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A Rock Glacier Inventory of the Tyrolean Alps (Austria)

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Abstract

Permafrost is widespread in the European Alps and includes a large number of rock glaciers, which are the typical and most common permafrost landform and particularly abundant in the Tyrolean Alps of Austria. We compiled a rock glacier inventory of all mountain groups of the Tyrolean Alps within the Alpine Space Program PermaNET to provide information for modeling the distribution of permafrost in the European Alps and to refine existing models. The inventory is based on the study of high-quality aerial photographs and laserscan images. Each rock glacier is documented by an orthophoto and by a datasheet which contains information such as coordinates, elevation, length, width, area, aspect (flow direction), shape, state, hydrology and bedrock in the catchment area. All rock glaciers are listed in an excel-sheet.

The rock glacier inventory of the Tyrolean Alps (Austria) includes 3145 rock glaciers which cover an area of 167.2 km². Of these, 517 (16.4%) were classified as active, 915 (29.1%) as inactive, and 1713 (54.5%) as fossil.

Tongue-shaped, talus-derived, ice-cemented rock glaciers are the most common type among active and inactive rock glaciers. Glacier-derived rock glaciers containing a massive ice-core are rare.

Most rock glaciers occur in the mountain groups of the central Alps in which bedrock is composed mainly of mica schists, paragneiss, orthogneiss and amphibolites ("Altkristallin").

The majority of active and inactive rock glaciers are exposed towards a northern (NW, N and NE) direction. Active and inactive rock glaciers exposed towards S, SE and SW are minimal. In contrast, fossil rock glaciers exposed towards SW, SE and particularly towards S are common.

The total amount of ice in active and inactive rock glaciers is estimated to be 0.19 - 0.27 km³ which is small compared to the ice volume contained in the glaciers of the Tyrolean Alps (13 km³).

The distribution of active and inactive rock glaciers indicates that the lower limit of discontinuous permafrost in the mountain groups located in the central part of the Tyrolean Alps of Austria is located at approximately 2500 m.

Permafrost ist in den europäischen Alpen weit verbreitet und beinhaltet eine große Zahl von Blockgletschern, die eine typische und sehr häufige Form des alpinen Permafrostes darstellen und besonders in den Tiroler Alpen (Österreich) zahlreich vorkommen. Wir erstellten im Rahmen des Alpine Space Programmes PermaNET ein Blockgletscher-Inventar für alle Gebirgsgruppen der Tiroler Alpen als Grundlage für die Modellierung der Verteilung des Permafrostes in den Europäischen Alpen sowie zur Verfeinerung bereits existierender Modelle. Das Inventar basiert auf der Auswertung hochqualitativer Orthophotos und Laserscan-Aufnahmen. Jeder Blockgletscher ist durch ein Orthophoto und ein Datenblatt dokumentiert, welches Angaben über Koordinaten, Höhe, Länge, Breite, Fläche, Exposition, Form, Zustand, Hydrologie und Festgesteine im Einzugsgebiet enthält. Alle Blockgletscher sind mit den entsprechenden Daten in einer Excel-Tabelle aufgelistet.

Das Blockgletscher-Inventar der Tiroler Alpen (Österreich) umfasst 3145 Blockgletscher mit einer Fläche von 167.2 km². Davon wurden 517 (16.4%) als aktiv, 915 (29.1%) als inaktiv und 1713 (54.5%) als fossil eingestuft. Unter den aktiven und inaktiven Blockgletschern sind zungenförmige, Eis-zementierte Blockgletscher, die sich aus Hangschutt entwickelt haben, weitaus am häufigsten. Blockgletscher, die sich aus schuttbedeckten Kargletschern entwickelt haben, sind offensichtlich selten.

Die meisten Blockgletscher befinden sich in den Gebirgsgruppen der Zentralalpen, in denen die Festgesteine aus diversen Glimmerschiefern, Paragneisen, Orthogneisen und Amphiboliten („Altkristallin") bestehen.

Ein Großteil der aktiven und inaktiven Blockgletscher ist nach NW, N und NE ausgerichtet. Nach SE, S und SW ausgerichtete aktive und inaktive Blockgletscher sind dagegen selten. Im Gegensatz dazu sind fossile Blockgletscher, die nach SW, SE und vor allem nach S ausgerichtet sind, häufig.

Das gesamte in aktiven und inaktiven Blockgletschern gespeicherte Eisvolumen wird auf 0.19 – 0.27 km³ geschätzt, ein im Vergleich zum Eisvolumen der Gletscher (13 km³) geringer Wert.

Aus der Verteilung der aktiven und inaktiven Blockgletscher kann die Untergrenze des diskontinuierlichen Permafrostes in den zentralen Gebirgsgruppen der westlichen österreichischen Alpen (Tirol) bei ungefähr 2500 m angenommen werden.

1. Introduction

Alpine permafrost is widespread in the European Alps and because of its temperature (close to 0°C) it is sensitive to cli-

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mate change. In Austria, up to 1600 (Ebohon and Schrott, 2008) to 2000 km² are probably permafrost affected (Lieb 1998). In Switzerland, about 5% of the land (~ 2100 km²) is underlain by permafrost. Rock glaciers are the most common and most spectacular feature of Alpine permafrost (Boeckli et al. 2012). Many rock glaciers in the Alps are located near the lower limit of discontinuous permafrost with temperatures between -2 and 0°C (Gärtner-Roer et al., 2010).

Lieb (1996) was the first to compile a rock glacier inventory for the eastern part of the Austrian Alps. He mapped 1451 rock glaciers of which 282 still contain ice and thus are classified as intact. An updated and extended version of the rock glacier inventory by Lieb (1996) was recently elaborated (Lieb et al., 2010) and is comprehensively described by Kellerer-Pirklbauer et al. (2012, this volume). Cremonese et al. (2010) presented the first version of a permafrost inventory for the European Alps including a rock glacier inventory which already exists for large parts of the European Alps.

Although active and inactive rock glaciers are expected to be more abundant in the western part of Austria (Tyrolean Alps), little information is available on the distribution of rock glaciers. A rock glacier inventory was compiled within the Alpine Space Program PermaNET to provide basic information on the distribution of alpine permafrost in this region and for modeling the permafrost distribution in the European Alps according to the method presented by Boeckli et al. (2012) which is based on rock glacier inventories and rock surface temperatures. The inventory should also help to verify and refine already existing models on the distribution of permafrost.

The aim of this paper is

- To present an inventory of all rock glaciers in the mountain groups of Tyrol
- To provide basic data on each rock glacier (e.g. coordinates, elevation, length, width, area, shape)
- To estimate the volume of ice stored in active and inactive rock glaciers

2. Study area and previous studies on rock glaciers in the Tyrolean Alps

The study area includes all mountain groups of the Tyrolean Alps of Austria (Eastern Alps). The mountain groups are shown on Fig. 1.

Only few active rock glaciers have been studied in detail in the Tyrolean Alps, mainly in the Ötztaler and Stubaier Alpen. Finsterwalder (1928) described the rock glacier at Innere Ölgrube and presented surface flow velocities. In 1938, Pillewizer started to measure flow velocities on Hochebenkar rock glacier in the Ötztaler Alpen near Obergurgl and at Ölgrube rock glacier in the Kaunertal. Since that time flow velocities on Hochebenkar rock glacier have been measured for more than 70 years (Pillewizer, 1957; Vietoris, 1958, 1972; Schneider and Schneider, 2001).

Later, aerial and terrestrial photogrammetry was used to determine flow rates which compared well with directly measured flow velocities from the field (Kaufmann, 1998; Kaufmann and Ladstätter, 2002, 2003; Ladstätter and Kaufmann, 2005).

Haeberli and Patzelt (1983) determined the thermal regime of Äußeres and Inneres Hochebenkar by applying the widely used method of measuring the base temperature of the snow cover (BTS). Additionally, they applied refraction seismics in order to estimate the ice content at various profiles.

Gerhold (1967, 1969) mapped and studied a number of rock

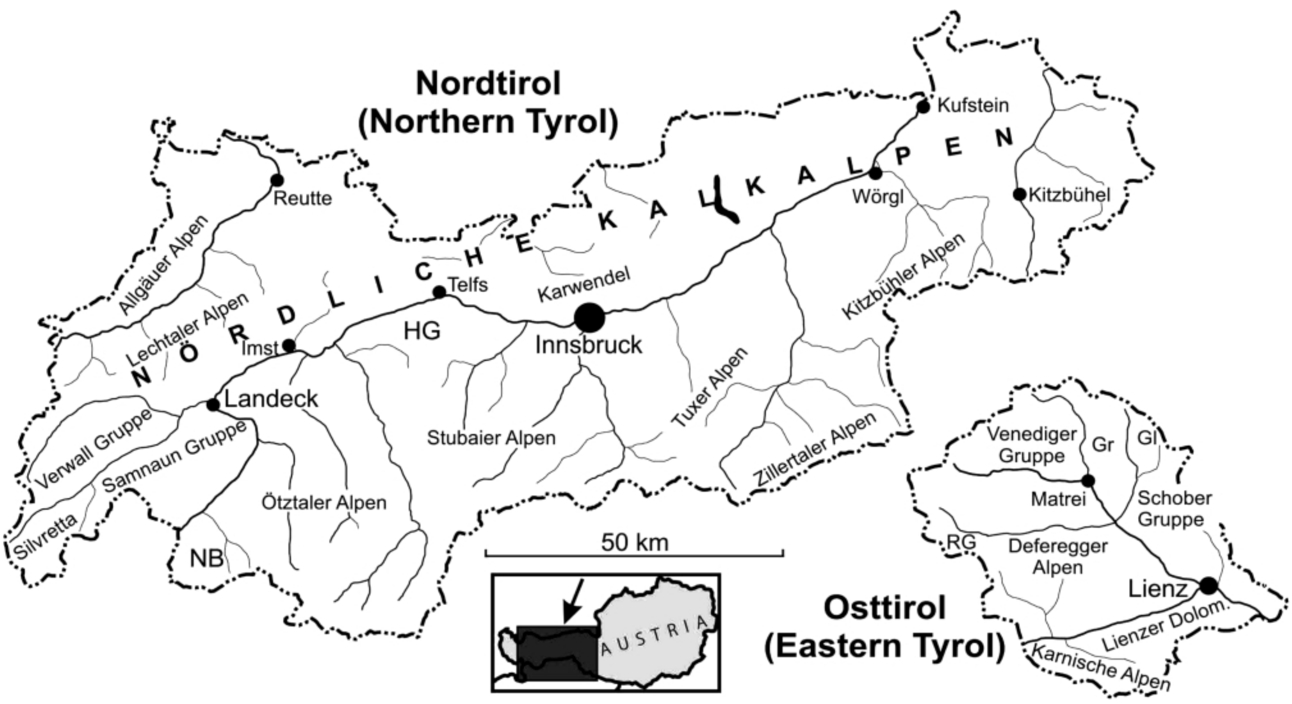

Figure 1: The extent of the mountain groups of the Tyrolean Alps (Northern and Eastern Tyrol). Gl = Glocknergruppe, Gr = Granatspitzgruppe, HG = Hochedergruppe, NB = Nauderer Berge, RG = Rieserfernergruppe.

