern part of the Eastern Alps lacks large areas which are currently affected by permafrost conditions. Today, only about 1600 (Ebohon and Schrott, 2008) to 2000 km² (Lieb, 1998a) of the Austrian Alps are presumably underlain by permafrost with only very small patches of permafrost in Eastern Austria (Kellerer-Pirklbauer, 2005). This fact strongly restricts potential areas for intact rock glaciers. The lower limit of intact rock glaciers might be used as a proxy for the lower limit of discontinuous permafrost on a regional scale (Lieb, 1996). The mean lower limit of all intact rock glaciers derived from this inventory is 2515 m a.s.l. However, there is no single summit east of 14°05' exceeding this height. Even if looking on federal-province scale, the mean lower limit of the province relevant for areas east of 14°05' (Styria) is 2357 m a.s.l.. Hence, in this area only the summit areas and some cirque headwalls are affected by permafrost, but certainly no larger cirque areas necessary for present rock glacier formation and evolution. Thus, in Eastern Austria permafrost occurs only as isolated or sporadic permafrost unsuitable for rock glacier formation. The easternmost proved occurrence of permafrost is situated near Hochreichart (N47°21'50'' and E14° 40'56'') at some 1900 m a.s.l. (Kellerer-Pirklbauer and Kühnast, 2009).

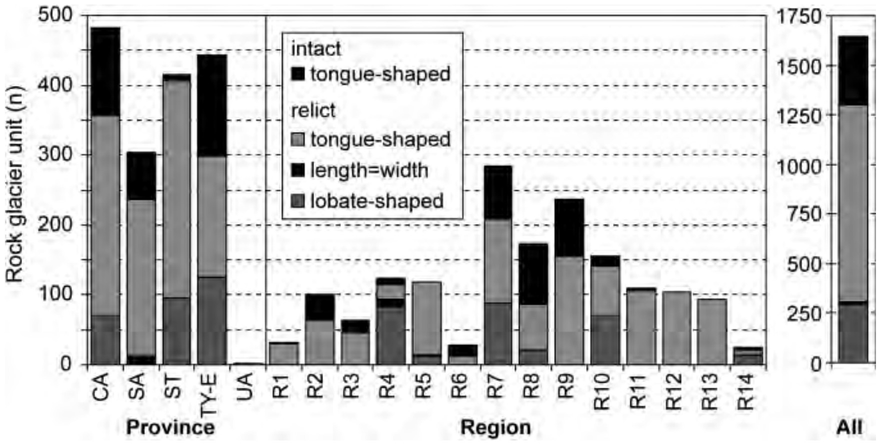

Figure 8: Rock glacier shape based on length-width comparison and differentiated between relict and intact rock glaciers for the entire investigated area, the four relevant federal provinces, and the 14 different study regions. Note that all intact rock glacier units are tongue-shaped.

