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ABSTRACT

1. Introduction

Rock glaciers are masses of coarse angular debris that characterize the periglacial mountain domain of several alpine areas of the world (Haeberli et al., 2006). They commonly display steep fronts and a system of transverse surface ridges and furrows, possibly the product of differential movement of discrete layers of enriched ice-debris (Kääb and Weber, 2004). They retain much of their morphology long after they have ceased moving, displaying smoothed surface topography and gentler front slopes (Hughes et al., 2003). Traditionally, rock glaciers are thought to exist mainly in climates that have low precipitation and low temperatures at altitudes below the equilibrium line of glaciers but above the lower permafrost limit (Haeberli, 1985). In other areas, rock glacier occurrence is linked to local effects which favour talus production rather than to regional climate (Humlum, 1998; Janke, 2007). Their genesis has long been discussed and researchers generally distinguish between rock glaciers of glacial origin (e.g., Martin and Whalley, 1987; Whalley and Martin, 1992) and periglacial origin (e.g., Haeberli, 1985; Barsch, 1988). Moreover, Humlum et al. (2007) suggested a coupled snow avalanche–debris supply in the accumulation of new rock glacier ice in some arctic areas of Svalbard. Indeed, physical evidence of both permafrost and glacial ice-cores has been noted on several rock glaciers (e.g., Brown, 1925; Guglielmin et al., 2004; Stenni et al., 2007; Ribolini et al., 2007, 2010) suggesting the idea of a *continuum* or a composite model where a combination of different processes lead to the inception of rock glaciers (Giardino and Vitek, 1988). With regard to relict forms the exact mode of formation of a rock glacier is difficult to determine (Whalley and Azizi, 2003), but climatic assumptions hold even if different modes of formation are envisaged since the evidence supporting the role of permafrost is considerable (Hughes et al., 2003). Permafrost in mountain areas is almost always associated with rock glaciers (Evin and Fabre, 1990); therefore, many researchers recognize rock glaciers as climatic and paleoclimatic indicators of actual or past permafrost conditions usable for paleoclimate reconstructions (e.g., Barsch and Updike, 1971; Kerschner, 1985; Harris and Pedersen, 1998; Hughes et al., 2003; Ribolini et al., 2007). Protalus ramparts are generally the result of ice reach ground creep and some authors tend to consider them as embryonic rock glaciers (Haeberli, 1985; Barsch, 1996; Scapozza et al., 2011). Balch ventilation due to air convection through coarse talus slope material is also seen as a possible factor contributing to the onset and preservation of ice, leading to the build-up of a ridge or rampart at the base of the talus (e.g., Francou, 1977; Delaloye and Lambiel, 2005). Some diagnostic criteria for defining active protalus ramparts (after Scapozza, 2015) are the absence of permanent snow/firn field, bulging morphology, a very steep front (40–45°), downslope movement and the presence of permafrost often highlighted by the presence of long-lasting summer-time snow patches behind the main ridge. Pronival ramparts (Matthews et al., 2011) are defined as depositional periglacial landforms (ramp or ridge) associated with the downslope margin of a perennial or semi-permanent snow bed formed by the sliding, rolling and/or bouncing of rock fall boulders. However, the shape and development of such ridges are influenced by other processes including snow push, solifluction, debris flow and snow avalanche. Their growth is self-limited by the progressive thickening of a stationary snow/firn field that can promote the inception of a small glacier leading to the destruction of the rampart or change in the shape of the rampart (Ballantyne and Benn, 1994). The distance between the ridge crests and the talus foot slope is <30–70 m which is considered the threshold conditions under which a firn body is sufficiently large to increase its basal shear stress, encouraging ice creep and basal sliding (Ballantyne and Benn, 1994).

The distribution of rock glaciers around the world has been investigated in several mountainous regions and particularly in the European Alps both at the local scale (e.g., Seppi et al., 2012; Scotti et al., 2013) and at the national scale (e.g., Guglielmin and Smiraglia, 1997; Kellerer-Pirklbauer et al., 2012; Rangecroft et al., 2014). The paper by Guglielmin and Smiraglia (1997) has been used as the starting reference for the revision of the old inventory. Before this, very little was known about rock glacier distribution in the north-eastern end of the Italian Alps, whereas in Slovenia, no rock glaciers were recognized until now. A recent LiDAR survey over the entire Friuli Venezia Giulia (FVG) region and Slovenia allowed us to conduct this analysis; the resultant high resolution DTMs allow accurate representations of terrain and detailed calculation of landform geometry and spatial attributes. Furthermore, in the south-eastern Alps, Colucci and Guglielmin (2015) found a close correlation between winter precipitation and glacial evolution, with a lesser contribution by summer temperature. This finding was a motivation to investigate the possible presence of periglacial forms in an area in which none are reported thus far. With this in mind, the aims of this work are: 1) to update the knowledge about periglacial alpine landforms in this sector of the Alps, including the distribution of rock glaciers and protalus (pronival) ramparts; and 2) to estimate the onset period of rock glaciers in relation to the paleoclimate evolution since the Last Glacial Maximum.

