



Nationwide aerial laser scanning reveals relict rock glaciers and protalus ramparts in Slovenia

Mihaela Triglav-Čekada¹, Blaž Barborič¹, Mateja Ferk², Matija Zorn²

¹Geodetic Institute of Slovenia, Jamova 2, SI-1000, Ljubljana, Slovenia

5 ²Research Centre of the Slovenian Academy of Sciences and Arts, Anton Melik Geographical Institute, Gosposka ulica 13, SI-1000, Ljubljana, Slovenia

Correspondence to: M. Triglav-Čekada (mihaela.triglav@gis.si)

Abstract

In 2015 the nationwide aerial laser scanning (lidar) of Slovenia became publicly available. These data enable a wide range of
10 detailed geomorphological studies, also in areas that are less accessible or covered with dense vegetation. This makes it
possible to identify potential rock glaciers and protalus ramparts in the Slovenian mountains. The laser scanning products,
the grey-shaded terrain model and the classified point cloud were used to identify and measure these features. All the
mountainous areas at elevations of approximately 1200 m above sea level (a.s.l.) were evaluated. During the Alpine Late
Glacial period these were in glacial and periglacial conditions. The mountain ranges of the Julian Alps, Karavanks, Kamnik-
15 Savinja Alps, Pohorje and Dinaric mountains (Trnovski Gozd and Snežnik) were evaluated. Twenty potential rock glaciers
and eight potential protalus ramparts were found. They are the most abundant in the Karavanks, followed by the Julian Alps,
with one potential rock glacier also on the Snežnik plateau. The majority of the potential rock glaciers are probably relicts,
due to the heavy vegetation cover, the low mean elevations (between 1040 m and 1850 m a.s.l.) and because their slopes are
directed more towards southern directions (65 % of rock glaciers). The identified rock glaciers rarely exceed 600 m in
20 length. The terminus slope angles of the identified objects are from 20° to 40°. Three of the identified protalus ramparts can
be regarded as relict, due to the total vegetation cover; the remaining five can be regarded as intact. The potential protalus
ramparts are found at elevations between 1220 m and 1950 m a.s.l. All the identified protalus ramparts are directed towards
southern directions, with terminus slope angles from 30° to 40°. The spatial distribution of the discussed permafrost objects
25 in Slovenia with regards to the bedrock composition presented on the geological map of Slovenia (scale 1:250,000) reveals
that 75 % of all objects can be found in thick-bedded Dachstein limestones with transitions to dolomite, while almost all the
remaining objects are found in Triassic dolomite.

Keywords

Rock glaciers, protalus ramparts, Slovenia, nationwide aerial laser scanning



1 Introduction

The availability of very-high-resolution digital elevation models derived from aerial laser scanning has only recently enabled spatial distribution studies of glaciers and permafrost features (Abermann et al., 2010; Knoll and Kerscher, 2009; Colucci et al., 2013; Krainer and Ribis, 2012). Mountain permafrost describes the areas where the subsurface material has below-zero temperatures all year round and can be recognised in talus areas in a continuum of landforms from rock glaciers to protalus ramparts. Previously, other theories have been proposed to describe the possible origins of such features, from retreating tongue glaciers buried under thick debris cover to rock or talus avalanches (Whalley and Azizi, 2003; Haeberli et al. 2006; Haeberli et al. 2010; Berthling, 2011; Benn and Evans, 2013; Scotti et al., 2013; Scapozza, 2015). Morphologically, rock glaciers are tongue-like or lobate bodies with ridges and furrows, usually resembling small glaciers; they have steep fronts, steep sides and a length greater than their width, and they mainly exist on the valley floor. The protalus ramparts have a single ridge with a very steep front (40-45°), but they occur on valley walls in front of a talus slope and they are generally wider than they are longer (Shakesby et al., 1987; Millar and Westfall, 2008; Berthling, 2011; Scapozza, 2015). Under the definition of permafrost a protalus rampart can be regarded as an embryonic stage of a talus rock glacier (Scapozza, 2015). Otherwise, the protalus (pronival) ramparts can be regarded as a ridge or a ramp of debris formed at the downslope margin of a perennial or semi-perennial snow field, which is located at the base of a steep slope or cirque (Shakesby, 1987; Scotti et al., 2013; Scapozza, 2015). To distinguish it from the permafrost creep, the latter should be referred to as a pronival rampart (Hedding, 2011). Rock glaciers represent the majority of objects recorded in regional permafrost inventories; the protalus ramparts represent a much smaller share, i.e., up to 13 % of all data (Scotti et al., 2013; Scapozza, 2015).

Rock glaciers and protalus ramparts are considered as intact when they contain permafrost. Intact rock glaciers can be considered as active, when they contain enough permafrost or ice to enable its movement, and inactive in other cases (Haeberli et al., 2006; Ribolini et al., 2010; Krainer and Ribis, 2012; Kääb, 2013; Kaufmann and Kellerer-Pirklbauer, 2015). The mean annual flow velocities of active rock glaciers are of the order of a few centimetres to several metres per year (Kaufmann, 2012; Scapozza, 2015) and they are measured by geodetic, photogrammetric or remote sensing methods (Kaufmann, 2012). The grain size of talus material in an active rock glacier layer usually decreases with depth, with larger rocks or pebbles on the top and finer grains on the bottom (Haeberli et al., 2006). Inactive rock glaciers can still contain small patches of permafrost or ice, but its share is too small to allow movement. In the permafrost-degradation process inactive rock glaciers finally turn to the relict or fossil forms, which no longer contain any permafrost. Morphologically, relict rock glaciers have a much more subdued relief, with collapsed structures on their surfaces, while their front is less steep than for intact glaciers (Scotti et al., 2013). Relict rock glaciers are highly vegetated, while the intact forms are not (Krainer and Ribis, 2012; Kaufmann and Kellerer-Pirklbauer, 2015). The alpine active rock glaciers are less than 10 % covered with pioneer plants, mainly mosses and lichens. The inactive rock glaciers are covered up to 70 % with sub-alpine dwarf shrubs, herbs, grasses and a few pioneer plants. In contrast, the relict rock glaciers are characterized by a dense vegetation cover, where more than 80 % of the rock glacier's surface is covered with coniferous trees, sub-alpine dwarf shrubs and grass



(Cannone and Gerdol, 2003; Burga et al., 2004). In the European Alps 75 % of rock glaciers are becoming relict (Cremonese et al., 2011). Intact rock glaciers are mainly exposed to the north, while the relict glaciers are exposed to the south (Krainer and Ribis, 2012; Scotti et al., 2013). Relict forms are usually located at lower elevations than the intact forms (Scotti et al., 2013). The intact rock glaciers are believed to have been formed about 3100 years ago, the relict rock glaciers during the
5 Alpine Late Glacial and they decayed between the end of the Alpine Late Glacial and the beginning of the Holocene around 11.6 ka ago (Frauenfelder and Kääb, 2000; Harris et al., 2009; Böhlert et al., 2011a, 2011b; Scotti et al., 2013).