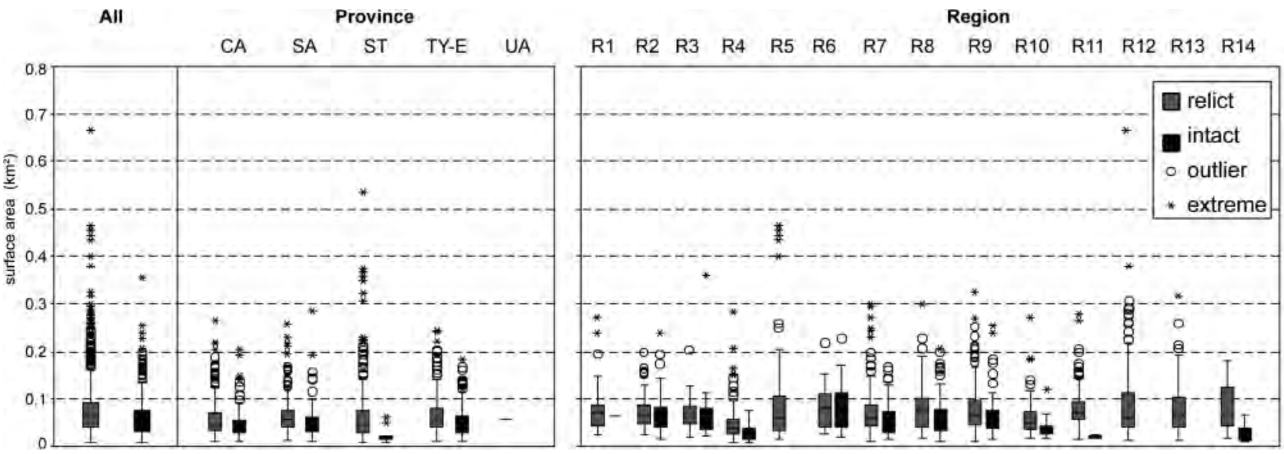

Figure 9: Box plot diagrams of the variations in the areal extent of all rock glacier units in the entire investigated area, the five federal provinces, and the 14 different study regions. For mean values refer to Table 4.

A further reason for the low number of intact rock glaciers at higher elevations in Central Austria is the fact that many of the "suitable" cirques for rock glacier formation at elevations with potentially discontinuous permafrost are simply still occupied by glaciers. This is particularly valid for the regions R2 (southwestern Salzburg) and R6 (northern part of Eastern Tyrol) where some of the largest glaciers of Austria exist (see Fig. 4 for present glacier extent). However, this is also valid for R3 (=southern Salzburg) and R9 (northwestern Carinthia) although to a minor extent. The best topoclimatic conditions for intact rock glaciers in the entire investigated area are defined by higher elevated cirques just below the regional snow line with discontinuous permafrost conditions in a relatively dry and continental climate to the south of the main drainage divide. These conditions are primarily found in the northern part of R7 (northern Defereggen Mountains), in the entire region R8 (Schober Mountains) and in the higher areas of R9 (Eastern Hohe Tauern Range, south). However, the highest cirques in R9 are occupied by glaciers. The importance of a minor difference in elevation by only 100 m for either rock glacier or glacier formation was well shown for two neighbouring cirques in the central Schober Mountains (Kellerer-Pirklbauer and Kaufmann, 2007; Kellerer-Pirklbauer, 2008b) thereby confirming earlier observations from Greenland and Antartica where glaciers are situated only slightly higher in elevation than rock glaciers (Humlum, 1999).

The optimal mountain range for present rock glacier formation and evolution is R8, i.e. the Schober Mountain located in a climatically sheltered position to the south of the main divide. In this region, permafrost is widespread and geological conditions favour the formation of relatively coarse-grained debris promoting efficient ground cooling (Gruber and Hoelzle, 2008). Furthermore, topography is suitable with steep rock walls delivering debris for the rock glaciers below and high-elevated flat areas (cirques) which allow the accumulation of frozen debris necessary for rock glacier evolution. Furthermore, this region houses only small glaciers (<0.7 km²) occupying few cirques. Most of the small glaciers are also heavily covered by debris and are therefore in many cases not easy to delineate in the field.

5.2 Relict rock glaciers

The 1300 relict rock glacier units are predominately tongue-shaped (77%) although a large portion is lobate-shaped, occur in a substantially wider range of elevations, are generally larger, longer and wider compared to intact ones, are predominantly exposed to NE and E and terminate at a regional scale 164 to 622 m lower than the intact ones. On a federal-province scale, the lowest rock glacier units are found in Styria related to the lower elevated catchment areas and the earliest deglaciation during the Lateglacial period. At a regional scale, the lowest rock glacier units occur in the Northern Alps (R1) and in the northern and eastern part of the Niedere Tauern Range (R4, R5, R12), yet the minimum elevation of a rock glacier lower limit is located in R9 (as already mentioned above). The generally lower summit elevations in Eastern Austria in combination with a generally drier climate towards the east favoured an early deglaciation during the Lateglacial period offering huge areas for the development of rock glaciers. Many of these rock glaciers turned probably into relict forms at the transition between the Lateglacial and the Holocene periods or even earlier.

Climate was generally more continental during the Lateglacial period in the central and eastern part of the Austrian Alps compared to the present (Kerschner, 2009) favouring rock glacier formation. In contrast, the relict rock glaciers in the more maritime Northern Alps were able to form in a narrower elevation range (upper limitation by glaciers vs. lower limitation by permafrost lower limit) because the lowering of the snow line during the stadials was more pronounced compared to the continental Central Alps causing the formation of glaciers also at lower elevations.