2. Study area

The study area extends from 45°25′ N to 46°52′ N and from 12°20′ E to 16°36′ E including the FVG region, the north-eastern-most region of Italy, and all of Slovenia (Fig. 1). The investigated area extends for 28,130 km^2, of which 4150 km^2 are mountainous areas (>1000 m a.s.l.). Bedrock there is dominated by sedimentary carbonate rocks, with some limited igneous and metamorphic rock outcrops in a narrow area of the Western Carnic Alps (Carulli, 2006) as well as Karavanke and Slovenian Prealps (Komac, 2005). The Tagliamento Amphitheater (Fig. 1b) represents the most well-preserved easternmost end moraine system of the South-Alpine foreland and is one of the largest systems of the southern Alps covering an area of 220 km^2. It represents the most evident feature of Quaternary glaciations in the FVG (Monegato et al., 2007).

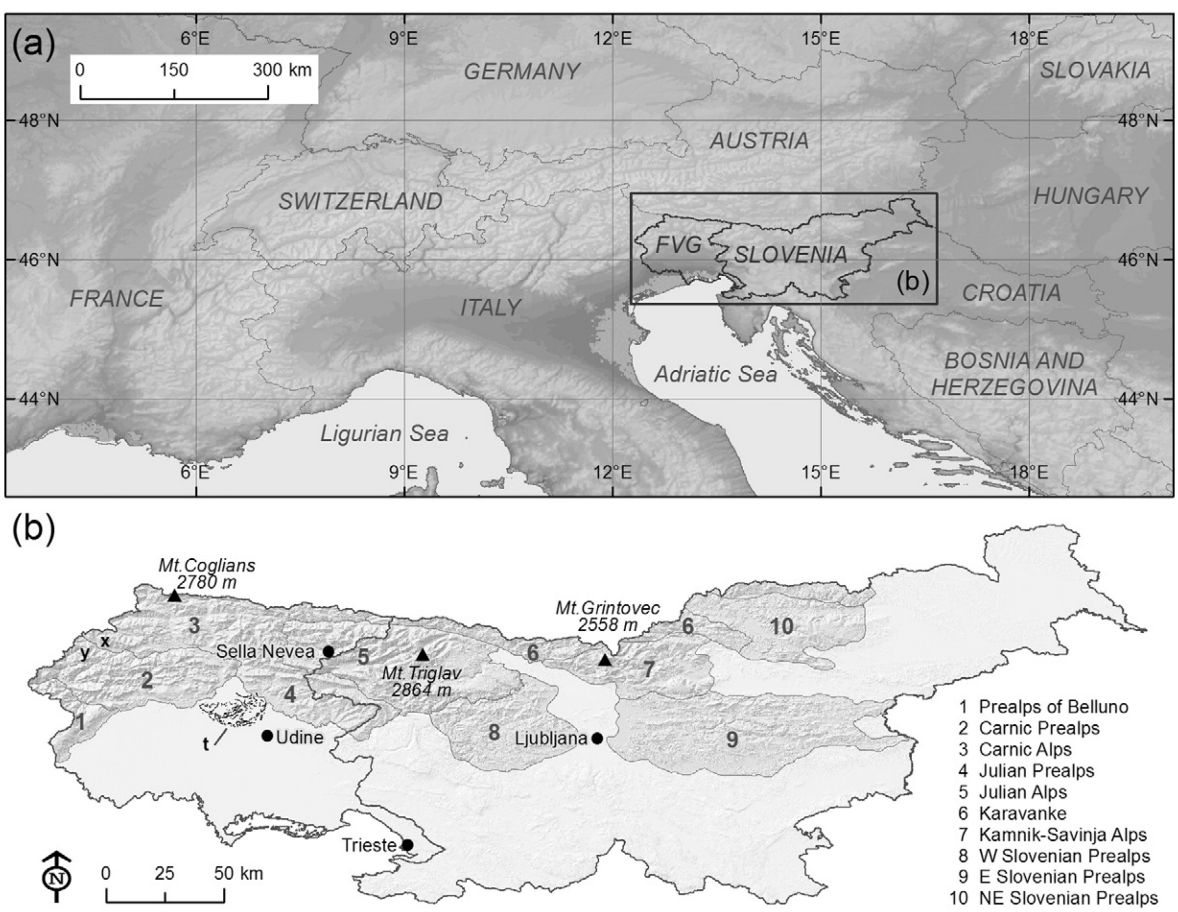


Fig. 1. Location of the Friuli Venezia Giulia (FVG) region and Slovenia. (a) European Alps. (b) Detail of the study area. t: Tagliamento end moraine system during the LGM. x: Tiarfin area (Fig. 7). y: Valbinon area (Fig. 2).

The higher peaks are represented by Mt. Coglians-Hohewarte (2780 m a.s.l.) in the Carnic Alps, Mt. Triglav (2864 m a.s.l.) in the Julian Alps and Mt. Grintovec (2558 m a.s.l.) in the Kamnik-Savinja Alps (Fig. 1b). In the Julian Alps, there is evidence of 14 permanent snow/firn bodies covering a total area of 0.266 km^2 (as of 2012) which was 1.559 km^2 during the Little Ice Age (LIA) maximum (Colucci, in press). They have northerly aspects and developed at the base of steep rock slopes which favour avalanche activity, snow blowing and summer shading. The presence of sporadic permafrost in the area has been recently highlighted by the widespread occurrence of permanent ice deposits (i.e., ground ice) in karstic caves (Colucci et al., 2016).