Different regional permafrost inventories around the world have been made (Shakesby et al., 1987; Frauenfelder and Kääb 2000; Dramis et al., 2003; Millar and Westfall, 2008; Krainer and Ribis, 2012; Colucci et al., 2013; Stotti et al., 2013; Scapozza, 2015; Schmid et al., 2015). Additionally, a permafrost inventory for the whole of the European Alps has been
10 made, with only Monaco, Liechtenstein and Slovenia not being included (Cremonese et al., 2011). The first nationwide aerial laser scanning of Slovenia, made during 2014–2015, allows us to fill this gap in the permafrost inventory of European Alps with data from Slovenia. In Slovenia, 6 % of its area is at elevations higher than 1200 m (Fridl et al., 1998) (Fig. 1), covering the highest peaks of the Alps (i.e., Julian Alps, Karavanks, Kamnik-Savinja Alps) and the Dinaric Mountains (i.e., Trnovski Gozd and Snežnik). Those areas were, in the time of the Alpine Late Glacial, in glacial or periglacial conditions
15 (Colucci et al., 2014; Ferk et al., 2015). Due to the fact that no active rock glaciers are known to exist in Slovenia, the laser scanning data enables us, for the first time, to study the relict permafrost features hidden under the vegetation on a general scale. By compiling an inventory of potential relict rock glaciers and protalus ramparts for Slovenia from the aerial laser scanning data, we seek to study: (i) the average slope exposition of the relict permafrost features, (ii) the spatial distribution with regard to the bedrock composition, and (iii) the average elevation and the size of the recognized features. Finally, we
20 seek to prove that stand-alone aerial laser scanning data is enough to discover larger potential relict permafrost features.

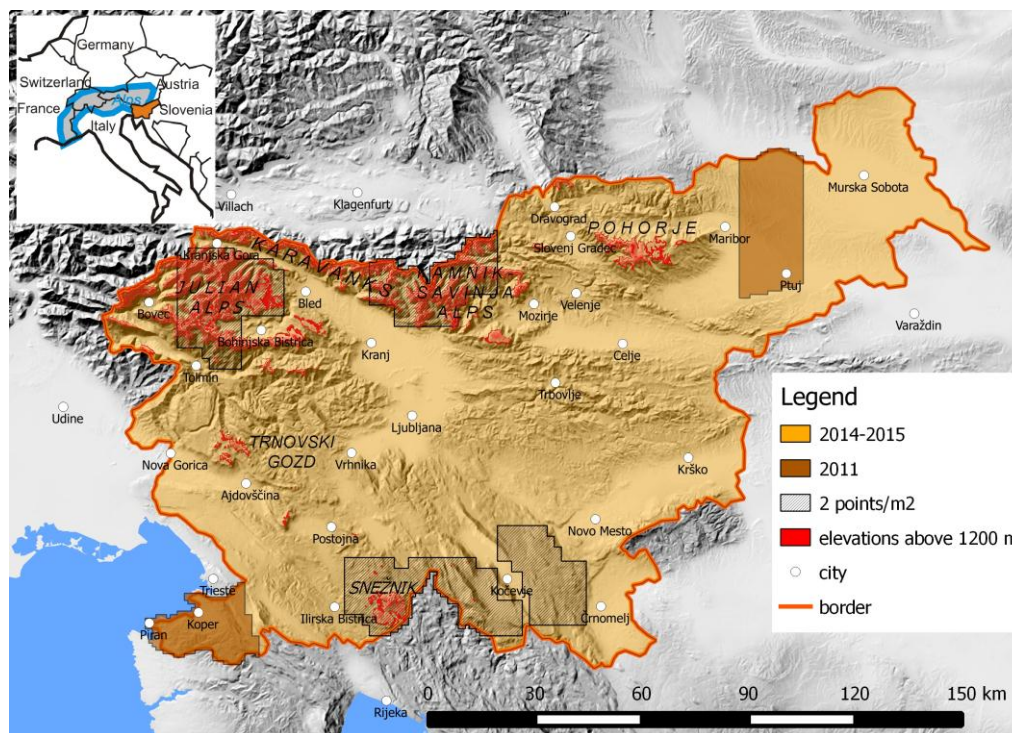


Figure 1. The potential areas of permafrost features in Slovenia at elevations higher than 1200 m and the division into aerial laser scanning densities (5 points/m² for the majority of Slovenia, 2 points/m² only in marked areas) and the years when the data were acquired.

2 Data

- 5 The source for the rock glacier and protalus rampart study was the nationwide aerial laser scanning data for Slovenia that was mainly acquired in 2014 and 2015 (Fig. 1). For the first time these data made it possible to gain a detailed look under the forests that cover approximately 60 % of the Slovenian territory (Hladnik and Žižek, 2012). The previously existing nationwide digital terrain models were based on aerial photogrammetry, where a smaller spatial resolution (5 m × 5 m) and vertical accuracy were achieved, and therefore they were unable to present the geomorphologic features under the forests.
- 10 The aerial laser scanning of Slovenia enabled the production of a digital terrain model with a 1 m × 1 m spatial resolution. The horizontal accuracy of the laser scanning data was 30 cm and the vertical accuracy was 15 cm. The laser scanning was conducted with point densities for the first returns of 5 points/m² for the majority of the area and 2 points/m² for the large forests and open alpine areas. The average point density for all the points was 11 points/m² for the whole country, covering approximately 20,000 km². To enable the best possible vegetation penetration of the laser points to the ground, the scanning
- 15 was only allowed in the leaf-off season, and in the highlands with coniferous forests during times without snow coverage. Therefore, the alpine regions were scanned in the middle of August 2014, when, unfortunately, a very wet and cold summer prevented the usual snow melting, which means that an unusually large number of snowfields are still present in the digital terrain model of the Slovenian Alps. In forests a maximum of 10 % of all the laser points can penetrate to the ground terrain



(Triglav-Čekada et al., 2010); therefore, the terrain under the vegetation in the Slovenian nationwide laser scanning is represented by densities that in some parts are even smaller than 1 point/m². Such small densities under the vegetation result in an unsmooth representation of the terrain under the forest in the grey-shaded terrain model compared to the areas without dense vegetation coverage.

- 5 The laser scanning covers the whole territory of Slovenia with a 250-m overlap on the borders. The outcomes of the nationwide aerial laser scanning are:
- (i) the classified point cloud stored in LAS format, where the points are classified on the ground, three types of vegetation (low – up to 1 m of vegetation height, medium – between 1 and 3 m, and high – more than 3 m), buildings and unclassified points;
 - 10 (ii) the terrain point cloud in LAS format (just points classified as ground);
 - (iii) digital terrain model in ASCII format with a grid size of 1 m × 1 m;
 - (iv) grey-shaded terrain model stored in a georeferenced TIFF format with a pixel size of 1 m × 1 m produced from the digital terrain model.