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glaciers in the western Ötztaler Alpen and discussed their formation and age. Kerschner (1978, 1985) inferred paleoclimatic conditions from fossil rock glaciers. Lieb (1991) studied the horizontal and vertical distribution of rock glaciers in the Hohe Tauern partly located in Tyrol.

Detailed investigations including morphology and debris properties, thermal regime of the debris layer, hydrology, flow velocities, and geophysical measurements were carried out at Sulzkar and Reichenkar rock glaciers in the western Stubaier Alpen by Krainer and Mostler (1999, 2000, 2001a, 2001b, 2002, 2004, 2006), Krainer et al. (2002, 2007) and Hausmann et al. (2007). Two active rock glaciers were studied in detail in the Kaunertal (Ölgrube and Kaiserberg) by Berger et al. (2004), Krainer and Mostler (2002, 2006).

In Eastern Tyrol, Buchenauer (1990) studied rock glaciers in the Schobergruppe and Rolshoven (1982) presented some data on rock glaciers in the Lasörlinggruppe of the Deferegger Alpen. No data on rock glaciers are available from the other mountain groups of the Tyrolean Alps.

3. Definitions and Methods

Barsch (1996) defined active rock glaciers as lobate or tongue-shaped bodies of perennially frozen unconsolidated material supersaturated with interstitial ice and ice lenses that move downslope or downvalley by creep as a consequence of the deformation if ice contained in them and which are, thus, features of cohesive flow. This definition includes process, material and form (see also Haeberli 1985, Haeberli et al., 2006). Besides active rock glaciers, inactive and fossil (relict) rock glaciers are distinguished. Inactive rock glaciers contain ice but do not move whereas in fossil or relict rock glaciers the ice is melted.

The rock glacier inventory of Lieb (1996) was based on black and white aerial photographs (Austrian aerial photograph map at 1:10.000) and provides a source of basic inventory information such as river basin, number of the rock glacier within the river basin, location name, mountain group, number of Austrian map, number of aerial photograph map, aspect, lower limit of the rock glacier, maximum length and width, activity, highest point of the catchment area of the rock glacier and difference between lower limit and highest point. However, additional information such as coordinates, area, surface morphology, shape, rock glacier springs and bedrock geology will be a useful source for modeling the distribution of permafrost (see Boeckli et al., 2012, Ebohon and Schrott 2008) and were partly considered in the updated inventory of Lieb et al. (2010).

The rock glacier inventory of Lieb (1996) also includes Eastern Tyrol. With a few exceptions, we identified all rock glaciers in Eastern Tyrol listed by Lieb (1996). Due to the better quality of the color orthophotos and laserscan images, we were able to map additional rock glaciers in all mountain groups of Eastern Tyrol.

As we identified rock glaciers from aerial photographs, the basic mode of identification was morphology. But as several processes may cause similar morphologic forms (e.g. talus derived vs. glacier derived rock glaciers), it is impossible to determine the mode of formation of rock glaci-

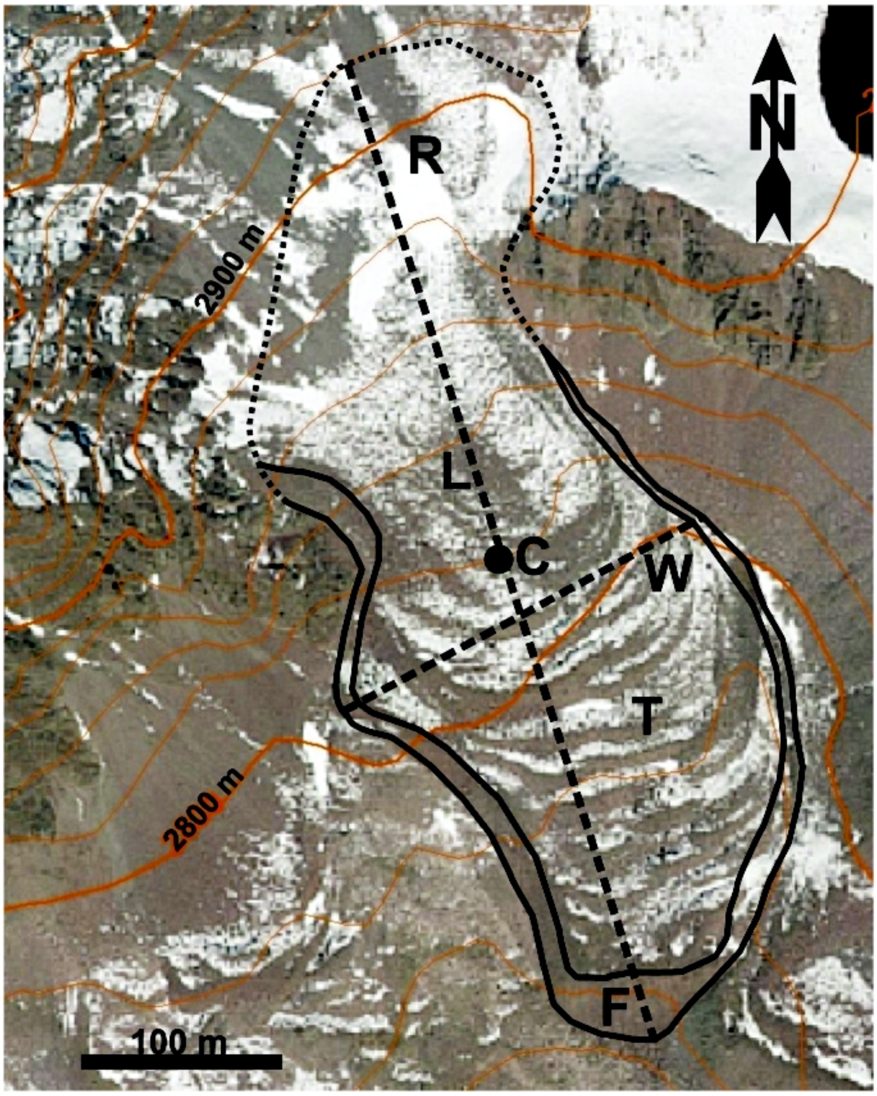

Figure 2: Orthophoto of a rock glacier (www.tirol.gv.at) with outline and characteristic parameters: R = rooting zone, F = front, T = transverse ridges and furrows, L = length, W = width of the rock glacier. C indicates the point of the coordinates. Due to the steep front which is bare of vegetation and the surface morphology characterized by well developed transverse ridges and furrows this rock glacier is classified as an active rock glacier (OA 304, Schrankar , Stubaier Alpen).

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ers from aerial photographs only. Therefore, we follow the suggestion of Vitek and Giardino (1987) that the term rock glacier should be regarded as generic rather than genetic.

All rock glaciers were determined from color orthophotos and laserscan images provided by the government of Tyrol (TIRIS, Land Tirol: Luftbildatlas Tirol, Laserscanning Tirol, www.tirol.gv.at). Orthophotos are from the years 2000 – 2006, laserscan images from the years 2006 – 2011 with a resolution of 1 m,

Parameter	Brief description
Int_Nr.	Internal serial number of the rock glacier (this is necessary in order for the database management query)
Int_Bearb. (person)	Name of person responsible for measurements
Int_digital	Digitized yes/no
Nummer (number)	FA (abbrevation of the main stream in the catchment area; FA = Fagge _ BL (Blockgletscher, rock glacier) + 3-digit number (= serial number)
Bezeichnung (designation)	Designation of the geographic name of the locality in which a rock glacier occurs according to the topographic map
Datum_Aufnahme (date of survey)	Date of data collection and GIS digitizing
Nr_OPH	Number of orthophoto on which the GIS digitizing was done
Koordinaten (coordinates)	As coordinate the point in the center of a rock glacier is indicated (Gauß-Krüger and UTM)
Hoehe_Stirn (elevation front)	Elevation at the base of the front of a rock glacier
Hoehe_Wurzelzone (elevation rooting zone)	Elevation of the rooting zone of a rock glacier
Mittlere_Hoehe (average elevation)	Average elevation of a rock glacier (elevation of the center of a rock glacier
max_Laenge (max. length)	Distance between front and rooting zone of a rock glacier
max_Breite (max. width)	Maximum width of a rock glacier
Flaeche_km² (area)	Area of a rock glacier in km²
Exposition (aspect)	Direction in which a rock glacier is or was moving (degree and direction)
Relief_Morphologie (relief, morphology)	Information on the surface morphology of a rock glacier observed on orthophotos such as longitudinal or transverse ridges and furrows, grain-size
Form (shape)	Information on the shape of a rock glacier, distinguished are tongue-shaped (length>width), lobate (width>length), complex (composed of two or more distinct generations) and rock glaciers with two or more tongues
Entstehung (formation)	Information on the formation of a rock glacier (as far as can be estimated from orthophotos): talus derived (ice-cemented), glacier derived (ice-cored), derived from moraines
Zustand (state)	Information on the state of a rock glacier as far as can be estimated from orthophotos: active (steep front bare of vegetation), inactive (less steep front, some vegetation) and fossil (covered with vegetation, particularly at the front)
Symbol (symbol)	1 active, 2 inactive and 3 fossil rock glacier
Gewaesser_Einzugsgebiet (stream of catchment area)	Main stream of the catchment area of a rock glacier
Gebirgsgruppe (mountain group)	Name of the mountain group in which the rock glacier is located
Gesteine (bedrock)	Information on the bedrock and loose sediment (talus, moraines, till deposits) in the catchment area of a rock glacier (taken from geologic maps)
Quellaustritt (spring)	Information if rock glacier springs occur at the front of a rock glacier (visible on orthophotos)
Analysen vorhanden (analyses available)	Information if geochemical data of the rock glacier spring are available
Schwermetallkonzentrationen (heavy metal concentrations)	Information if data exist on heavy metal concentrations in the meltwater released at the rock glacier spring
Pegeldaten (gaging data)	Information if discharge data (gauging station) on the surface runoff of a rock glacier exist
Literatur (literature)	Information if literature exists on a rock glacier or not (with reference)
Bemerkungen (comments)	Additional comments on a rock glacier

TABLE 1: Parameters of the data sheet.