The wider elevation range in rock glacier occurrence is related to the fact that the rock glacier units which are nowadays relict evolved during substantially different climatic conditions in the Lateglacial period, whereas most intact ones are primarily of Holocene age where the climate variability was substantially less (e.g. Ivy-Ochs et al., 2009). As mentioned in chapter 2, major relevant readvances of glaciers in the Lateglacial and early Holocene periods occurred between >15.4 ka and ca. 8.4 ka with generally drier conditions in the Central Alps as shown by palaeoglaciological studies (Kerschner and Ivy-Ochs, 2007; Kerschner, 2009). These studies further show that the lowering of the equilibrium line altitude (ELA) for the central Austrian Alps was about 700 m during Gschnitz, about 400-500 m during Senders/Clavadel, about 150-200 m during Egesen (up to 400 in the maritime Northern Alps), 120 m during Kartell, and 80 m during Kromer relative to the ELA during the Little Ice Age (LIA) maximum glacier advance at around AD 1850. The ELA is related to precipitation/snow and temperature whereas permafrost is only related to temperature. Therefore, the ELA depression is only a rough proxy for permafrost lowering.

According to Kerschner (2009), the lowering of the summer temperature during Gschnitz was about 10°C, that of Egesen about 3.5°C relative to the LIA conditions at around AD 1850. According to this author, the lowering of the mean annual air temperature (MAAT) was slightly greater. Assuming a MAAT lowering of 11°C for Gschnitz and 4°C for Egesen as well as a vertical lapse rate of 0.65°C/100 m, the lowering of permafrost was ca.1700 m for Gschnitz and ca.600 m for the Egesen. As shown by Ivy-Ochs et al. (2009), increasingly drier conditions during the latest Lateglacial and during the earliest Holocene caused glacier downwasting and hence an optimal phase for rock glacier evolution. During Kartell permafrost still existed some 300 m (Ivy-Ochs et al., 2009) lower compared to the 20th century (see also below). This means a lowering of the MAAT of 1.3 to 2.0°C if using the same lapse rate as above. After this transition period and until about 3.3 ka BP glaciers were smaller than today for most of the time, forest growth was possible at higher elevations (Ivy-Ochs et al., 2009) and the lower limit of permafrost was presumably also shifted upwards. Therefore, a major termination for the formation and evolution of present relict rock glaciers was during the latest Lateglacial/earliest Holocene transition. These values for permafrost limits illustrate that substantially different environmental conditions favoured rock glacier formation in a complex time-space framework during the Lateglacial and early Holocene.

Datings of rock glacier units in the investigated area are rare. So far, only relative dating was carried out applying the Schmidt-hammer exposure-age dating (SHD) method at nine rock glaciers, 5 of them intact and 4 relict (Kellerer-Pirklbauer, 2008 c; Rode and Kellerer-Pirklbauer, 2012). The 5 intact ones started to form after Egesen, most likely even after the Preboreal. The 4 relict ones started to form possibly already during Senders/Clavadel or Daun, but most likely not during Gschnitz (Rode and Kellerer-Pirklbauer, 2012). The SHD results show that all dated rock glaciers formed over long time spans lasting several thousand years during the Lateglacial and Holocene period.

Absolute dating of rock glaciers in Austria so far has only been carried out in Western Austria, in the Larstig Valley (Ivy-Ochs et al., 2009). In this valley, two relict rock glaciers terminating at about 2100 and 2120 m a.s.l. were dated applying surface exposure age dating with cosmogenic 10Be. Results revealed a final stabilisation no later than 10.5 ±0.8 ka, hence a Kartell/Preboreal Oscillation age. A currently still active rock glacier in the same valley terminates at about 2400 m a.s.l., indicating that during the Preboreal the lower limit of permafrost was up to 300 m lower and the MAAT 2°C cooler. These assumptions are only correct, however, if both rock glaciers – relict and intact – reached their lowest possible limit in terms of permafrost existence.