The classification of the point cloud on the ground, buildings and vegetation was made using gLidar software, where the 15 algorithms described in Mongus and Žalik (2014) and Mongus et al. (2014) were used. The elevation data are stored in heights above sea level and in two horizontal coordinate systems: the new D96/TM (geodetic datum 1996, Transverse Mercator projection – this is the Slovenian realisation of ETRS89) and the old D48/GK (geodetic datum 1948, Gauss-Krüger projection). For details about the transformations between the two systems see Berk and Komadina (2013). The data are stored in files covering 1 km² or 5 km² for the grey-shaded terrain model. The nomenclature for 1 km² is defined by its 20 lower-left corner; therefore, the file GK_410_145 is described with the coordinates 412000 m, 148000 m in the D48/GK coordinate system. The data are freely available (http://gis.arso.gov.si/evode/profile.aspx?id=atlas_voda_Lidar%40Arso).

An additional source for an easier identification of the talus material behind the inspected objects was the orthophoto images made as part of the Cyclical aerial surveying of Slovenia (CAS) from large-format aerial photogrammetric images. Stereoscopic images for orthophoto production were acquired in a different year than the aerial laser scanning. The 25 orthophoto is produced on a scale of 1:5,000 with a pixel size of 0.5 m for the mountainous areas. The CAS project started in 1975; the permanent 3-year cycle for imaging the whole of Slovenia was introduced in 1985; and the orthophoto is regarded as its standard product from 2001 onwards.

The study of the bedrock composition of the identified objects is based on the Geological map of Slovenia on a scale of 1:250,000 (Buser, 2010). This map was compiled from the basic geological map on a scale of 1:100,000, which was later 30 updated using the facts gained from extensive fieldwork lasting more than 15 years (Komac, 2005).



3 Method

The inventory of potential rock glaciers and protalus ramparts was compiled via a visual inspection of the grey-shaded terrain model with a 1 m × 1 m pixel size. Due to the nicely described relief features in the grey-shaded terrain model the identification is similar to identifying objects from Google Maps (Schmid et al., 2015). The rock glaciers and protalus ramparts were identified on the basis of their flow patterns and structures, which include ridges and furrows and the frontal ridge appearance as well as the texture differences of such features compared to the surrounding slopes (Fig. 2). When an object was found, detailed measurements were made in a classified point cloud. This classified point cloud enables measurements of the heights, slope angles, areas and a general study of the vegetation coverage. Fig. 2 shows a protalus rampart (no. PR_1) and a rock glacier (no. RG_1), both under coniferous forest. No detailed fieldwork was conducted yet, due to the fact that the intention of this research was to obtain a general overview of the spatial distribution and the common characteristics of such potential objects in Slovenia.

The objects were classified on the basis of their morphology (Scotti et al., 2013), where rock glaciers can be distinguished depending on the source of the sedimentary material that is transported downslope on the talus and debris types. A talus rock glacier is located at the base of a talus slope. A debris rock glacier forms downslope from the end moraines of small glaciers, mainly located in cirques, and is composed of reworked glacier debris. Only the objects that have some kind of terminal edge, with a steep front, were included, so as not to confuse them with glacier moraines. Due to the fact that all the examples of protalus ramparts presented in this study are found on talus slopes we will treat them as a relict embryonic stage of talus rock glaciers, as proposed by Scapozza (2015), and not as pronival ramparts. It would be hard to distinguish relict pronival ramparts from relict terminal moraines based only on a grey-shaded terrain model identification, especially in cirques that are no longer filled with snowfields. Therefore, the ramps of debris formed at the end of small cirques were not accounted for in our inventory as we treat them as glacial terminal moraines.

The landform attributes include geographical coordinates (described with aerial laser scanning 5 km² in which the object is presented), mountain sectors, elevation (minimum of terminus, maximum and mean), height of the terminus, terminus slope angle, length and width, slope aspects, vegetation coverage, and bedrock composition (Table 1). The topographic attributes like the slope aspect, the geographical location (the name of the nearest mountain) and the existence of nearby watercourses were defined from the grey-shaded terrain model and additional detailed topographic maps. The elevations, terminus slope angles and vegetation coverage were measured in a classified point cloud. The bedrock composition is defined based on a general geological map of Slovenia.

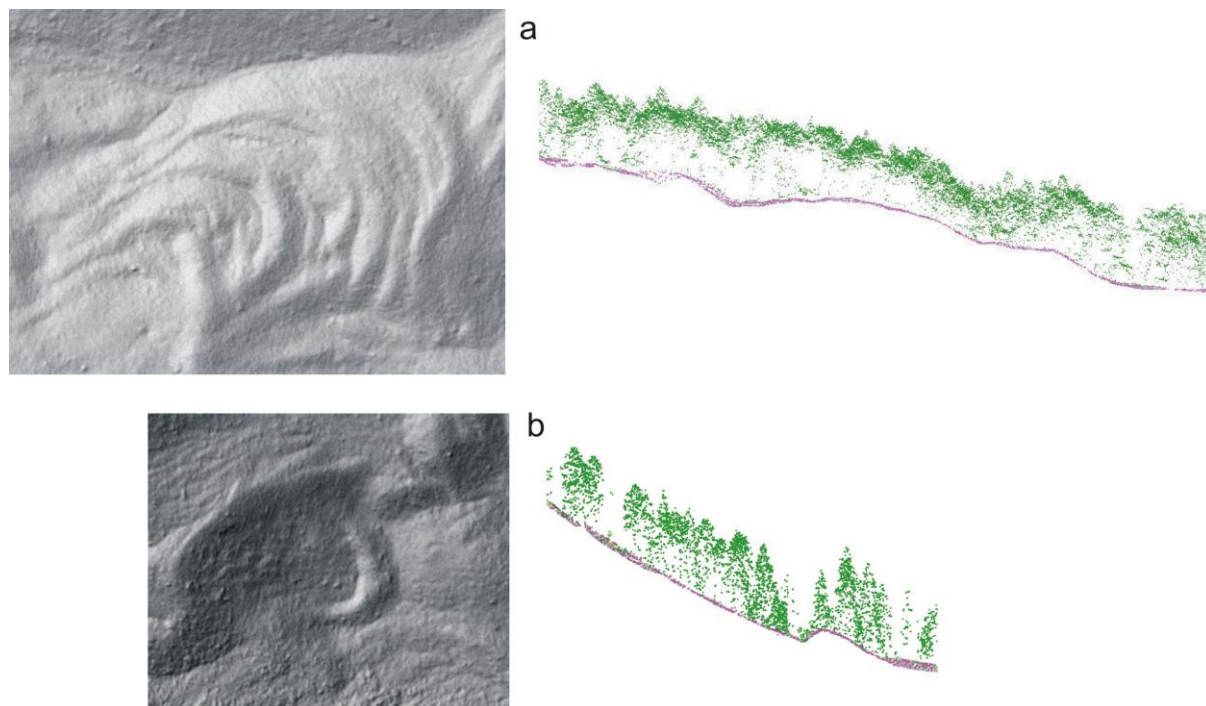


Figure 2. Rock glacier (no. RG_1) (a) and protalus rampart (no. PR_1) (b) in the grey-shaded terrain model and in a side view of the classified point cloud (pink points – ground, green points – vegetation).