The mean annual precipitation (*MAP*) is at its highest in the Julian Alps with totals higher than 3300 mm, representing one of the highest mean values for the European Alps (Norbiato et al., 2007). In the inner Alpine area the *MAP* decreases to 1600–1800 mm because of the rain shadow effect of the southern ridges, while towards the east the *MAP* decreases down to <1000 mm. The mean annual air temperature (*MAAT*) is mainly influenced by the altitudinal lapse rate but shows a decreasing trend from the prealpine reliefs to the inner alpine sector and towards the east in Slovenia. The spatialized 1981–2010 *MAAT* shows extremes ranging from ca. −2.6 °C on the highest peaks to ca. 15.2 °C off the coast. Assuming the normal vertical lapse rate of 6.5 °C km^{-1}, the altitude of the mean annual 0 °C-isotherm is estimated at 2370 ± 90 m a.s.l. The −2 °C isotherm, which defines environments where frost action is dominant (French, 2007), is estimated at 2665 ± 90 m a.s.l.

3. Methods

3.1. Landform identification and climatic analyses

The inventory of landforms has been compiled by the inspection of aerial orthorectified photographs (orthophotos) with medium resolution (0.5 m pixel; 1998, 2003, 2011, and 2014) and high resolution (0.15 m pixel; 2006–2009), provided by the Civil Defense of Region Friuli Venezia Giulia and the Surveying and Mapping Authority of the Republic of Slovenia.

A high resolution (1.0 m cell size) digital terrain model (DTM) interpolated from airborne laser scanning (LiDAR) data acquired between September 2006 and September 2009 (Civil Defense of FVG) for the FVG and between February 2011 and April 2015 for Slovenia (http://gis.arso.gov.si/evode/; last accessed 11 January 2016) served as the basis for geomorphological mapping and morphometric analysis. The hillshade derived from the DTM was crucial especially in the recognition of landforms buried by vegetation where orthophotos are less useful (Fig. 2).

Maps of climate and paleoclimate conditions in the FVG were computed using monthly temperature grids of 480 × 480 m derived from the OSMER dataset (1996–2005) recalculated following Colucci and Guglielmin (2015) over the 30-yr period of 1981–2010. For the Slovenian side a 1 × 1 km grid of 1981–2010 *MAAT* values from the Slovenian Environment Agency were used. For the LIA (1350–1850 CE), we used the same approach by processing the data for the 30-yr period of 1851–1880 (Colucci and Guglielmin, 2015), which is the oldest

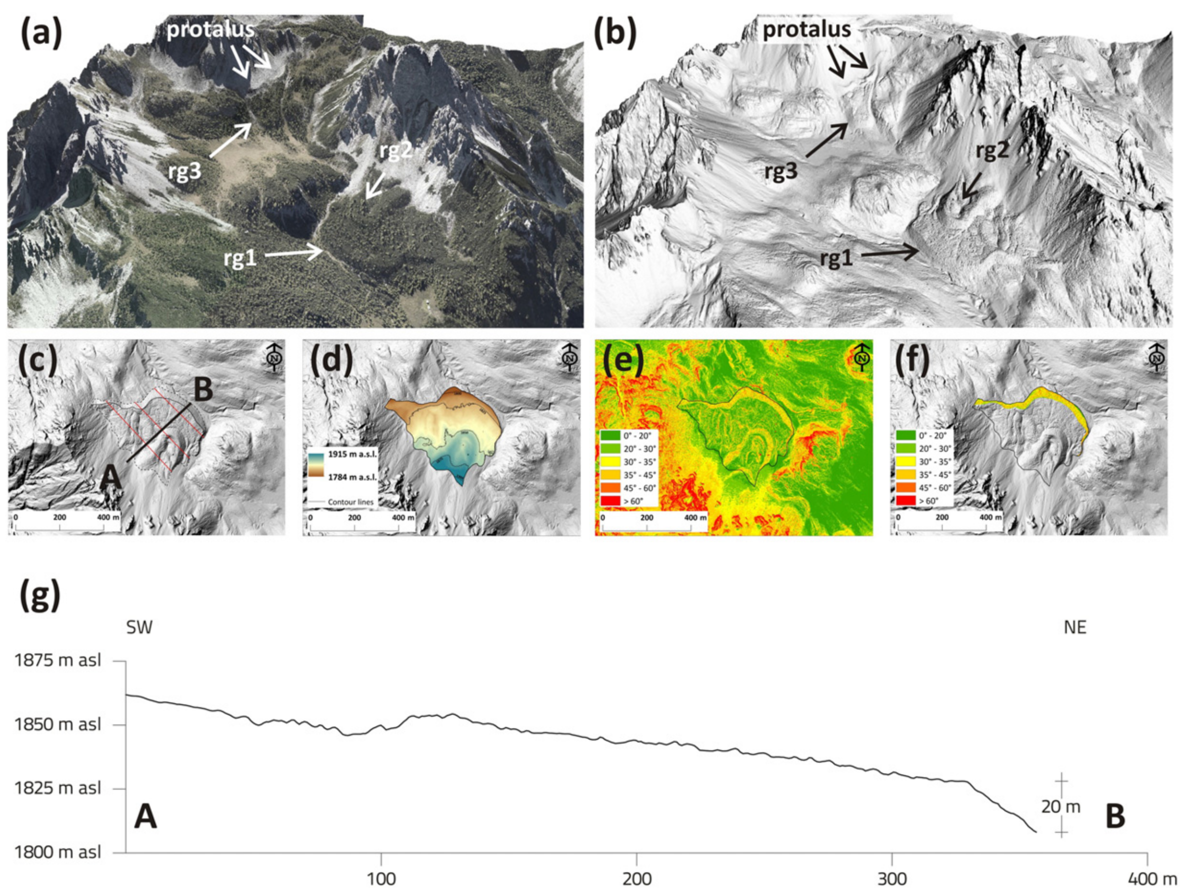


Fig. 2. An example of the methodology used in this research. (a) 3D image from a high-resolution orthophoto and the DTM. Rock glaciers are indicated as rg1, rg2 and rg3. (b) Hillshade. (c) Calculation of area, length and width. (d) Calculation of minimum, maximum and mean altitude from the high resolution DTM. (e) Slope analysis. (f) Computation of front steepness. (g) Section of the longitudinal profile shown in (c).