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partly 25 cm.

Each rock glacier is documented by an orthophoto (jpeg) on which the outline of the rock glacier is shown (Fig. 2), and by a datasheet which contains all the information listed below. All rock glaciers are listed in an excel-sheet.

Most rock glaciers are easily recognized on orthophotos due to their typical morphological features. They are mostly clearly defined showing a distinct front and distinct flanks. Additionally, many rock glaciers display a distinct surface morphology of longitudinal and/or transverse ridges and furrows (Fig. 2).

The definition of the upper boundary (rooting zone) is difficult and somewhat arbitrary. A few rock glaciers were difficult to recognize as their outlines are not clearly defined. In these cases the surface morphology (indicating downslope creep) was the criterion for definition as rock glacier. As transitions exist between small rock glaciers and large solifluction lobes, we defined the size of a rock glacier by drawing the lower limit of length at 50 m and the width at 35 m.

A data sheet was created which contains various parameters of each rock glacier such as coordinates, data on the morphometry, state, hydrology and bedrock in the catchment area. All parameters are listed and briefly explained in Table 1.

4. Results

In the Tyrolean Alps (Austria), 3145 rock glaciers were identified which cover an area of 167.2 km^2. Of these, 517 (16.4%) were classified as active, covering 45.3 km^2, 915 (29.1%) as inactive, covering 42.1 km^2 and 1713 (54.5%) as fossil covering 79.6 km^2. Rock glaciers occur in all mountain groups of the Tyrolean Alps (see Figs. 1 – 6 and Tab. 2).

4.1 Active Rock Glaciers

Active rock glaciers are present in all mountain groups of Tyrol with summit heights above 2700 m (except in the Tyrolean part of the Granatspitz- and Glocknergruppe). They are particularly abundant in the mountain groups of the Central Alps (Verwall-, Silvretta- and Samnaungruppe, Ötztaler and Stubaier Alpen, Deferegger Alpen, Schobergruppe), rare in the Nördliche Kalkalpen (Northern Calcareous Alps), Zillertaler Alpen, Venedigergruppe, and absent in the Lienzer Dolomiten, Karnische Alpen (Carnic Alps), Kitzbühler Alpen. About 68% of all active rock glaciers occur in the Ötztaler and Stubaier Alpen (Figs. 3 – 6, Tab. 2). All elevations are in meters above sea level (a.s.l.).

The average elevation of the 517 active rock glaciers is 2704 m which is about 100 m higher than that of inactive rock glaciers and about 370 m higher than that of fossil rock glaciers (see Tab. 2). Active rock glaciers are most common at elevations between 2500 and 2850 m (Fig. 7). The front of about 80% of all active rock glaciers occurs at elevations between 2400 and 2800 m. The highest active rock glacier was observed in the Ötztaler Alpen with the front located at an elevation of 3100 m, and the rooting zone at 3230 m.

Active rock glaciers exposed towards a northern direction occur at elevations which are 300 – 400 m lower than that of rock glaciers exposed towards a southern direction (Fig. 8).

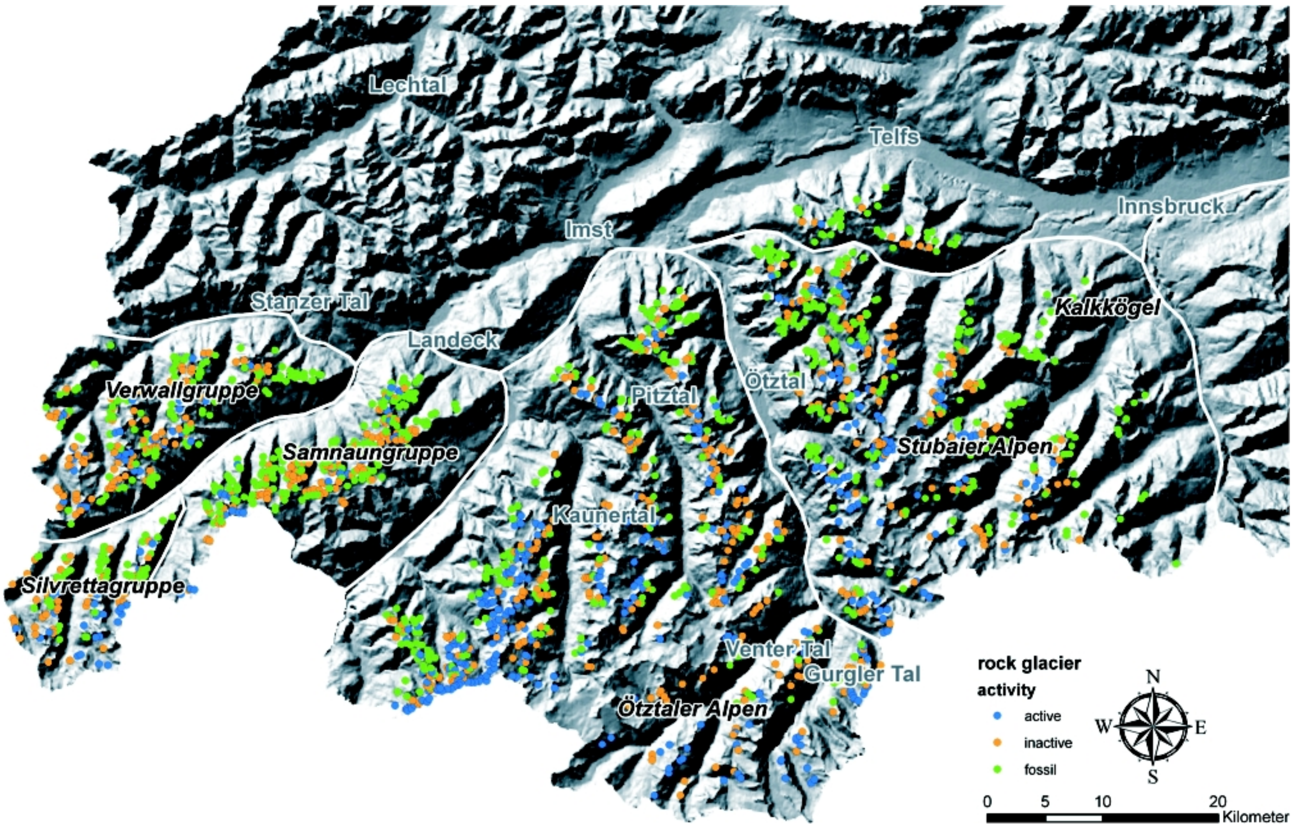

Figure 3: Distribution of rock glaciers in the Ötztaler and Stubaier Alpen, Samnaun-, Silvretta- and Verwallgruppe.

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The average elevation of the lower limit (front) of active rock glaciers is at 2377 m in the Nördliche Kalkalpen, at 2479 m in the Tuxer Alpen, and highest in the mountain groups of the central Alps ranging from 2520 (Stubaier Alpen) to 2762 m (Venedigergruppe, southern part). The average elevation of the lower limit (front) is also high in the Deferegger Alpen, Rieserfernergruppe and Schobergruppe (ranging between 2538 and 2679 m) which are located south of the central Alps. The highest average elevations of the rock glacier front are observed in the highest mountain groups: Ötztaler Alpen – 2704 m and Venedigergruppe – 2762 m (no active rock glaciers occur in the Tyrolean part of the Glocknergruppe).

Active rock glaciers exposed (flowing) towards northern directions are more abundant than active rock glaciers exposed towards south (Tab. 4).

Active rock glaciers are up to 1650 m long and 980 m wide. The largest active rock glacier covers an area of 0.59 km². The average length is 451 m, which is much longer than that of inactive and fossil rock glaciers. The average width is 201 m and the average area covered by active rock glaciers is 0.088 km². About 90% of all active rock glaciers cover an area of < 0.2 km² (Figs. 11, 12).

Most active rock glaciers (463 or 89.6%) are tongue-shaped, 43 (8.3%) are lobate, 6 (1.1%) have two tongues and 5 (1%) of all active rock glaciers display a complex form.

The majority of active rock glaciers (393 or 76%) is classified as talus derived, ice cemented rock glaciers, 115 rock glaciers (22.2%) probably are of glacial origin containing a massive ice core, 6 rock glaciers (1.1%) derived from talus and moraine, and 3 rock glaciers (0.5%) from moraines. At 96 active rock glaciers (18.6%) a spring was visible on the aerial photograph. At 36 active rock glaciers (7%) a small lake is developed at the front.