3 Results

5 3.1 Statistics

The visual inspection of the grey-shaded relief model was made on areas with elevations of, or higher than, 1200 m above sea level (a.s.l.). This includes the mountain ranges of the Julian Alps, Karavanks, Kamnik-Savinja Alps, Pohorje, Trnovski Gozd and Snežnik (Fig. 1) where we inspected more than 120 locations in detail. We found potential rock glaciers and protalus ramparts only in the Karavanks, Julian Alps and on the Snežnik plateau. In the Karavanks we identified 12 rock glaciers and 3 protalus ramparts. In the Julian Alps we identified 7 rock glaciers and 5 protalus ramparts. Additionally, one potential rock glacier was identified on the Snežnik plateau (Fig. 3). Altogether, we identified 20 rock glaciers and 8 protalus ramparts. The potential rock glaciers and protalus ramparts are presented on the general map (Fig. 3) and in Table 1 and 2. The majority of the identified rock glaciers can be regarded as talus rock glaciers, only two (RG_10 and RG_17) can be regarded as potential debris rock glaciers. All the identified protalus ramparts can be regarded as talus.

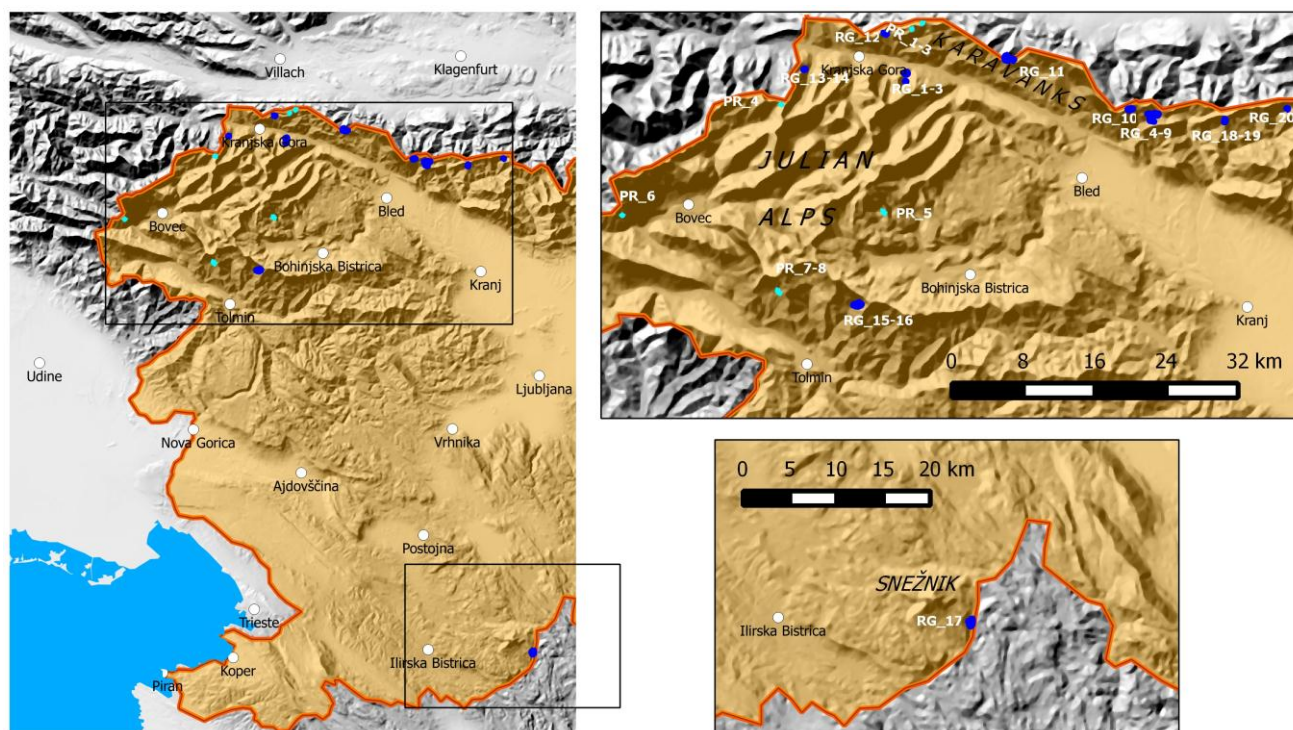


Figure 3. General map of the identified objects: RG – rock glacier and PR – protalus ramparts.

Lithologically, the Julian Alps are formed from relatively large homogeneous units of Triassic limestones and dolomites, which typically form high mountain plateaus surrounded by steep peaks and are dissected by deep glacial valleys. The Karavanke mountains, on the other hand, are lithologically very heterogeneous, formed from Carboniferous and Permian shale, quartz sandstone and conglomerates, and several lithostratigraphic units of Triassic Carbonates (Buser, 2010). Morphologically, they form steep and narrow ridges that are elongated in the west-to-east direction. The identified rock glaciers were mainly formed in (1) thick-bedded Dachstein Limestone with transitions to dolomite, (2) thick-bedded Triassic dolomite, and (3) Mesozoic carbonate and clastic rocks.

The forest timberline in Slovenia is at elevations between 1500 m and 1900 m a.s.l. (Fridl et al., 1998). The identified rock glaciers presented in Table 1 are mainly located under the timberline at an average mean elevation of 1416 m a.s.l., with the object located at mean elevations from 1040 m to 1850 m. The majority of the identified rock glaciers are covered by a thick coniferous forest, while only 6 of them are covered just with sparse shrubs and some individual trees. This can lead us to the conclusion that those objects are relict ones. Nevertheless, in Table 1, in the column Water, it states whether, if in the vicinity of the rock glacier (up to approx. 100 m from the object) some kind of stream can be identified. In the vicinity of 15 rock glaciers, occasional water streams can be identified. Only one, no. RG_11, has a watercourse that originates directly from the rock glacier. This object is also located at a relatively high mean elevation of 1850 m a.s.l., with mainly sparse vegetation. It has a relatively large terminus angle of 30° and is located on the northern side of the mountains, which could



mean that it has the potential to be an intact rock glacier. This rock glacier is located on the Austrian side of the border. RG_10 has the largest terminus angle of 40° and sparse vegetation; therefore, this object could also potentially be intact.

The other 18 identified rock glaciers have terminus angles between 20° and 35°. The 13 rock glaciers are located more on the southern sides of the mountain peaks from which they originate, 7 are more to the north. Only 8 of them have maximum dimensions greater than 400 m × 120 m. If these objects were square, the area of each would be greater than 4 ha. The heights of the terminus ridge above the surrounding areas are between 6 m and 51 m, with an average height of 20 m. The heights of the inside ridges are much smaller, with average heights between 3 and 6 m.