Table 1
Recorded attributes of the studied rock glaciers and protalus/pronival forms.

Rock glaciers	Protalus/pronival forms
Number	Number
Name	Name
Geographic coordinates of the centroid	Geographic coordinates of the centroid
Municipality	Municipality
Mountain sector	Mountain sector
Mean altitude	Mean altitude
Maximum altitude	/
Minimum altitude	/
Area	Area
Aspect	Aspect
Length	Length
Width	Width
Mean slope degree of the entire landform	/
Mean slope degree of the front	/
Mean elevation of the front	/
Minimum elevation of the front	/
Highest elevation of the mountain top	/
Relationships with glacial forms (glaciers, glacierets, snow banks, moraine systems)	/
Location (valley bottom, cirque, furrow, slope)	/
Lithology	Lithology
Lithological/geological formation of the feeding basin	Lithological/geological formation of the feeding basin
Presence/absence of springs at the front	/
Spring temperature	/
Presence/absence of lakes at the front	/
Relationship between front and local vegetation limit (above/below tree line, above/below meadows)	Relationship between front and local vegetation limit (above/below tree line, above/below meadows)
Relationships and types of cover vegetation (coniferous continuous/discontinuous, broadleaved continuous/discontinuous, meadows continuous/discontinuous, absent)	Relationships and types of cover vegetation (coniferous continuous/discontinuous, broadleaved continuous/discontinuous, meadows continuous/discontinuous, absent)
/	Presence/absence of a snow/firn field

available data and generally recognized as the end of the LIA (preindustrial time). Paleoclimate reconstruction for the Younger Dryas was made by subtracting 3.5 °C (Frauenfelder et al., 2001) from the recalculated 1961–1990 *MAAT* values, which is in agreement with the average anomalies of −2 °C during the early Holocene with respect to late preindustrial time (Mauri et al., 2015).

3.2. Rock glaciers

Several landform attributes were assigned to rock glaciers (Table 1), which allowed for the making of further analyses. It is acknowledged that the upper limit of a rock glacier (rooting zone) is not easy to determine (e.g., Krainer and Ribis, 2012) and sometime is chosen arbitrarily. Consistent effort was put on determining where the rock glacier meets the input accumulation zone above it by looking at surface morphology (Fig. 2). We further classified the rock glaciers according to their geometry where a tongue-shaped rock glacier presents a length/width ratio > 1 and a lobate rock glacier a length/width ratio < 1, respectively (Wahrhaftig and Cox, 1959). The location of other landforms such as talus or debris rock glaciers (Barsch, 1996) was also noted. The degree of activity of rock glaciers has been inferred using a geomorphological approach given the lack of geophysical investigations to determine the presence or lack of ice, and because no horizontal or vertical displacement of the landforms was available. As such, we subdivided the rock glaciers into active (likely with ice), relict (likely without ice), and those of uncertain activity when the landforms were not fully supported by all the necessary characteristics of active or relict classes. The term “relict” used in this paper corresponds to a state of climatic inactivity of the landform, where the presence of ice is not anymore supported by the present climate. Active rock glaciers are those having a steep front that ismostly steeper than the angle of repose of the material (35°), a mean longitudinal convex relief, and a stable water temperature of springs at the front in the range of 0–2 °C (Haeberli, 1985). Despite several works using vegetation coverage as an indicator of activity, some species can be present even with relatively high movements (<35 cm yr^{-1}) (Cannone and Gerdol, 2003). Therefore, we carefully used vegetation as a proxy for landform activity only when field surveys were available. The surface topography is generally characterized by a system of pronounced furrows and ridges that is transversal to the flow of the rock glacier and which originated from over-thrusting of internal

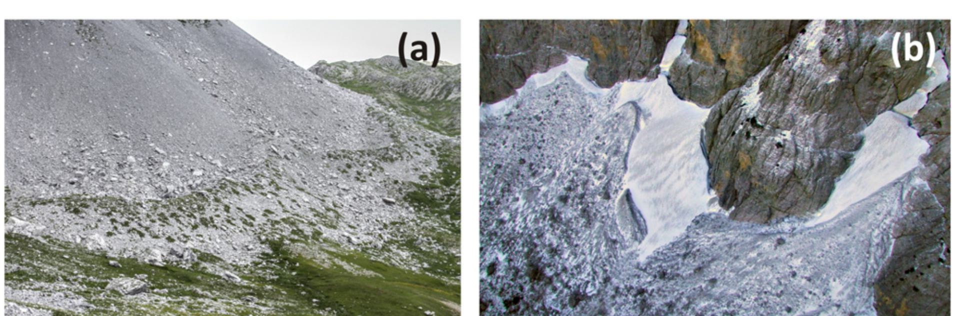


Fig. 3. Examples of the studied periglacial features: (a) protalus ramparts in early August 2015, and (b) pronival ramparts in the Julian Alps with a permanent ice patch photographed in late October 2014.

shear planes and differential movements of distinct layers under compressive flow (e.g., Wahrhaftig and Cox, 1959; Haeberli, 1985; Kääb and Weber, 2004). Relict rock glaciers have a less steep front (<35°) and present a generally concave longitudinal profile resulting from the lack of ice; they are often characterized by thermokarst depressions on the surface topography (Haeberli, 1985).