Most active rock glaciers (479 or 92.6%) are located in mountain groups composed of metamorphic rocks ("Altkristallin") including various types of mica schist and paragneiss, orthogneiss and amphibolites. Only few active rock glaciers (38) are located in mountain groups composed of rocks belonging to the Tauern Window (orthogneiss, marble, calcareous mica-schist, greenschist: Zentralgneis, Hochstegenmarmor, Kalkglimmerschiefer, Prasinit), Lower Engadine Window (schist: Bündnerschiefer), tonalite (Rieserferner Gruppe), serpentinite of the Lower Austroalpine Unit (Tarntal Mesozoic) of the Tuxer Alpen and Nördliche Kalkalpen (mainly dolomite and limestone: Hauptdolomit, Wettersteinkalk, Kössener Schichten, Plattenkalk, sedimentary rocks of Jurassic age).

4.2 Inactive Rock Glaciers

The average elevation of the 915 inactive rock glaciers is about 2600 m which is significantly lower than that of active rock glaciers (Tab. 2, 3). They occur mostly between elevations of 2360 and 2700 m (Fig. 7). The front of 79% of all inactive rock glaciers is located at an elevation between 2300 and 2700 m. Inactive rock glaciers occur in all mountain groups (Figs. 3 – 6). The average elevation of the lower limit (front) of inactive rock glaciers is < 2500 m in the Nördliche Kalkalpen

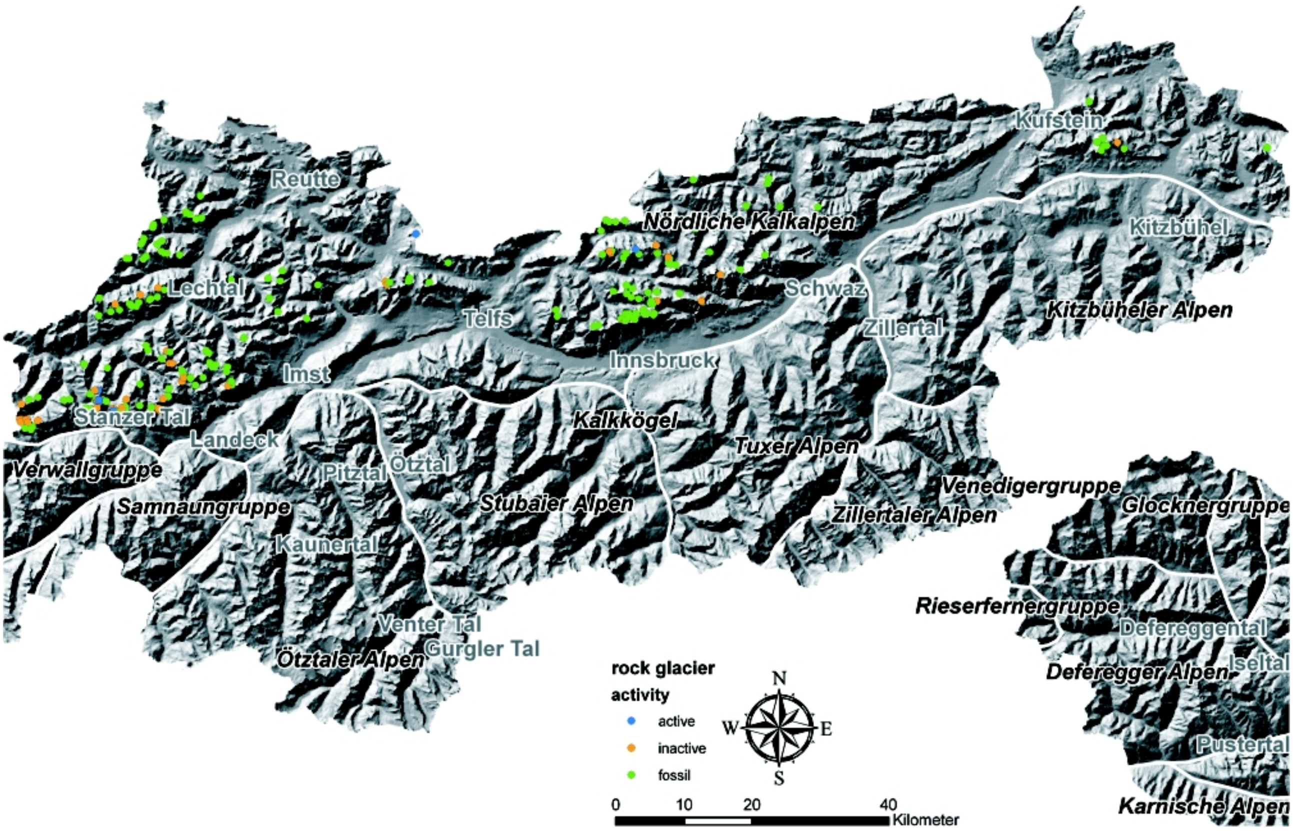

Figure 4: Location of Rock glaciers in the Nördliche Kalkalpen (Northern Calcareous Alps).

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(2307 m), Tuxer Alpen (2493 m), Silvretta- (2469 m) and Verwallgruppe (2499 m). In the mountain groups of the central Alps, the average elevation of the lower limit ranges from 2502 m (Stubaier Alpen) to 2654 m (Venedigergruppe). In the Deferegger Alpen, Rieserferner- and Schobergruppe the average elevation of the lower limit ranges from 2565 to 2579 m. In the southernmost mountain groups, the average elevation of the lower limit is 2180 m in the Lienzer Dolomiten and 2355 m in the Karnische Alpen. The highest inactive rock glacier is located in the Ötztaler Alpen (front at 3240 m and rooting zone at 3300 m). The difference in average elevation between inactive rock glaciers exposed towards northern and southern directions is less clear compared to active rock glaciers and is approximately 100 – 200 m (Fig. 9).

Inactive rock glaciers are up to 1310 m long and 900 m wide. The largest area covered by an inactive rock glacier measures 0.736 km². 91% of all inactive rock glaciers have an area of less than 0.1 km² (Figs. 11, 12). Most inactive rock glaciers (719 or 78.6%) are tongue shaped, 168 (18.4%) are lobate, 17 (1.8%) are complex and 11 (1.2%) have two tongues. The average length of inactive rock glaciers is 292 m, the average width 167 m and the average area 0,046 km².

The distribution of inactive rock glaciers concerning aspect is similar to that of active rock glaciers with preference of directions towards N, NW and NE although rock glaciers exposed towards S, SW and SE are more abundant (Tab. 4).

The majority (862 or 94.2%) of inactive rock glaciers is classified as talus-derived, ice-cemented rock glacier, 23 (2.5%) probably contain a massive ice core, 15 (1.6%) evolved from talus and moraine, and 13 inactive rock glaciers evolved from moraine.

On the aerial photographs rock glacier springs were recognized at the front of 90 inactive rock glaciers (9.8%). Small lakes are developed at the front of 67 inactive rock glaciers (7.3%).

Like active rock glaciers, most inactive rock glaciers are found in mountain groups composed of metamorphic rocks ("Altkristallin"). Subordinately inactive rock glaciers (66 or 7.2%) are located in catchment areas in which the bedrock is orthogneiss (Zentralgneis; Tauern Window), 45 (4.9%) with rocks of the Schieferhülle (mainly calcareous micaschist and greenschist - Kalkglimmerschiefer, Prasinit of the Tauern Window), 41 are located in the Nördliche Kalkalpen and Lienzer Dolomiten with mainly carbonate sedimentary rocks of Triassic and Jurassic age in the catchment area, 29 (3.2%) are located in the Tuxer Alpen composed mainly of quartzphyllite, 10 (1.1%) in the Engadine Window with mainly schists (Bündnerschiefer) as the source rock, and 9 inactive rock glaciers (1%) with other source rocks (Rieserferner tonalite, serpentinite, Paleozoic rocks of the Karnische Alpen).

4.3 Fossil Rock Glaciers

More than 54% (1713) of all rock glaciers are classified as fossil with an average elevation of 2330 m which is much lo-

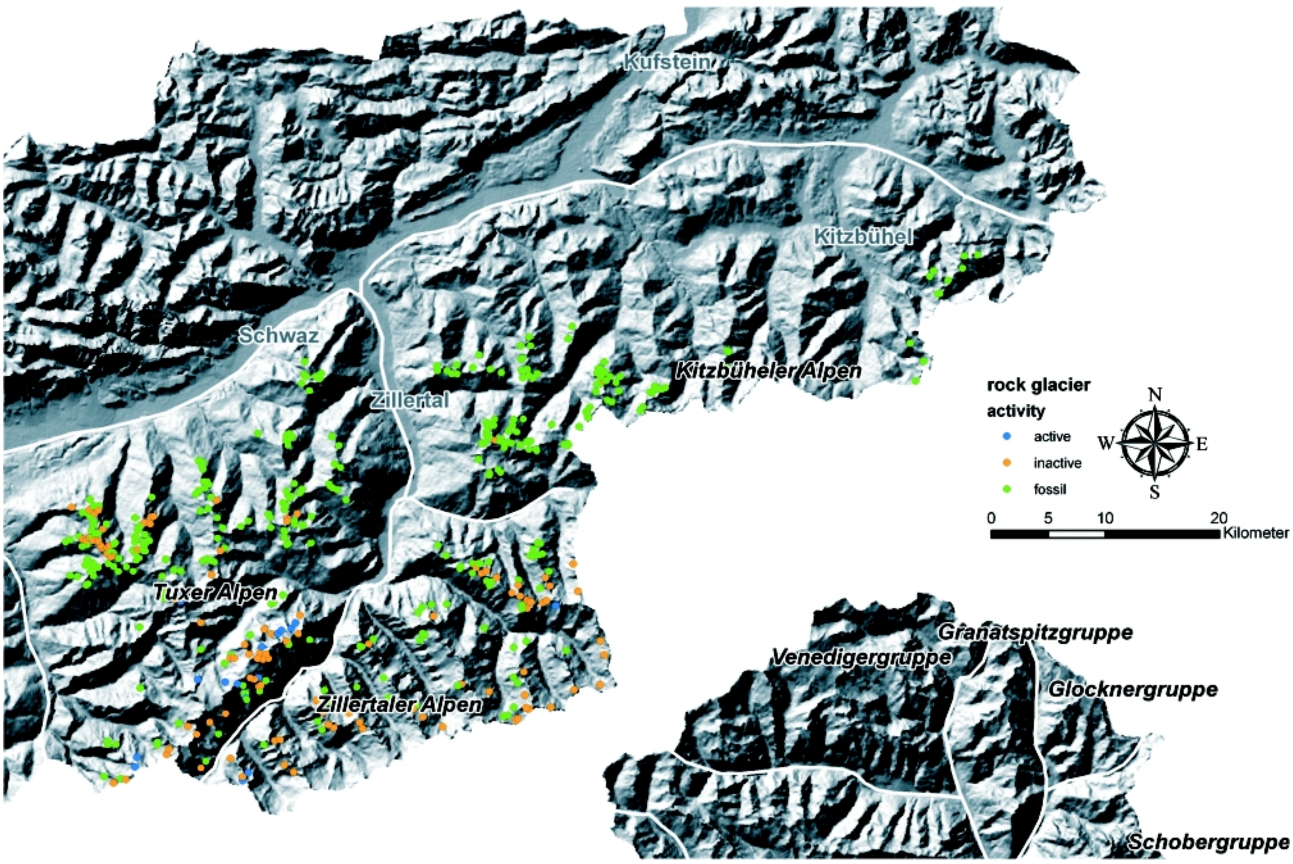

Figure 5: Distribution of rock glaciers in the SE of northern Tyrol (Tuxer, Zillertaler and Kitzbühler Alpen).