The eight potential protalus ramparts are located at a mean average height of 1566 m a.s.l. (Table 2), which is higher than the previously mentioned potential rock glaciers. Due to the fact that they are mainly located above the timberline, they tend to be covered with sparse shrubs (4 objects), although in one example there is no vegetation at all. Therefore, five potential protalus ramparts can be regarded as potentially intact forms, while three potential protalus ramparts are covered with dense coniferous forest, which means they can be regarded as relict forms. The activity status of the potential protalus ramparts should be defined in the future based on field measurements. All the protalus ramparts are located on the southern sides of mountain peaks, from which the talus feeding them originate. The ridge height on the terminus side is from 7 m to 15 m, when it can be distinguished from the slope on which it is located. When the ridge cannot be distinguished from the on-going slope in Table 2 this is marked with a slope. The terminus slope angles are generally higher than those for potential rock glaciers with angles from 30° to 40°. Mainly in the vicinity of the protalus ramparts some kind of occasional water streams can be identified, only in two cases they do not have it.

20 **Table 1.** The potential rock glaciers.

ID_RG	Location in GK_5000	Name (mountain area)	Mean elev. [m a.s.l.]	Max. elev. [m a.s.l.]	Min. elev. [m a.s.l.]	Max. length × width [m]	Slope aspect	Height of the terminus [m]	Height of inside ridges [m]	Term. slope angle [°]	Water	Vegetation
RG_1	410_145	Rutarški vršič (Julian Alps)	1040	1097	1012	400x180	NE	32	6-10	35	yes	forest
RG_2	410_145	Rutarški vršič (Julian Alps)	1040	1110	1018	250x120	NE	7	4	30	no	forest
RG_3	410_145	Rutarški vršič (Julian Alps)	1225	1245	1218	180x100	SE	6	6	25	no	forest
RG_4	435_140	Smokuška planina (Karavanke)	1540	1570	1518	130x370	SE	15	4	20	yes	forest (20 m)
RG_5	440_140	Smokuška planina (Karavanks)	1400	1603	1368	560x300	NW	20		30	yes	forest
RG_6	440_140	Smokuška planina (Karavanks)	1385	1390	1368	50x120	SE	12		30	yes	forest
RG_7	435_140	Smokuška planina (Karavanks)	1545	1600	1517	120x140	S	30		30	yes	forest
RG_8	440_140	Smokuška planina (Karavanks)	1513	1600	1475	80x120	S	23		30	yes	forest
RG_9	440_140	Smokuška planina (Karavanks)	1510	1520	1481	120x600	SE	7	4	30	yes	forest
RG_10	435_140	Stol - Srednja peč (Karavanks)	1850	1895	1765	540x200	S	51	5-10	40	no	shrubs, sparse vegetation
RG_11	435_140	Frauenkogel-Hahnkogel (Karavanks), AUT	1650	1705	1430	280x600	NE	22	4	30	yes	sparse vegetation, forest at the front
RG_12	410_150	Vošča (Karavanks)	1540	1600	1490	480x130	SE-E	8	3-4	20	no	forest



RG_13	400_145	Macesnovec – Planica (Julian Alps)	1256	1287	1244	90x120	NE	18	8	30	yes	forest
RG_14	400_145	Macesnovec – Planica (Julian Alps)	1305	1320	1280	100x170	NE	23	3-4	30	yes	forest
RG_15	405_120	Planina Razor (Julian Alps)	1330	1420	1255	640x230	SW	20	2	30	yes	shrubs with some trees
RG_16	405_120	Planina Razor (Julian Alps)	1290	1297	1265	90x240	SE	21	2-3	30	yes	shrubs with some trees
RG_17	460_45	Snežnik – Cifre (Snežnik)	1145	1189	1096	870x480	N	40	5-16	25	no	forest
RG_18	445_140	Kočve gora (Karavanks)	1708	1732	1690	80x110	S	8	2-4	25	yes	individual shrubs
RG_19	445_140	Kočve gora (Karavanks)	1620	1624	1620	140x210	S	8	2-3	30	yes	individual shrubs
RG_20	455_140	Košutnikov turn (Karavanks)	1420	1444	1422	120x40	SE	19	3-5	30	yes	forest

Table 2. The potential protalus ramparts.

ID_PR	Location in GK_5000	Name (mountain area)	Mean elev. [m a.s.l.]	Max. length × width [m]	Slope aspect	Height of the terminus [m]	Term. slope angle [°]	Water	Vegetation
PR_1	410_150	Lepi vrh (Karavanks)	1690	70x30	SE	11	40	yes	forest
PR_2	410_150	Murnovec (Karavanks)	1740	70x30	SE	13	35	yes	forest
PR_3	410_150	Murnovec (Karavanks)	1700	90x30	S	12	30	yes	forest
PR_4	395_140	Kotova Špica (Julian Alps)	1950	120x20	S	slope	30	no	no
PR_5	410_130	Planina v Lazu (Julian Alps)	1660	330x100	SW	slope	30	no	sparse forest
PR_6	380_130	Mala Baba (Julian Alps)	1318	120x20	S	slope	40	yes	sparse shrubs, deciduous trees at front
PR_7	395_120	Planina Leskovca (Julian Alps)	1220	90x22	SW	7	30	yes	sparse shrubs
PR_8	395_120	Planina Leskovca (Julian Alps)	1250	300x30	SW	15	30	yes	sparse shrubs

3.2 Detailed description

Under the Rutarški Vršič (1696 m) in the northern part of the Julian Alps there are three relict talus rock glaciers under dense, mainly coniferous forest (Table 1, Fig. 2a, Fig. S1). The rock glacier RG_1 is the most prominent rock glacier in this inventory and was the initiator of this research. Therefore, a field survey was conducted, where we found that the rock glacier is made of fine-grained material (Fig. 4). It has a very steep front angle of 35° and a height of 32 m. Next to its northern edge is RG_2, which is much smaller and not such a prominent feature, with a smaller front angle and height. The rock glacier material originates from the southern slopes of Rutarški Vršič, built from thick-bedded Dachstein limestone with transitions to dolomite and thick-bedded Triassic dolomite. Some material may also originate from the northern slopes, made from carbonate clastic rocks. The third rock glacier RG_3 is around 900 m upstream on the Beli Potok watercourse to the south. Again, this rock glacier is not as prominent as RG_1 and it can probably be regarded as an embryonic talus rock glacier. The source area for this rock glacier material consists of thick-bedded Dachstein limestone with transitions to dolomite and thick-bedded Triassic dolomite.



Figure 4. Left, the overgrown surface of GR_1, and right, the exposed material of the rock glacier (photo: B. Barborič).

The next, very numerous group of six rock glaciers (from RG_5 to RG_9) can be found on the Smokuška Planina mountain pasture, which is located under the mountains Vrtača/Wertatscha (2180 m), Srednji Vrh (1798 m) and Veliki Vrh (2060 m) in the Karavanks (Fig. S2). The most south-eastern object (RG_5) is a typical relict lobate rock glacier, where its length far exceeds its width. Three glaciers RG_6, RG_7, and RG_8 can be regarded as more embryonic talus rock glaciers with just one, or a maximum of two, lobes. All these objects are hidden under dense coniferous forests. The source area for these rock glacier materials consists of thick-bedded Dachstein limestone with transitions to dolomite.

From this group of rock glaciers, another 2 km more to the west, is the TG_10 glacier (Fig. S3) under the mountains Stol (2236 m) and Srednja Peč (1920 m). It is a debris rock glacier formed from cirque glacier remnants and additional talus material. It has a very high terminus height of 51 m and a steep terminus angle of 40°. It is covered with shrubs and sparse vegetation, which could indicate that it is not a relict form. The rock glacier material originates from the surrounding ridges made from thick-bedded Dachstein limestone with transitions to dolomite.