3.3. Protalus and pronival forms

The inventory comprises also protalus ramparts and pronival ramparts (Fig. 3). We characterize these landforms in respect to the activity according to a geomorphological approach looking at the steepness of the front. In addition we highlight the contingent presence or absence of a perennial or semi-permanent snow/*firn* field. These could be considered as indicators of activity in the case of pronival ramparts, while the presence of long-lasting summer snow fields in a protalus rampart could be an indicator of permafrost presence. With regard to the relict forms, owing to the difficulty in distinguishing the real origin of the two forms especially via remote sensing, we consider them all together. Landform attributes are reported in Table 1.

3.4. Field observations

In order to assess the reliability of the inventory, we conducted field surveys during the summer and autumn of 2012 and 2013, and during the autumn of 2015 to better characterize the vegetation cover, verify the presence or absence of active springs, and measure water temperature during August and September. The measurement was made with a Pt100 thermistor class A-1/10 operating in the range of −50 °C to 250 °C, with an accuracy better than ±0.06 °C at 0 °C (±0.05%) and a resolution of 0.1 °C. During early March 2013, we also performed bottom temperature of snow cover (*BTS*) measurements by using a 4-m-long aluminium probe equipped with the same thermistor. All the measurements were carried out with a snow thickness exceeding 0.8–1.0 m (Haeberli, 1973).

4. Results

4.1. Rock glaciers

We mapped 53 rock glaciers covering an area of 3.45 km^2. Rock glaciers are concentrated in the Carnic Alps (28 rock glaciers, 53% of the total) and in the Carnic Prealps (14 rock glaciers, 26%). Seven rock glaciers (13%) exist in the Julian Alps, and only two (4%) in each of the Karavanke and the Kamnik-Savinja Alps. The largest rock glacier covers an area of 0.51 km^2. The tongue shaped geometry is predominant (53%) compared to the lobate one (47%). The mean slope of the rock glaciers is 22.6° with the majority (72%) falling in the range of 19°–27°.

Forty-nine rock glaciers (92%) have been classified as relict, and only four (8%) of uncertain activity. The latter include: a) one rock glacier having a mean front slope equal to 35°; b) two rock glaciers having slightly convex longitudinal profiles; and c) one rock glacier with a spring having abundant water at a constant temperature of 2.5 °C. The regional median of the elevations of rock glacier fronts is at 1778 m a.s.l., with a standard deviation of 130 m, representing the lowest altitude of relict rock glaciers in the Italian Alps (Guglielmin and Smiraglia, 1997; Dramis et al., 2003). Rock glaciers mostly develop on slopes with NW, N and NE aspects (Fig. 4c) and predominantly at altitudes of 1708–1846 m a.s.l. (I and III quartile; Fig. 4b) with a median elevation of 1777 m. Rock glaciers facing NW to E tend to develop at lower altitudes with mean elevations between 1704 and 1824 m a.s.l extending from 1471 m to 1975 m. (Fig. 4a), while south-facing rock glaciers have mean elevations