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Mountain Group	number of r.g.	area	active r.g.	area	inactive r.g.	area	fossil r.g.	area
Ötztaler-Stubaier Alpen		km²	number	km²	number	km²	number	km²
Gschnitztal/Obernbergtal	23	1.207	1	0.059	6	0.281	16	0.866
Stubaital	114	6.998	21	2.748	33	1.575	60	2.674
Sellrain	105	5.739	16	1.332	27	1.186	62	3.221
Hochedergruppe	29	0.731	1	0.022	9	0.148	19	0.561
Ötztal	451	30.494	135	14.157	142	8.07	174	8.267
Pitztal	147	7.742	44	3.295	51	2.11	52	2.337
Kaunertal	123	7.305	41	3.481	47	2.294	35	1.53
Nauderer Berge	205	12.927	95	7.193	35	1.378	75	4.356
Samnaungruppe	292	12.933	31	1.904	93	3.529	169	7.5
Silvrettagruppe	129	7.584	29	3.063	41	2.182	59	2.34
Verwallgruppe	242	11.808	36	2.021	89	4.528	117	5.259
Nördliche Kalkalpen	212	10.801	7	0.269	39	1.321	166	9.211
Kitzbühler Alpen	110	3.792	0	0	2	0.081	108	3.711
Tuxer Alpen	244	11.295	14	2.191	56	2.72	174	6.384
Zillertaler Alpen	110	5.232	3	0.256	51	2.511	56	2.451
Northern Tyrol	**2536**	**136.588**	**474**	**41.991**	**721**	**33.914**	**1342**	**60.668**
Eastern Tyrol								
Venedigergruppe	43	2.809	5	0.518	34	2.11	4	0.181
Granatspitzgruppe	15	1.258	0	0	9	0.605	6	0.653
Glocknergruppe	8	0.431	0	0	7	0.38	1	0.051
Schobergruppe	122	6.625	17	1.436	51	2.18	54	3.009
Deferegger Alpen	370	16.593	17	1.033	83	2.78	270	12.733
Rieserfernergruppe	19	1.178	4	0.365	7	0.192	8	0.62
Lienzer Dolomiten	10	0.46	0	0	2	0.1	8	0.36
Karnische Alpen	22	1.299	0	0	1	0.011	21	1.288
Eastern Tyrol	**609**	**30.653**	**43**	**3.352**	**194**	**8.166**	**372**	**18.895**
Tyrol	**3145**	**167.241**	**517**	**45.343**	**915**	**42.08**	**1714**	**79.563**

TABLE 2: The distribution of rock Glaciers in the various mountain groups of the Tyrolean Alps (Austria).

wer than that of active and inactive rock glaciers (Tab. 2, 3). The most common elevation of fossil rock glaciers is 2160 – 2500 m (Fig. 7). The front of 67% of all fossil rock glaciers is located at elevations between 2100 and 2500 m. The highest fossil rock glacier occurs in the Ötztaler Alpen (front at 2755 m, rooting zone at 2920 m).

Fossil rock glaciers are widespread in all mountain groups (Figs. 3 – 6). They are up to 1400 m long, 1020 m wide and the largest fossil rock glacier covers an area of 0.655 km². 90% of the fossil rock glaciers cover an area less than 0.1 km².

The average size of fossil rock glaciers is similar to that of inactive rock glaciers: The average length is 284 m, average width 175 m and average area 0.046 km² (Figs. 11, 12).

Most fossil rock glaciers (1298 or 75.8%) are tongue shaped, the percentage of rock glaciers with lobate shape is higher (365 or 21.3%) than that of lobate active and inactive rock glaciers. 26 fossil rock glaciers (1.5%) display two tongues, 3 (0.2%) have three tongues and 21 (1.2%) have a complex shape.

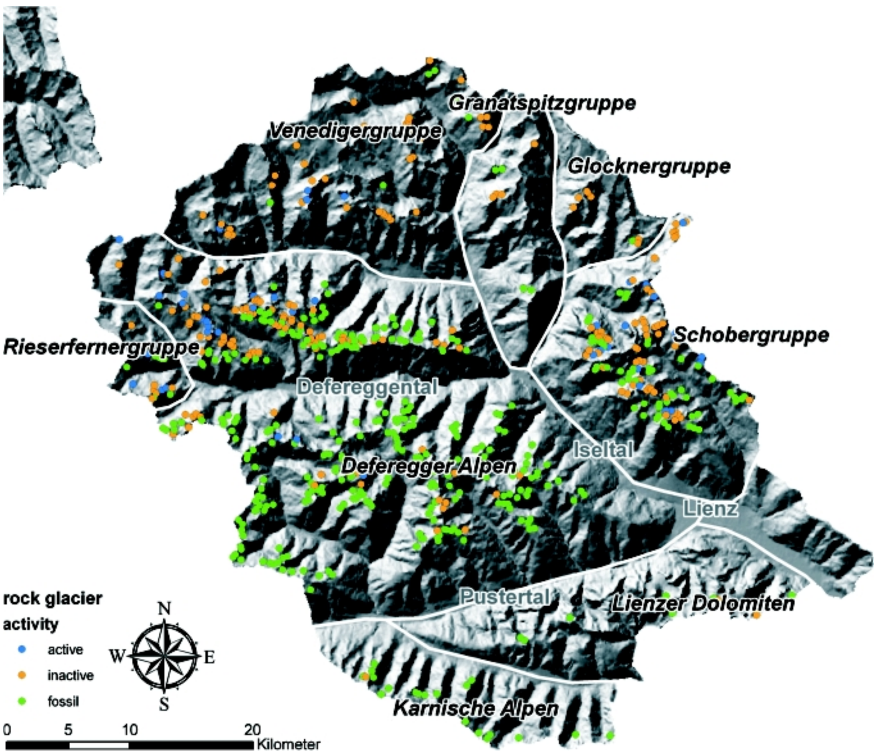

FIGURE 6: Rock glaciers in eastern Tyrol (Venediger, Granatspitz, Glockner, Schober and Rieserfernergruppe, Defereggger Alpen, Lienzer Dolomiten and Karnische Alpen).

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	active rock glaciers	inactive rock glaciers	fossil rock glaciers
number of rock glaciers	**517**	**915**	**1713**
elevation front (m)	2628 (2190 - 3100)	2542 (1960 - 3240)	2279 (1450 - 2755)
elevation rooting zone (m)	2797 (2330 - 3230)	2665 (2020 - 3300)	2384 (1550 - 2920)
average elevation (m)	2704 (2310 - 3150)	2598 (1990 - 3220)	2330 (1500 - 2820)
length (m)	451 (70 - 1650)	292 (50 - 1310)	284 (50 - 1400)
width (m)	201 (40 - 980)	167 (35 - 900)	175 (30 - 1020)
area (km²)	0.088 (0.018 - 0.59)	0.046 (0.003 - 0.736)	0.046 (0.002 - 0.655)

Table 3: Average and range of elevation, length, width and area of active, inactive and fossil rock glaciers in the Tyrolean Alps (Austria).

The distribution of fossil rock glaciers concerning aspect differs to that of active and inactive rock glaciers as exposure directions towards SW and SE, particularly towards S are common (Tab. 4).

A few fossil rock glaciers (16 or 0.9%) are probably of glacial origin, 40 (2.3%) evolved from moraine and talus, 9 (0.5%) from moraine and 1648 (96.2%) are classified as talus-derived rock glaciers, which were ice-cemented.

At the front of 165 fossil rock glaciers (9.6%), a rock glacier spring was observed. Small lakes occur at the front of 62 fossil rock glaciers (3.6%).

Bedrock in the catchment area of 1165 fossil rock glaciers (67%) are metamorphic rocks ("Altkristallin"), 210 rock glaciers (12.2%) are located in areas composed of quartzphyllite, 171 (10%) in the Nördliche Kalkalpen and Lienzer Dolomiten composed of mainly Triassic carbonate rocks, 55 (3.2) in the Tauern Window with orthogneiss (Zentralgneis) as bedrock, 43 (2.5%) in the Tauern Window with rocks of the Schieferhülle (calcareous micaschist, greenschist: Kalkglimmerschiefer; Prasinit), 21 (1.2%) in the Karnische Alpen composed of Paleozoic sedimentary rocks, 16 (0,9%) in the Brenner Mesozoic (metamorphic carbonate sedimentary rocks), 16 (0.9%) in the Greywacke Zone (Paleozoic metamorphic rocks), 11 (0.6%) in the Tarntal Mesozoic, 8 (0.5%) in the Rieserfernergruppe (tonalite), and 7 (0.4%) in the Engadine Window.