In the Karavanks above the village of Hrušica another possibly intact feature, RG_11, can be found (Fig. S4). It is located on the Austrian side of the border in the cirque on the north side of the mountains Hruški Vrh/Rosenkogel (1776 m) and Dovška Baba/Frauenkogel (1891 m). It consists of different smaller objects, from the largest lobate rock glacier in the middle, to individual lobes on the south and north sides, and lobes in the catchment area of the watercourse; however, we have mapped it all as a single object. The front slope angle and the height listed in Table 1 are given for the largest lobate rock glacier. It is mainly covered with shrubs and sparse vegetation, except for the front of the lobate part, where coniferous trees with heights up to 8–10 m can be seen. The rock glacier material originates from the surrounding ridges made from carbonate clastic rocks.

In the Karavanke, approximately 12 km further to the west, above the village of Gozd Martuljek, we find RG_12 under the mountain Vošca/Woscha (1737 m) (Fig. A5). It is not such a prominent object, as it has a small front angle and height. It is covered with dense coniferous forests; therefore, it is a relict form. The rock glacier material largely originates from the top



parts of the surrounding ridges made of carbonate clastic rocks and it slides over thick-bedded and massive dolomite rocks in the foothills.

About 3 to 4 kilometres to the east, the only three protalus ramparts in the Karavanks can be seen: PR_1, PR_2, PR_3 (Fig. 2b, Fig. S11, Fig. S12) under Lepi Vrh (1926 m) and Murnovec (1864). These protalus ramparts are covered with dense coniferous forests and are therefore most likely relict forms. The protalus ramparts under Murnovec have an almost perpendicular direction, as they are, as expected, built of talus material from the neighbouring ridges. The PR_2 is more prominent than the PR_3. The top of the ridge in the hinterland of PR_1 consists of thick-bedded Dachstein limestone with transitions to dolomite. However, the middle section of the slopes above PR_1 is built of thick-bedded Triassic dolomite. The protalus ramparts PR_2 and PR_3 material originates from thick-bedded Dachstein limestone with transitions to dolomite.

More to the eastern part of the Karavanks above the town of Tržič, following the river Tržiška Bistrica, we find two small rock glaciers, RG_18 and RG_19 (Fig. S8), on the southern slopes under Kofce Gora (1967 m). They are covered with individual shrubs. The rock glacier material originates from the surrounding ridges made of thick-bedded Dachstein limestone with transitions to dolomite.

A further 7 km to the east the rock glacier RG_20 (Fig. S9) was formed under the Košutnikov Turn (2133 m). It is covered with a dense coniferous forest: comprising smaller trees on the upper part of the rock glacier and trees more than 30 m high in the front. The rock glacier material originates from massive Upper Triassic dolomite. On the north of the rock glacier an active rock-fall cone can be seen, which threatens to bury the rock glacier in the future.

Let us return to the Julian Alps, with two remaining pairs of rock glaciers. The first two, RG_13 and RG_14 (Fig. S6), are located under the mountains Macesnovec/Monte Larice (1224 m) and Mala Ponca/Ponza Piccola (1925 m) near the Italian border. The objects are not so prominent and are covered with dense coniferous forests. The rock glacier material originates from thick-bedded Triassic dolomite.

Under Vogel (1923 m) on the southern side of the Julian Alps is the mountain pasture Planina Razpor. It is covered with shrubs and individual trees. The whole area can be regarded as a combination of two, not so prominent, relict rock glaciers, RG_15 and RG_16 (Fig. S7). The rock glacier material originates from thick-bedded Dachstein limestone with transitions to dolomite.

The only potential rock glacier in the Dinaric Mountains is on the Slovenian/Croatian border under the Snežnik mountain. From five moraine like objects, clearly seen in the grey-shaded terrain model data, only one has a steep and high side edge and can therefore be regarded as a potential debris rock glacier, RG_17 (Fig. S10). This rock glacier is located in a karstic depression that lacks surface water and is covered with dense mixed forest. Its 40-m high side edge is on the west side of the rock glacier in Fig. S10. The moraine material compounding the rock glacier originated from the surrounding ridges made from Jurassic light-grey limestone.

The five identified potential protalus ramparts in the Julian Alps (Fig. S13-S16) might even be active, because they are mainly covered with sparse shrubs and some trees, only one, PR_6, at Mala Baba/Baba Piccola (1936 m) has a front covered



with dense forest, with trees up to 12 m high. One, PR_4, at Kotova Špica/Monte Trmine (2351 m) has no vegetation coverage. The protalus rampart material PR_5 and PR_6 originates from massive Upper Triassic dolomite, and for PR_4, PR_7 and PR_8, from thick-bedded Dachstein limestone with transitions to dolomite.

4 Discussion

5 For their formation the rock glaciers require bedrock material that disintegrates into blocks and talus; therefore, the most favourable types of rocks enabling rock glacier formation are granites and gneisses, and among the sedimentary rocks, limestones and dolomites (Žurawek, 2003; Haeberli et al., 2006; Johnson, 2007). In the Italian Alps the number of rock glaciers doubles in areas where the rock glaciers are fed by metamorphic rocks, when compared to the other areas with the same climatic conditions (Guglielmin and Smiraglia, 1998). The most frequent rock glaciers in the Niedere Tauern Range, 10 Austria, are found in mica schist, but only due to the most abundant occurrence of this type of rock in the study area (Kellerer-Pirklbauer, 2007). Additionally, Kellerer-Pirklbauer (2007) found a significant correlation between the lengths of the rock glaciers and the material from which they originate: gneiss produces relatively long rock glaciers, while mica schist produces short glaciers.

An analysis of the spatial distribution of periglacial features in Slovenia with regards to the bedrock composition reveals a 15 high correlation between the rock glacier's appearance and the thick-bedded Dachstein limestones with transitions to dolomite: 75 % (15) of all the discussed rock glaciers and 75 % (6) of the protalus ramparts are formed in this bedrock. Only 15 % (3) of the rock glaciers and 25% (2) of the protalus ramparts are found in Triassic dolomite. As limestone and dolomite are both known to be favourable types of rocks with respect to rock glacier formation the spatial distribution of Slovenian rock glaciers and protalus ramparts is primarily correlated to the glacier and periglacial extent in the Alpine Late Glacial, as 20 the majority of Slovenian rock glaciers can be regarded as relict forms. The 65 % of identified Slovenian rock glacier slopes are oriented more to the southern directions, which indicates that those objects are relict, as already shown by the example of the Tyrolean Alps in Austria by Krainer and Ribis (2012). Additionally, the rock glaciers are covered with at least sparse shrubs (30 %) and forest (60 %), which also supports the theory that they are relict (Cannone and Gerdol, 2003; Burga et al., 2004). Only two rock glaciers with steep front angles and without a lot of vegetation could potentially be intact and probably 25 inactive (RG_10 and RG_11). Both are located at relatively high elevations in the Karavanks. In contrast, other identified rock glaciers are found at relatively low mean elevations, from 1040 m to 1850 m a.s.l., which further supports the theory that they are relict periglacial features (Scotti et al., 2013).