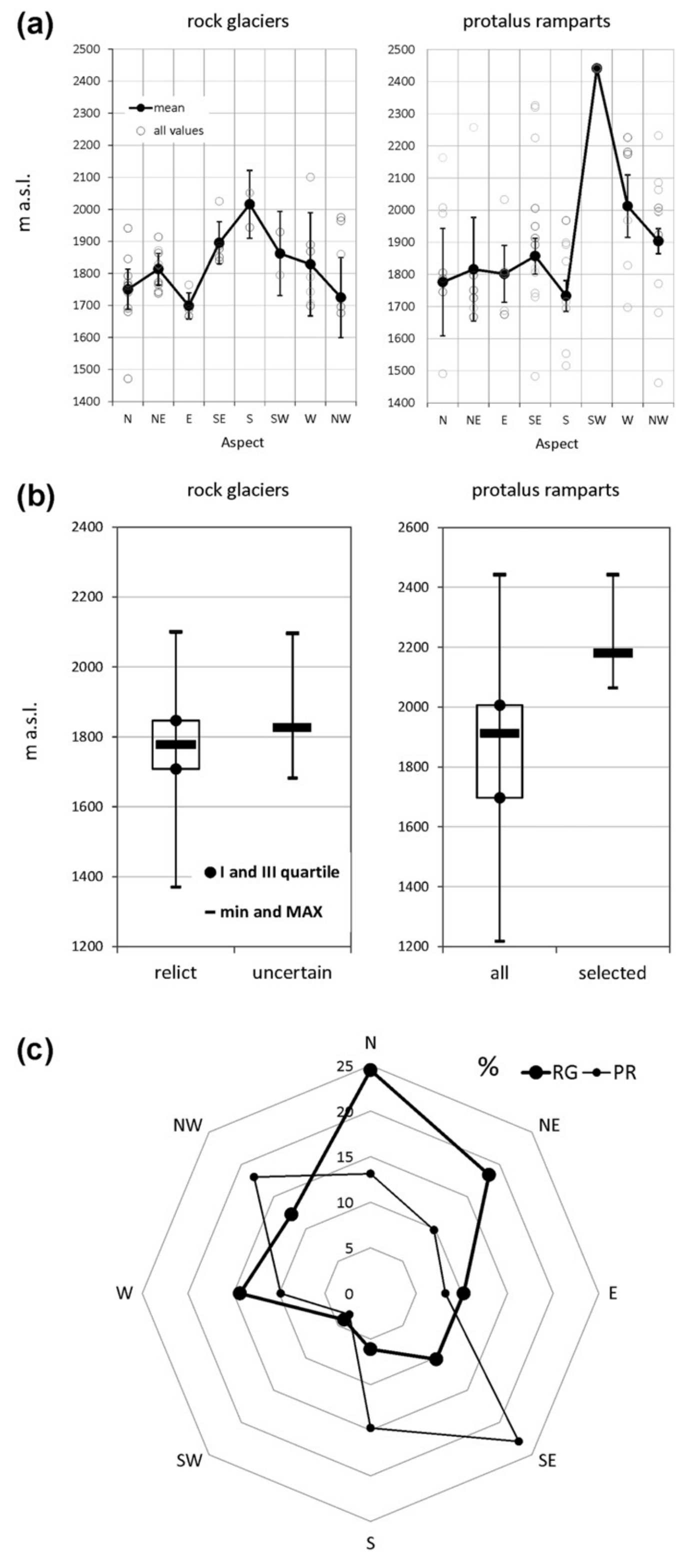


Fig. 4. Main characteristics of the rock glacier and protalus rampart distribution: (a) Altitudinal distribution of rock glaciers and protalus ramparts according to aspect (bars indicate the 95% confidence interval); (b) altitudinal distribution of relict rock glaciers and protalus ramparts: minimum, lower quartile, median, upper quartile and maximum are drawn (four rock glaciers of uncertain activity and seven protalus rampart, considered to be active because of the presence of long-lasting snow patches, are depicted only with median, minimum and maximum altitudes); (c) polar diagrams showing aspect distribution of rock glaciers (RG) and protalus ramparts (PR). The four lowest rock glaciers in the Julian Alps are not considered in the statistics.

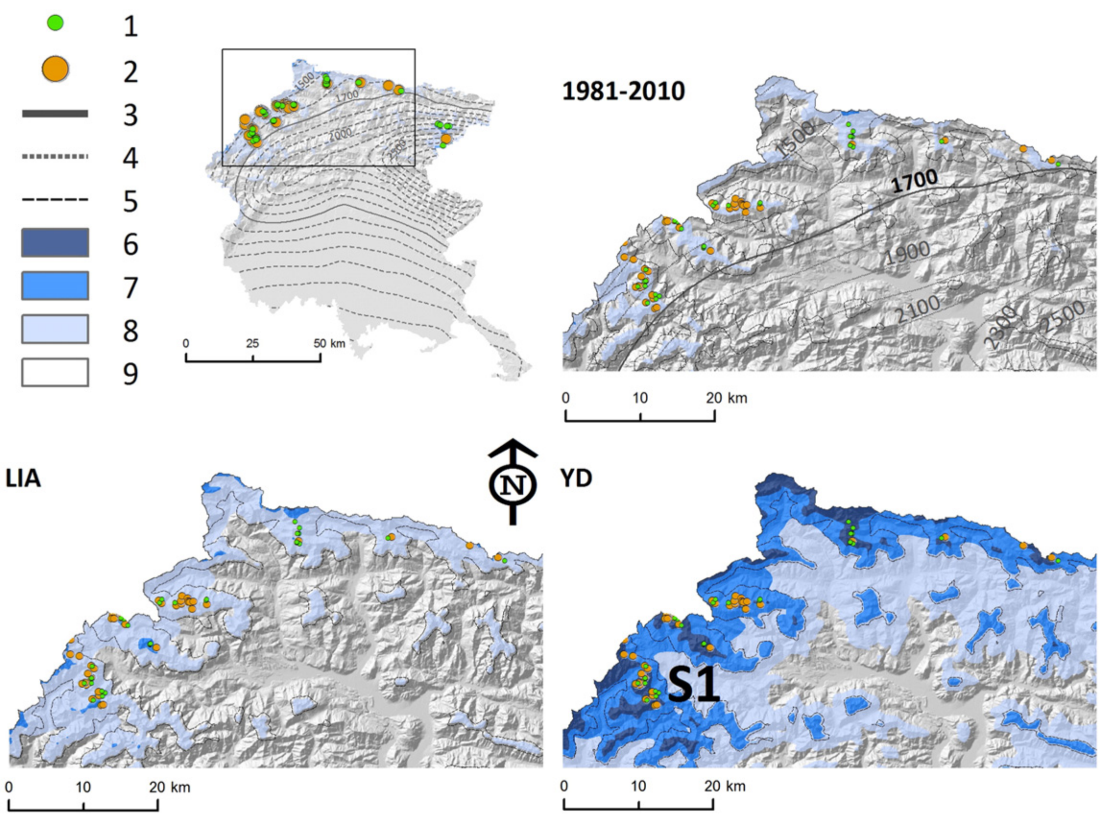


Fig. 5. Maps of *MAAT* in the FVG calculated for the 30-yr period 1981–2010, the LIA and the YD. Numbers in the legend (upper left) respectively refer to: 1) protalus rampart; 2) rock glacier; 3) 1700 mm w.e.; 4) 1961–2000 *MAP* contour line (step of 100 mm w.e.); 5) 1400 m a.s.l. contour line; 6) *MAAT* < −2 °C; 7) *MAAT* = −2–0 °C; 8) *MAAT* = 0–3 °C; 9) *MAAT* > 3 °C. S1 is commented in the discussions. DEM derived by LiDAR surveys between 2006 and 2009 by the Civil Defense of Region FVG.