4.4 Estimated Ice Volume

The rock glacier inventory allows a rough estimation of the ice volume of active and inactive rock glaciers. The area of the frozen core of active and inactive rock glaciers is smaller than the entire area of the rock glacier by about 20%. The average thickness of the frozen core of active rock glaciers is estimated to be 15 m and that of inactive rock glaciers 10 m. From geophysical data Hausmann et al. (2007, 2012) calculated an ice content of 40 – 60 % for the active rock glaciers Reichenkar, Kaiserberg and Ölgrube. Two cores from the active rock glacier Lazaun (Schnalstal, South Tyrol) yielded average ice contents of 43% for core Lazaun I and 22% for core

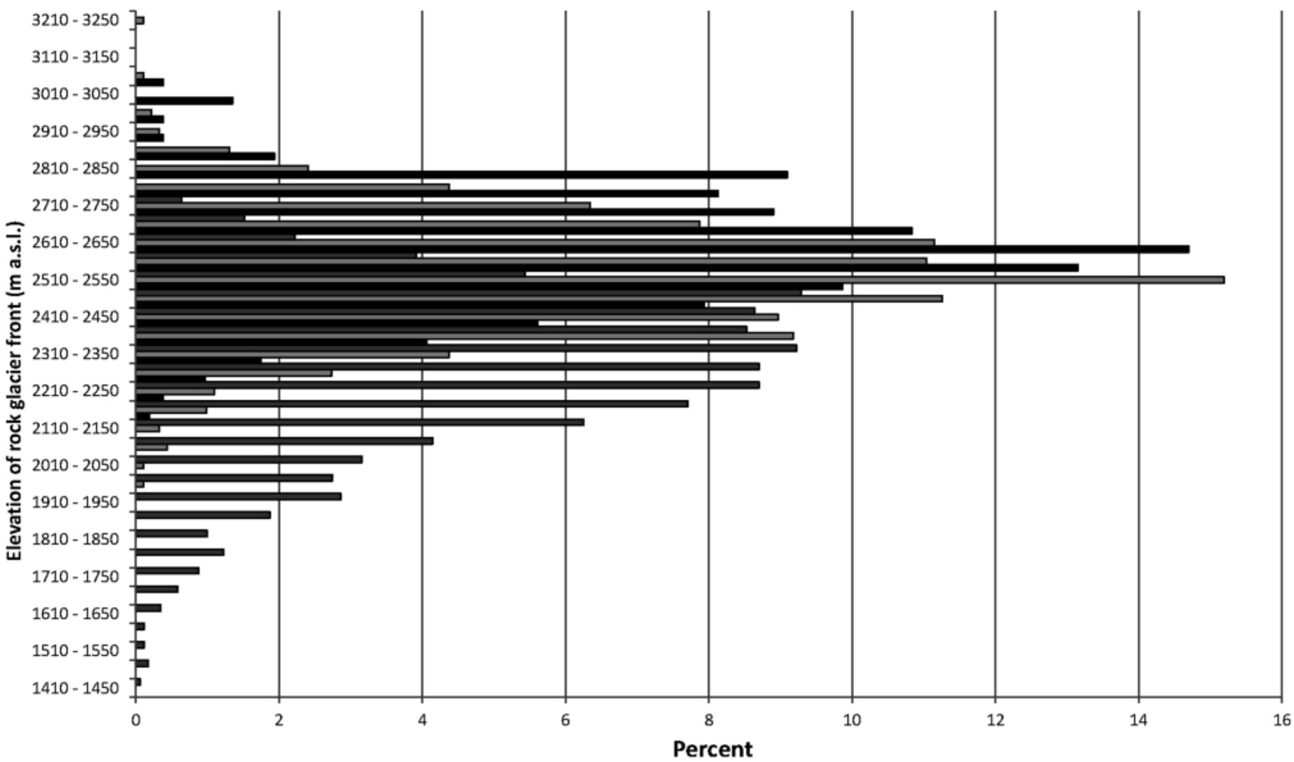

Figure 7: Distribution of active (black), inactive (light gray bars) and fossil rock glaciers (dark gray bars) according to elevation.

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Lazaun II which was drilled near the front (unpubl. data). The majority of active and inactive rock glaciers are smaller, ice-cemented rock glaciers which have lower ice contents as those mentioned above. Therefore the average ice content of active rock glaciers is estimated to be in the order of 30 – 40% and that of inactive rock glaciers 10 – 15%. The result is an ice volume of 0.16 – 0.22 km³ for all active rock glaciers, and 0.03 – 0.05 km³ for all inactive rock glaciers of the Tyrolean Alps. Thus the total amount of ice in active and inactive rock glaciers is approximately 0.19 - 0.27 km³.

aspect	active r.g.	inactive r.g.	fossil r.g.
N (335 - 25)	27.1	24.7	18.1
NE (25 - 65)	11.6	10.4	11.8
E (65 - 115)	11.6	12.9	15.2
SE (115 - 155)	2.3	6.6	7.9
S (155 - 205)	4.8	9.8	15.8
SW (205 - 245)	4.1	7.3	8.1
W (245 - 295)	21.3	13.6	13.4
NW (295 - 335)	17.2	14.7	9.7

Table 4: Distribution of active, inactive, and fossil rock glaciers of the Tyrolean Alps (Austria) according to aspect (flow direction).

5. Discussion

Lieb (1991) studied the horizontal and vertical distribution of 546 rock glaciers (236 intact, 310 fossil) in the mountain groups of the Hohe Tauern. He recognized that the number of rock glaciers increases from N to S, also the lower limit of the rock glaciers increases from N towards the S. From the lower limit of intact (active and inactive) rock glaciers Lieb (1991) estimates that the lower limit of discontinuous permafrost in the Hohe Tauern is at an elevation of approximately 2500 m. In the Hohe Tauern, most rock glaciers are exposed towards NW to NE, rock glaciers exposed towards W are also abundant. This is in contrast to fossil rock glaciers which are mostly exposed towards SW to SE.

In the western part of the Austrian Alps, the distribution of rock glaciers concerning aspect shows a similar trend as observed in the eastern part by Lieb (1991). Active and inactive rock glaciers show a preferred aspect towards N, NW and NE, whereas rock glaciers facing towards S, SE and SW are rare. Less clear is the trend with fossil rock glaciers which show a high percentage exposed towards S, SE and SW. It seems that under cooler climatic conditions aspect is less important than under warmer climatic conditions.

The average elevation of the lower limit of intact rock glaciers exposed towards N is at 2409 m and towards S at 2559 m. The lower limit of most intact rock glaciers in the Hohe Tauern (>80%) lies between an elevation of 2300 and 2700 m, that of fossil rock glaciers between 2100 and 2600 m (>75%) (Lieb 1991).

Lieb (1991) argues that climatic conditions are responsible for the abundance of rock glaciers in mountain groups south of the central Alps. He also states that bedrock geology has also an influence on the distribution of rock glaciers as they are concentrated in areas composed of metamorphic rocks ("Altkristallin").

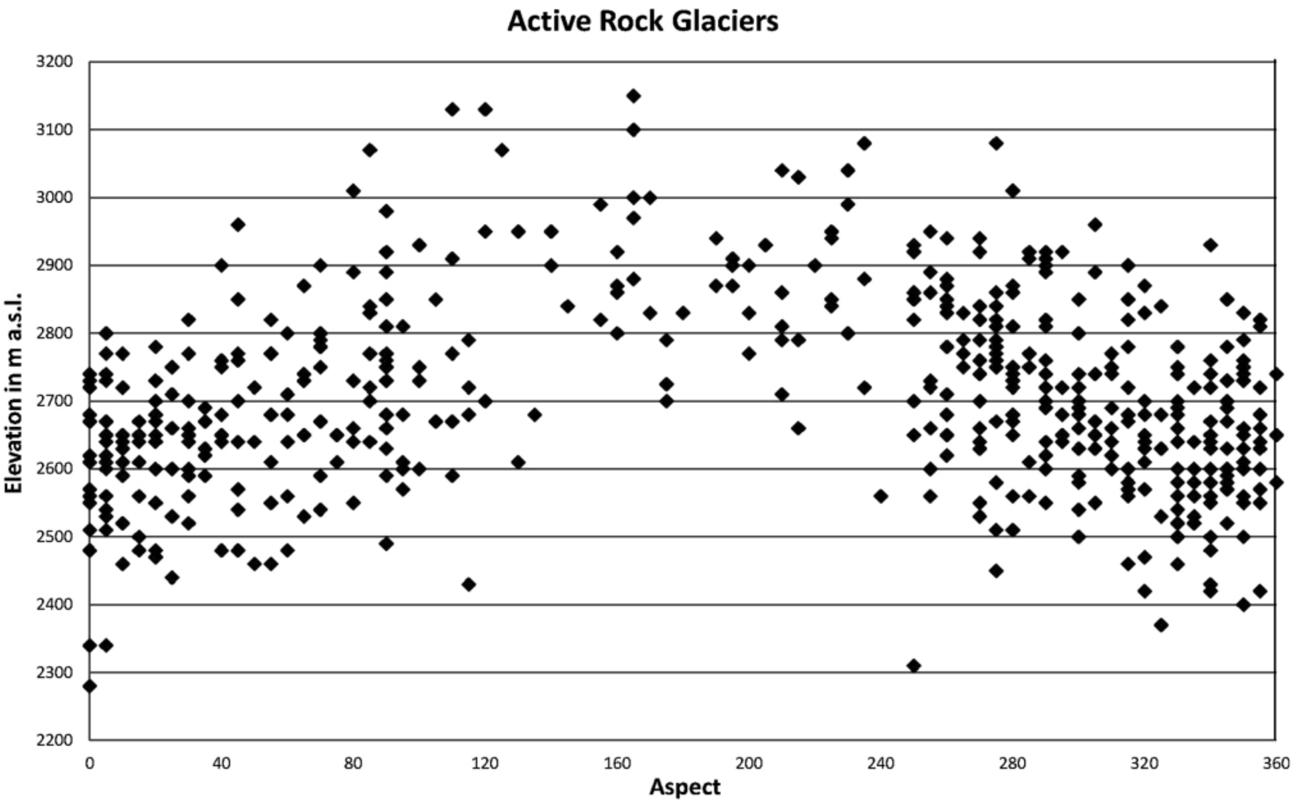

Figure 8: The average elevation of active rock glaciers related to aspect. Active rock glaciers exposed towards a northern aspect occur at elevations which are 300 – 400 m lower than that of rock glaciers exposed towards a southern aspect.