Following the palaeoclimatic considerations above, the generally largest difference between relict and intact rock glaciers in terms of altitudinal range should be in the regions where glaciers generally disappeared first in the cirques. This conclusion is confirmed looking for instance on the difference between the mean lower limits of relict and intact rock glaciers in the different provinces, which is lowest in Eastern Tyrol and highest in Styria. This is less clear at a regional scale because in some regions with a high number of relict rock glaciers the intact ones are absent or rare. Furthermore, the considerations above also reveal that the group of relict rock glaciers is very heterogeneous in terms of initiation/formation period.

6. Conclusions and Outlook

This study clearly shows the high relevance of rock glaciers in the alpine area of Central and Eastern Austria. We elaborated a polygon-based rock glacier inventory comprising 1647 rock glacier polygons or units covering an area of 119 km². 1300 rock glacier units are relict and only 347 still contain permafrost and are intact (either active or inactive). Most rock glaciers are monomorphic with only one generation of lobes, and 98 are complex (polymorphic) with up to five generations. In Eastern Austria permafrost occurs only as isolated or sporadic permafrost unsuitable for rock glacier formation, hence all intact rock glaciers are located in central Austria.

The federal province with the highest number of rock glacier units in the study area is Carinthia followed by Eastern Tyrol and Styria. However, if looking on the rock glacier density, Eastern Tyrol clearly exceeds all other federal provinces. Intact rock glacier units occur mainly in the two provinces Carinthia and Eastern Tyrol whereas by far most of the relict rock glacier units are located in Styria.

Most relict rock glaciers units are found in the NE aspect, whereas most intact rock glaciers are facing towards NW. In general relict rock glacier units are slightly longer (387 m) and larger (75,129 m²) compared to intact ones (351 m; 61,299). In all investigated federal provinces and in all 14 regions the rock glacier units are generally longer than wide (hence tongue-shaped rock glaciers). Furthermore, the mean elevation difference between relict and intact rock glaciers regarding upper and lower limits is comparable with 413 m for the lower limit and 421 m for the upper limit. However, on a federal-province or regional scale all these patterns are more diverse.

At a regional scale it was revealed that the Schober Mountains (R8), located in the provinces of Eastern Tyrol and Carinthia, is certainly the region with the ideal present topoclimatic and geological conditions for rock glacier formation in the entire investigated area. R8 is lacking larger glaciers (largest glacier slightly less than 0.7 km²) and many glaciated areas are heavily covered with supraglacial debris.

The optimal regions for relict rock glaciers are found in the Niedere Tauern Range located in the Styria and – to a minor extent – in Salzburg (R4, R5, R11 and R12). In this wider region glaciers disappeared relatively early. Furthermore, the lowering of the lower limit of permafrost during the Lateglacial and early Holocene period was substantial and is estimated to be up to 1700 m (during Gschnitz) relative to AD 1850. The estimated permafrost lowering values, early deglaciaion and the long duration of the Lateglacial period allowed optimal rock glacier formation and evolution conditions for several thousand years until the early Holocene necessary for large and complex rock glaciers to form. Formation periods of several thousand years are confirmed by rock glacier dating results from earlier studies.

The largest polymorphic rock glacier in Niedere Tauern Range exceeds 1 km² in size. The different units or generations are presumably related to different cold periods or stadials during the Lateglacial and early Holocene period. The deciphering of these complex landforms is a goal for future research.

Of very little importance regarding rock glacier occurrence are the three regions R1, R6 and R14 related either due to unsuitable topographic conditions or due to the fact that cirques and valley heads that possibly could house rock glaciers are still occupied by glaciers.

A major drawback in the presented rock glacier inventory is the spatial resolution of the DEM used for delineating the rock glacier polygons as well as for deriving relevant topographic parameters. Furthermore, it is difficult to detect relict rock glaciers in areas covered by forest. For both drawbacks, airborne laser scanning (ALS) data used for generating high-resolution DEMs (≥1m grid resolution) with vegetation cover filtered-out by considering last pulse ALS data for DEM construction would substantially improve the detection and delineation of rock glaciers. ALS data are already the basis for a rock glacier inventory currently in progress for Northern Tyrol (Krainer and Ribis, 2012). Furthermore, recently released ALS data are currently used for elaborating an improved inventory for parts of the province of Styria (A. Kellerer-Pirklbauer, G. Winkler, M. Pauritsch, June 2012).

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