between 1860 and 2016 m a.s.l, extending from roughly 1800 m to 2100 m a.s.l. This pattern is common to several existing reports from the European Alps (e.g., Barsch, 1996; Guglielmin and Smiraglia, 1997; Scapozza and Mari, 2010) and likely highlights the influence of solar radiation on subsurface thermal regime (Hoelzle, 1992; Guglielmin and Cannone, 2011). Nine rock glaciers (17%) occur above the tree line, while the other 44 show the surface covered by discontinuous to continuous vegetation, mainly *Pinus mugus*, larch and spruce. The lowest rock glaciers of our inventory are located in the Julian Alps. Four of them are situated significantly below the calculated regional median elevation of rock glacier fronts. Their fronts are at 1076 m a.s.l. on average, which is close to the ELA in the LGM at ca. 1200 m in the Julian Alps (Monegato et al., 2007; Colucci et al., 2014).

4.2. Protalus and pronival ramparts

Sixty-six protalus and pronival ramparts were mapped covering an area of 0.48 km^2. They are predominantly located in the Carnic Alps (22), Julian Alps (17) and Karavanke (14), and the remaining 13 are scattered among the Carnic Prealps, Kamnik-Savinja Alps and Julian Prealps. The majority is distributed between 1697 m and 2007 m a.s.l. (I and III quartile) with a median elevation of 1913 m a.s.l. Seven were considered active protalus ramparts because of the presence of long-lasting, but not permanent, snowfields as highlighted in the orthophotos and during field campaigns. They are separately shown in Fig. 4b. This could indicate the presence of permafrost patches that support the persistence of the snow patches. They are located at higher altitudes between 2063 and 2442 m a.s.l with a median elevation of 2181 m a.s.l. The possible presence of permafrost was also highlighted through *BTS* measurements in the Carnic Prealps at 2258 m a.s.l. The survey was performed in late February 2013 in an area occupied by two protalus ramparts that gave values ranging between −6.6 °C and −4.5 °C which issufficient to hypothesize the presence of permafrost. Our findings seem to partially agree with the available alpine permafrost index map (Boeckli et al., 2012) as shown in Fig. 7.

Besides active protalus ramparts, we also classified nine active pronival ramparts, located in front of permanent snow/firn bodies and small glacierets, of which seven are in the Julian Alps (Colucci, in press) and two are in the Kamnik-Savinja Alps. These ridges produce a damming effect for avalanches which enhance accumulation of winter snow, a significant impact on the local mass balance. The fallen material likely slides and rolls down through these permanent ice bodies representing an additional and still active contribution to the build-up of the ridges, highlighted by the presence of patches of fresh debris deposits mainly over the topographic surface of the glacierets and in the internal side of the ridges. Overall, together with rock glaciers, we inventoried 119 periglacial landforms in the study area.

5. Discussion

5.1. Distribution of rock glaciers and estimated formation age

The altitudinal range of rock glaciers analysed here is the lowest for the southern Alps and comparable with that for relict rock glaciers in the Northern Alps of Austria (1798 m) and in the Austrian Niedere Tauern Range (1823|1850 m) (Kellerer-Pirklbauer et al., 2012). Rock glaciers are widespread periglacial landforms in the

Alps and the modern active ones are generally seen as indicators of the presence of discontinuous mountain permafrost in areas with *MAAT* ≤ 2 °C (Haeberli, 1985; Barsch, 1996; French, 2007). Based on *MAAT* during 1981–2010 (Figs. 5 and 6) and the topographic setting, the current distribution of rock glaciers in the Carnic Alps and Prealps falls entirely in areas with *MAAT* < 3 °C and *MAP* < 1700 mm water equivalent (w.e.) On the contrary, in the Julian Alps and Prealps as well as in the Karavanke and Kamnik-Savinja Alps, rock glaciers are located in an area with *MAP* > 1700 mm w.e. Almost all the rock glaciers were classified as relicts, which represent the local lower limit of permafrost at the time of their decay (e.g., Frauenfelder et al., 2001). However, it is well known that rock glaciers may reach lower altitudes compared to the climatic permafrost boundaries (Harris and Pedersen, 1998). For this alpine sector, the studies on speleothems reported by Frisia et al. (2005) and Belli et al. (2013) indicate two periods with drier and colder conditions: between 12.8 ± 0.3 ka and 11.9 ka and between ca. 10.8 ± 0.2 ka and 10.1 ± 0.2 ka. After these periods, no considerable colder and drier conditions compared to the present day were detected in the south-eastern Alps. Therefore, it is reasonable to speculate that these two periods could be the most favourable for permafrost to form rock glaciers. Despite the low number of dated rock glaciers (e.g., Dramis et al., 2003; Stenni et al., 2007; Scapozza et al., 2010) Younger Dryas (YD) or Holocene ages of the relict rock glaciers have been suggested (Frauenfelder et al., 2001; Lambiel and Reynard, 2001). Moreover, in the Alps active rock glaciers are about 400–500 m higher than the relict ones, corresponding to a temperature drop of ca. 2.6–3.3 °C (Frauenfelder et al., 2001). Sector S1, highlighted in Fig. 5, showed the lowest average *MAAT* value during the YD (−1.9 ± 0.7 °C) and the highest mean altitude of rock glacier fronts (1822 ± 163 m a.s.l.). Here, the highest rock glacier (Tiarfin, Figs. 1 and 7) had a *MAAT* value of −2.6 °C with five of the 19 rock glaciers having *MAAT* ≤ −2.0 °C. Higher *MAAT* and lower elevation characterize the remaining rock glaciers with *MAAT* at the front ranging from −1.6 °C to 2.1 °C during the YD. The mean annual 0 °C-isotherm during the YD is estimated at about 1400 m a.s.l. (Figs. 5 and 6). If we still assume that *MAAT* < −2 °C is valid for rock glacier development, we can hypothesize that: i) in the south-eastern Alps, the lowering of *MAAT* during the YD was greater than the assumed value of −3.5 °C; ii) the local conditions of the rock glaciers allowed permafrost aggradation at *MAAT* higher than −2.0 °C because of surface characteristics with Balch ventilation (e.g., Harris and Pedersen, 1998) or low radiation conditions at shady positions; and iii) these rock glaciers were formed in cold and dry periods older than the YD. The high *MAAT* values for the lowest rock glaciers in the Julian Alps suggest a temperature drop of at least 7.1–7.6 °C, which is in accordance with the LGM temperature reconstruction for this sector of the Alps (Kuhlemann et al., 2008). Therefore, we hypothesize that these rock glaciers were formed during the LGM.