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In a study of the relationship between bedrock type and distribution of 332 rock glaciers in the Niedere Tauern Kellerer-Pirklbauer (2007) showed that metamorphic rocks such as mica schists, paragneisses and orthogneisses are by far the most abundant bedrock type. This is also observed in the western part of the Austrian Alps where more than 70% of all

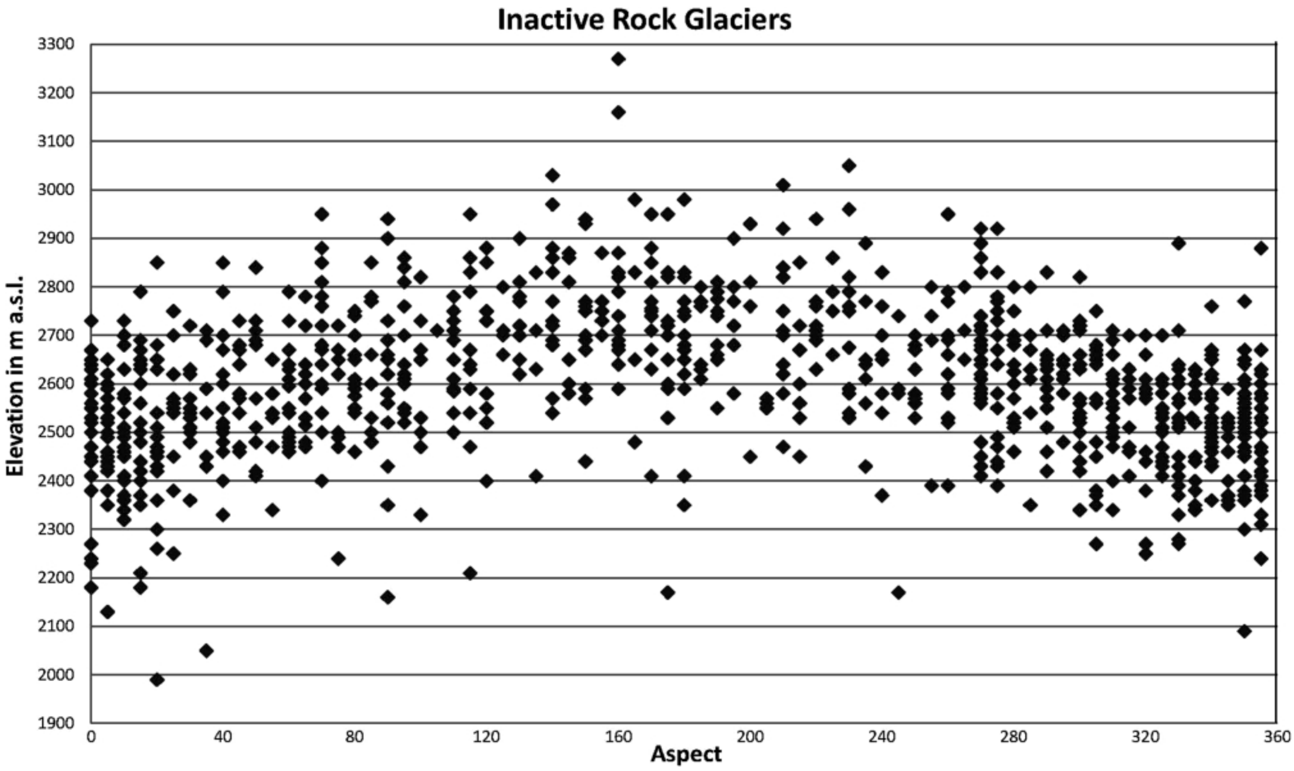

Figure 9: The average elevation of inactive rock glaciers related to aspect. Inactive rock glaciers exposed towards a northern aspect occur at elevations which are 100 - 200 m lower than that of rock glaciers exposed towards a southern aspect.

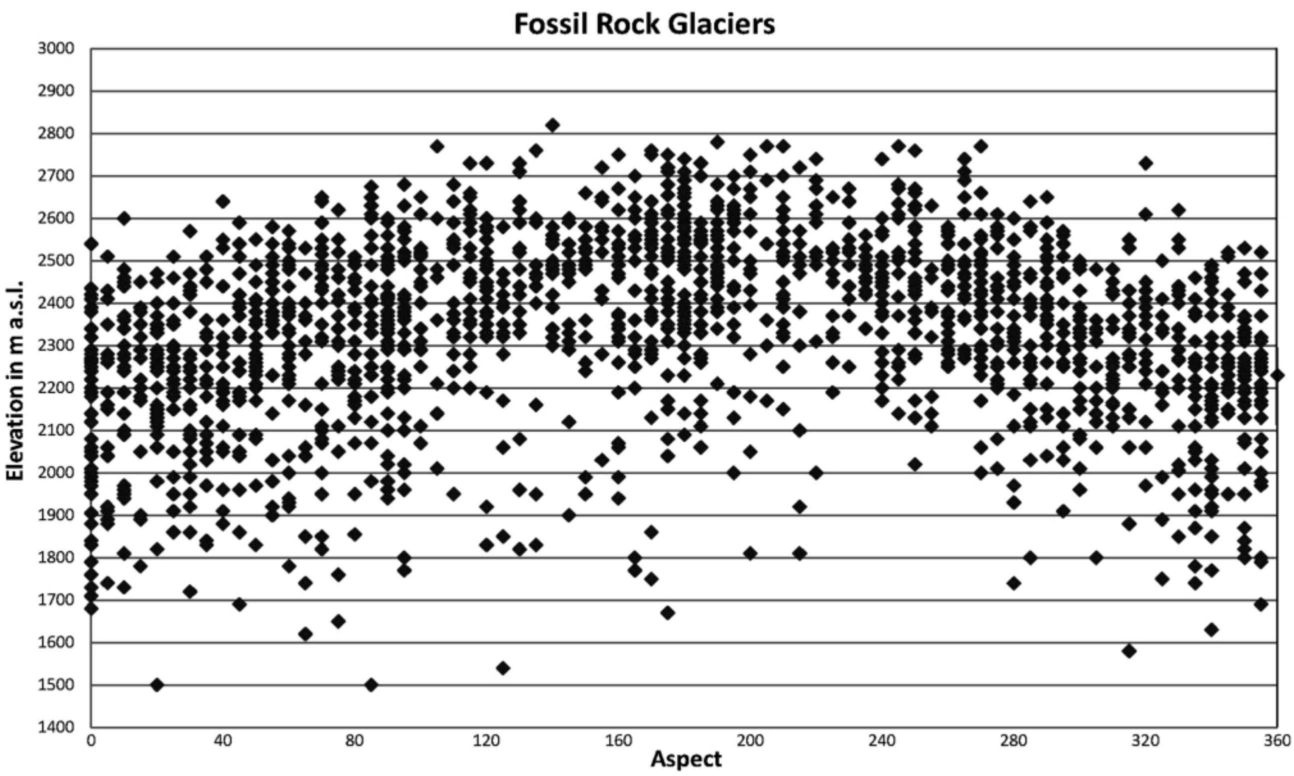

Figure 10: The average elevation of fossil rock glaciers related to. Fossil rock glaciers exposed towards a northern aspect occur at elevations which are 100 - 300 m lower than that of rock glaciers exposed towards a southern aspect.

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rock glaciers occur in mountain groups composed of rocks summarized under the term "Altkristallin". In general, rock glaciers may develop in all major bedrock types if the local topoclimatic conditions are favorable (Kellerer-Pirklbauer, 2007). The fact that most mountain ranges in Austria which are favorable for the formation of rock glaciers are composed of metamorphic rocks, particularly micaschists and gneisses ("Altkristallin") explains that by far most rock glaciers are composed of these types of metamorphic rocks. It is also evident that in parts of the Hohe Tauern which are composed of compact orthogneiss with poorly developed schistosity ("Zentralgneis" of the Tauern Window) and in areas composed of fine-grained metamorphic rocks (phyllites, calcareous mica schists) which disintegrate into fine-grained material, rock glaciers are less abundant than in areas composed of metamorphic rocks termed "Altkristallin".

The average lower limit of inactive rock glaciers is low in the mountain groups north of the central Alps (at 2307 m in the Nördliche Kalkalpen, 2439 m in the Tuxer Alpen, 2469 m in the Silvrettagruppe, 2499 m in the Verwallgruppe), highest in the mountain groups of the central Alps (Ötztaler, Stubaier und Zillertaler Alpen, Venedigergruppe) ranging from 2500 to 2650 m. It is also high in the Deferegger Alpen and Schobergruppe with elevations of 2565 – 2580 m and very low in the southernmost mountain groups (2180 m in the Lienzer Dolomiten and 2355 m in the Karnische Alpen). The data show that also in the western part of the Austrian Alps the average lower limit of discontinuous permafrost is close to an elevation of 2500 m.

Age-determinations on rock glaciers in the Tyrolean Alps are very rare (Kellerer-Pirklbauer, 2008, Ivy-Ochs et al., 2009). Fossil (relict) rock glaciers which commonly are strongly or completely covered with vegetation are older features compared to the intact (active and inactive) rock glaciers and are interpreted to have formed during and after the Lateglacial deglaciation period (Kellerer-Pirklbauer et al., 2012, this vol.). Intact rock glaciers formed during the Holocene, some of them probably during retreat of debris-covered cirque-glaciers after the Little Ice Age (Berger et al., 2004).