The majority of the identified potential rock glaciers were found in the Karavanks (12 objects) that were not covered with extensive glaciers at the time of Alpine Late Glacial. Only traces of smaller cirque glaciers were identified (Ferk et al., 30 2015). Therefore, one potential rock glacier (RG_10) can be regarded as a debris rock glacier that formed from already-available cirque glacier moraine material. Others are probably talus rock glaciers that were formed in periglacial environmental conditions.



On the other hand, the Julian Alps were covered with extensive ice fields and valley glaciers flowing down to the surrounding basins. Only the highest ridges and peaks were above the ice fields (Ferk et al., 2015); the periglacial environments were probably at lower elevations. Therefore, the mean elevation of the identified rock glaciers in the Julian Alps (1212 m a.s.l.) is approximately 300 m lower in comparison to those in the Karavanks (1557 m a.s.l.). The most prominent rock glacier (RG_1) is found at an elevation of 1040 m a.s.l.

Glaciers were also formed in the Dinaric Mountains during the Late Glacial, on the Trnovski Gozd and Snežnik mountain, where glacial accumulation features are preserved, with one potential debris rock glacier (RG_17) on Snežnik, which was formed from already-available glacier moraine material. Minor cirque glaciers were also formed on the Pohorje mountains in the most eastern and lowest part of the Slovenian Alps, which are formed from metamorphic rocks, but no rock glaciers could be identified there so far.

5 Conclusion

In this study we mapped 20 potential rock glaciers and 8 potential protalus ramparts in Slovenia based only on national aerial laser scanning data and knowledge about the bedrock composition gained from a general geological map. The existence of such objects in Slovenia was unknown prior to the availability of this national aerial laser scanning data, due to the fact that the majority of them are hidden under dense vegetation, which hinders their identification on an orthophoto.

Based on the vegetation coverage, slope aspect direction and mean elevation we concluded that almost all identified rock glaciers can be regarded as relicts, except for two, which may potentially be intact. A half of the protalus ramparts might be relict due to the heavy vegetation coverage (dense coniferous forest), while a half are possibly active. The rock glacier slope angles are oriented 65 % in a southern direction and 35 % in a northern direction. All the identified protalus ramparts are oriented in a southern direction. The terminus slope angles of the potential rock glaciers are from 20° to 35° and from 30° to 40° for the potential protalus ramparts. They are located at mean elevations from 1040 m to 1850 m a.s.l. The identified rock glaciers rarely exceed 600 m in length.

The spatial distribution of the identified objects is in close correlation to the areas outside the Alpine Late Glacial maximum glacier extent, and more abundant in areas that were at that time influenced by periglacial environmental conditions.

Regarding the lithology, they are extensively correlated to thick-bedded Dachstein limestones with transitions to dolomite.

This study fulfilled its expectations in proving that the national aerial laser scanning data with a DTM grid size of 1 m × 1 m enables the identification of potential permafrost features hidden under dense vegetation based only on the morphological characteristics of these objects. This inventory of potential rock glaciers and protalus ramparts in Slovenia provides an ideal starting point for detailed studies of individual objects. The described methodology could enable similar studies of relict permafrost features in other mountainous areas where national aerial laser scanning has become available.



Acknowledgements. This work was funded by the Slovenian Research Agency project J2-5479 and program P6-0101. The Aerial laser scanning of Slovenia was funded by the Slovenian Ministry for Environment and Spatial Planning and conducted by Geodetic Institute of Slovenia, Flycom d.o.o and Faculty of Electrical Engineering and Computer Science of the University of Maribor. The authors wish to thank Dr Paul McGuinness for the English proofreading.

5 **Supplement** – Figures of all objects discussed, presented on grey-shaded relief model.

References

- Abermann, J., Fisher, A., Lambrecht, A., Geist, T.: On the potential of very high-resolution repeat DEM in glacial and periglacial environments, *The Cryosphere*, 4, 53-65, 2010.
- Benn, D. I., Evans, D. J. A.: *Glaciers & Glaciation*. Routledge, New York, 802 p, 2013.
- 10 Berk, S., Komadina, Ž.: Local to ETRS89 datum transformation for Slovenia: triangle-based transformation using virtual tie points, *Survey Review*, 45/328, 25-34, 2013.
- Böhlert, R., Egli, M., Maisch, M., Brandová, D., Ivy-Ochs, S., Kubik, P.W., Haeberli, W.: Application of a combination of dating techniques to reconstruct the Lateglacial and early Holocene landscape history of the Albula region (eastern Switzerland), *Geomorphology* 127, 1-13, 2011a.
- 15 Böhlert, R., Compeer, M., Brandová, D., Maisch, M., Kubik, P.W., Haeberli, W.: A combination of relative-numerical dating methods indicates two high Alpine rock glacier activity phases after the glacier advance of the Younger Dryas, *The Open Geography Journal*, 4, 115-130, 2011b.
- Buser, S.: *Geological Map of Slovenia 1:250 000*. Geological Survey of Slovenia, Ljubljana, 2010.
- Burga, C.A., Frauenfelder, R., Ruffet, J., Hoelzle, M., Käab, A.: Vegetation on Alpine rock glacier surfaces: a contribution
20 to abundance and dynamics on extreme plant habitats, *Flora* 199, 505-515, 2004.
- Berthling, I.: Beyond confusion: Rock glaciers as cryo-conditioned landforms, *Geomorphology*, 131, 98-106, 2011.
- Cannone, N., Gerdol, R.: Vegetation as an ecological indicator of surface instability in rock glaciers, *Artic, Antarctic and Alpine Research*, 35, 384-390, 2003.
- Colucci, R.R., Boccali, C., Guglielmin, M.: Il Permafrost montano del Friuli Venezia Giulia, *Evidenze Attuali e Relitte. Sotto*
25 *Zero*, Semiannual Journal of the »Unione Meteorologica del Friuli Venezia Giulia«, 2, 18-21, 2013.
- Colucci, R.R., Monegato, G., Žebre, M.: Glacial and proglacial deposits of the Resia Valley (NE Italy): new insights on the onset and decay of the last Alpine Glacial Maximum in the Julian Alps. *Alpine and Mediterranean Quaternary*, 27, 85-104, 2014.
- Cremonese, E., Gruber, S., Phillips, M., Pogliotti, P., Boeckli, L., Noetzli, J., Suter, C., Bodin, X., Crepez, A., Kellerer-
30 Pirklbauer, A., Lang, K., Letey, S., Mair, V., Morra di Cella, U., Ravel, L., Scapozza, C., Seppi, R., Zischg, A.: Brief Communication: An inventory of permafrost evidence for the European Alps. *The Cryosphere*, 5, 652-657, 2011.



- Dramis, F., Giraudi, C., Guglielmin, M.: Rock glacier distribution and paleoclimate in Italy. Proceedings of the 8th International Conference on Permafrost, Zürich, Switzerland, 1, 199-204, 2003.
- Ferk, M., Gabrovec, M., Komac, B., Zorn, M., Stepišnik, U.: Pleistocene glaciation in Mediterranean Slovenia. In: Hughes, P.D. & Woodward, J.C. (eds) Quaternary Glaciation in the Mediterranean Mountains. Geological Society, London, Special Publications, 433, 2015.
- 5 Frauenfelder, R., Kääb, A.: Towards a palaeoclimatic model of rock-glacier formation in the Swiss Alps. *Annals of Glaciology* 31, 281-286, 2000.
- Fridl, J., Kladnik, D., Orožen Adamič, M., Perko, D. (eds): *Geografski atlas Slovenije: Država v prostoru in času*. Mladinska knjiga, Ljubljana, 1998.
- 10 Guglielmin, M., Smiraglia, C.: The rock glacier inventory of the Italian Alps, PERMAFROST – seventh international conference, Yellowknife (Canada), Collection Nordicana 55, 375-382, 1998.
- Haeberli, W., Hallet, B., Arenson, L., Elconin, R., Humlum, O., Kääb, A., Kaufmann, V., Ladanyi, B., Matsuoka, N., Springman, S., Vonder Mühll, D.: Permafrost creep and rock glacier dynamics, *Permafrost and Periglacial Processes*, 17, 189-214, 2006.
- 15 Haeberli, W., Noetzli, J., Arenson, L., Delaloye, R., Gärtner-Roer, I., Gruber, S., Isaksen, K., Kneisel, C., Krautblatter, M., Phillips, M.: Mountain permafrost: development and challenges of a young research field, *Journal of Glaciology*, 56, 200, 1043-1058, 2010.
- Harris, C., Arenson, L., Christiansen, H., Etzelmüller, B., Frauenfelder, R., Gruber, S., Haeberli, W., Hauck, C., Hoelzle, M., Humlum, O., Isaksen, K., Kääb, A., Kern-Lütschg, M., Lehning, M., Matsuoka, N., Murton, J., Noetzli, J., Phillips, M., Phillips, M., Ross, N., Sepälä, M., Springman, S., Vonder Mühll, D.: Permafrost and climate in Europe: monitoring and modelling thermal, geomorphological and geotechnical responses, *Earth-Science Reviews*, 92, 117-171, 2009.
- 20 Hedding, D.W.: Pronival rampart and protalus rampart: a review of terminology, *Journal of Glaciology*, 57, 1179-1180, 2011.
- Hladnik, D., Žižek Kulovec, L.: Forest area assessment in the Slovenian forest inventory design. *Zbornik gozdarstva in lesarstva*, 97, 31-42, 2012.
- 25 Johnson, B.G., Thackray, G.D., Van Kirk, R.: The effect of topography, latitude, and lithology on rock glacier distribution in the Lemhi Range, central Idaho, USA. *Geomorphology*, 91, 38-50, 2007.
- Kääb, A.: Rock Glaciers and Protalus Forms. In: Elias, S.A. (eds) *Encyclopedia of Quaternary Science*. Amsterdam, Elsevier, 535-541, 2013.
- 30 Kaufmann, V.: The evolution of rock glacier monitoring using terrestrial photogrammetry: The example of Äusseres Hocheberkar rock glacier (Austria). *Austrian Journal of Earth Science*, 105/2, 63-77, 2012.
- Kaufmann, V., Kellerer-Pirklbauer, A.: Active rock glaciers in changing environment, *Wiener Schriften zur Geographie und Kartographie*, 21, 179-190, 2015.



- Kellerer-Pirklbauer, A.: Lithology and the distribution of rock glaciers: Niedere Tauern Range, Styria, Austria, *Zeitschrift für Geomorphologie*, 51/2, 17-38, 2007.
- Knoll, C., Kerschner, H.: A glacier inventory of South Tyrol, Italy, based on airborne laser-scanner data, *Annals of Glaciology*, 50(53), 46-52, 2009.
- 5 Komac, M.: Statistics of the Geological Map of Slovenia at scale 1:250 000, *Geologija*, 48/1, 177-126, 2005.
- Krainer, K., Ribis, M.: A rock glacier inventory of the Tyrolean Alps (Austria), *Austrian Journal of Earth Sciences*, 105/2, 32-47, 2012.
- Krainer, K., Kellerer-Pirklbauer, A., Kaufmann, V., Lieb, G.K., Schrott, L., Hausmann, H.: Permafrost research in Austria: history and recent advances, *Austrian journal of earth sciences*, 105/2, 2-11, 2012.
- 10 Millar, C.I., Westfall, R.D.: Rock glaciers and related periglacial landforms in the Sierra Nevada, CA, USA; inventory, distribution and climate relationships, *Quaternary International*, 188, 90-104, 2008.
- Mongus, D., Žalik, B.: Computationally efficient method for the generation of digital terrain model from airborne lidar data using connected operators, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 7, 1939-1404, 2014.
- 15 Mongus, D., Lukač, N., Žalik, B.: Ground and building extraction from LiDAR data based on differential morphological profiles and locally fitted surfaces. *ISPRS Journal of Photogrammetry and Remote Sensing*, 93, 145–156, 2014.
- Ribolini, A., Guglielmin, M., Fabre, D., Bodin, X., Marchisio, M., Sartini, S., Spagnolo, M., Schoeneich, P.: The internal structure of rock glaciers and recently deglaciated slopes as revealed by geoelectrical tomography: insight on permafrost and recent glacial evolution in the Central and Western Alps (Italy-France), *Quaternary Science Reviews* 29, 507-521, 2010.
- 20 Scapoza, C.: Investigation on protalus ramparts in the Swiss Alps, *Geographica Helvetica*, 70, 135-139, 2015.
- Schmid, M.O., Baral, P., Gruber, S., Shahi, S., Shrestha, T., Stumm, D., Wester, P.: Assessment of permafrost distribution maps in the Hindu Kush Himalayan region using rock glaciers mapped in Google Earth, *The Cryosphere*, 9, 1089-2099, 2015.
- 25 Scotti, R., Brardinoni, F., Alberti, S., Frattini, P., Crosta, G.B.: A regional inventory of rock glaciers and protalus ramparts in the central Italian Alps, *Geomorphology*, 189, 136-149, 2013.
- Shakesby, R.A., Dawson, A.G., Matthews, J.A.: Rock glaciers, protalus ramparts and related phenomena, Rodane, Norway: a continuum of large-scale talus-derived landforms, *Boreas*, 16, 305-317, 1987.
- Whalley, W.B., Azizi, F.: Rock glaciers and protalus landforms: Analogous forms and ice sources on Earth and Mars, *Journal of Geophysical Research*, 108/4, 2003.
- 30 Triglav-Čekada, M., Crosilla, F., Kosmatin-Fras, M.: Theoretical lidar point density for topographic mapping in the largest scales, *Geodetski vestnik*, 54, 403-416, 2010.
- Žuravek, R.: The problem of the identification of relict rock glaciers on sedimentological evidence. *Landform Analysis* 4, 7-15, 2003.