The total amount of ice in active and inactive rock glaciers is very small compared to the ice volume of glaciers. Lambrecht and Kuhn (2007) estimated an ice volume of 17.7 km^3 for all glaciers in the Austrian Alps in 1998. According to the Austrian Glacier Inventory 70.5 % of all glaciers are located in Tyrol (Hasslacher and Lanegger, 1988) with an ice volume of approximately 13 km^3. The ice volume stored in rock glaciers accounts for only about 1.5 – 2.3% of the ice volume of glaciers.

As the annual ablation rate of rock glaciers is also much smaller than that of glaciers, the amount of meltwater released from the melting of permafrost ice of active and inactive rock glaciers is very small compared to that of glaciers. Krainer and Mostler (2002) showed that most of the water released from active rock glaciers is derived from snowmelt and rainfall. Therefore, in glaciated mountain groups the influence of permafrost-derived meltwater from rock glaciers on the discharge pattern is extremely small.

It is expected that climate warming will cause a decrease

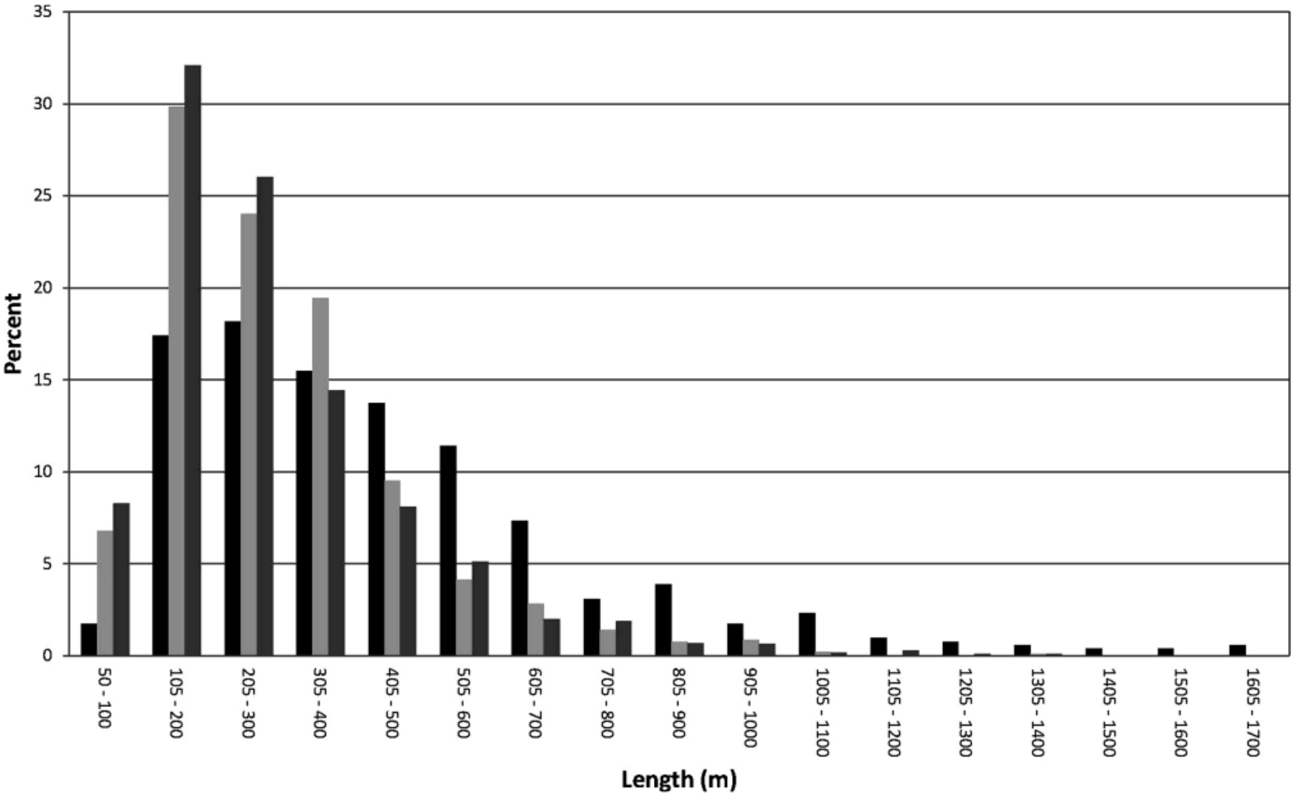

Figure 11: The percentage of active (black bars), inactive (light gray) and fossil rock glaciers (dark gray) according to length.

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in the number of active and inactive rock glaciers and an increase of fossil rock glaciers during the next decades.

6. Conclusion

In the Tyrolean Alps (Austria) 3145 rock glaciers were recorded which cover an area of 167.2 km². Of these, 517 (16.4%) were classified as active, 915 (29.1%) as inactive, and 1713 (54.5%) as fossil.

Most active and inactive rock glaciers are tongue-shaped, talus-derived, ice-cemented rock glaciers. Glacier-derived rock glaciers containing a massive ice-core seem to be rare.

The distribution of active and inactive rock glaciers indicates that the lower limit of discontinuous permafrost in the western part of the Austrian Alps is located at an elevation of approximately 2500 m.

The total amount of ice in active and inactive rock glaciers is estimated to be 0.19 - 0.27 km³ which is small compared to the ice volume contained in the glaciers of the Tyrolean Alps.

Most rock glaciers occur in the mountain groups of the central Alps in which bedrock is composed mainly of mica schists, paragneiss, orthogneiss and amphibolites ("Altkristallin").

Active and inactive rock glaciers exposed towards a northern direction occur at elevations up to 400 m lower compared to rock glaciers exposed towards south and most active and inactive rock glaciers are exposed towards a northern (NW, N and NE) direction, rarely towards S, SE and SW.

Active and inactive rock glaciers occur in mountain groups with summit elevations above 2700 m. The highest active and inactive rock glaciers were recognized in mountain groups with the highest peaks (Ötztaler Alpen, Venedigergruppe).

Compared to the first version of the permafrost inventory for the European Alps presented by Cremonese et al. (2010), which includes 4795 rock glaciers from seven regions in Austria, France, Italy and Switzerland, the Tyrolean Alps of Austria contain a high number of rock glaciers, which are particularly abundant in the Stubaier and Ötztaler Alpen. The inventory provides additional data for the modeling of the spatial distribution of permafrost in the European Alps (see Boeckli et al., 2012).

The relatively small ice volume of rock glaciers and the small melting rates compared to the glaciers of the Tyrolean Alps suggest that the amount of meltwater derived from active and inactive rock glaciers is very small compared to the meltwater derived from glaciers. Thus water derived from the melting of permafrost ice of active and inactive rock glaciers has only little influence on the discharge pattern in the Tyrolean Alps.

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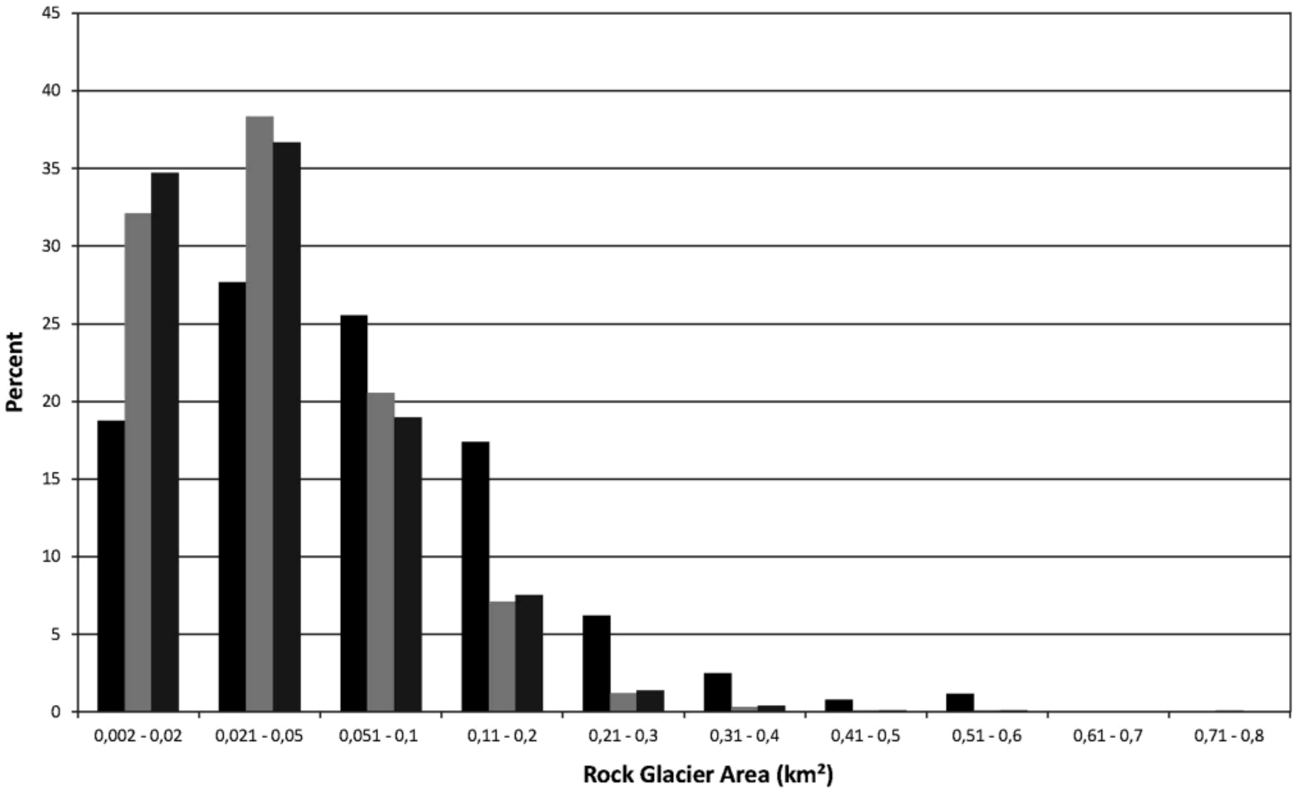

Figure 12: The percentage of active (black bars), inactive (light gray) and fossil rock glaciers (dark gray) according to area.

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