5.2. Protalus and pronival ramparts

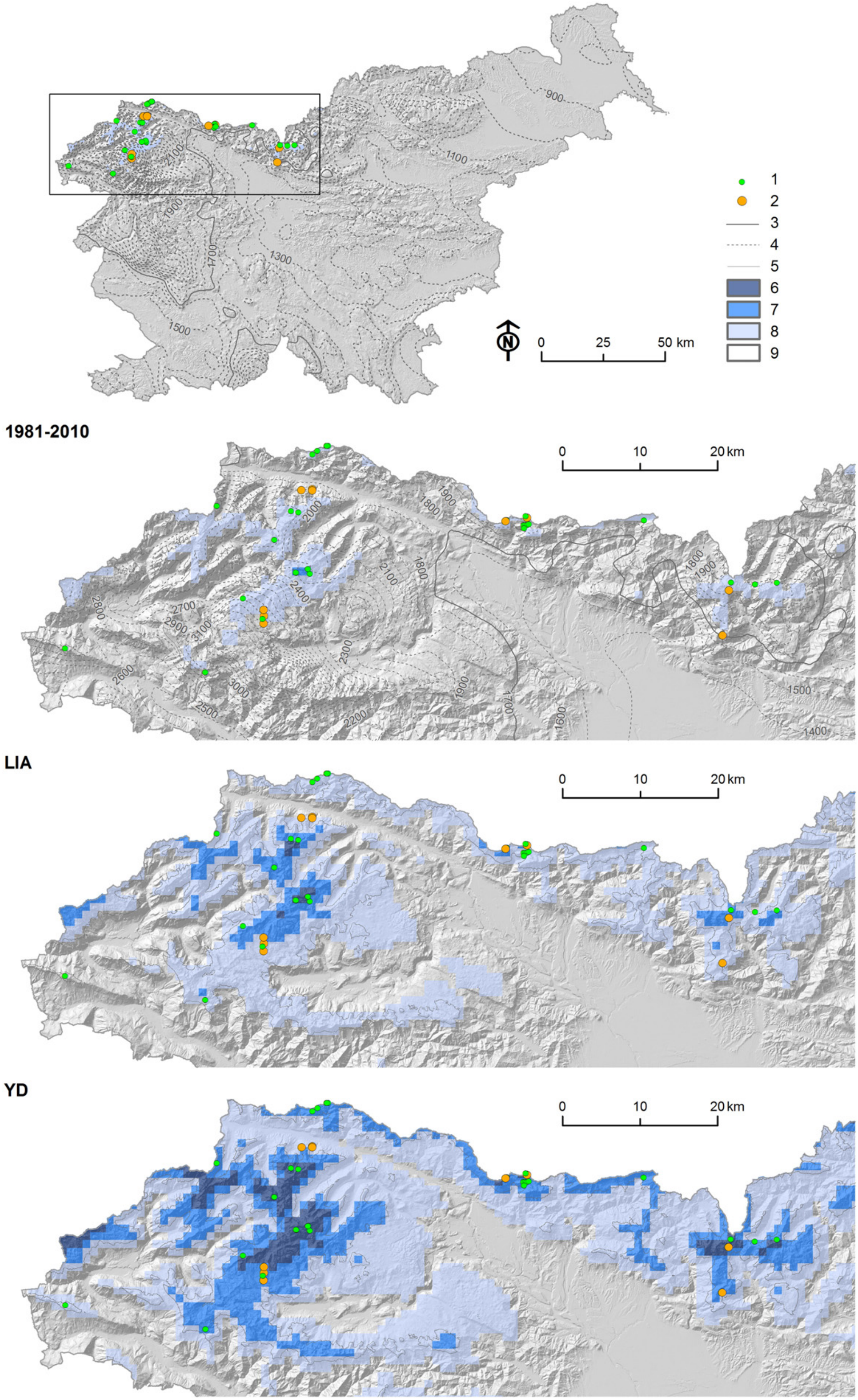
In the inventory, protalus ramparts with a number comparable to that of the rock glaciers were recognized, which differs from other inventories elsewhere in the Alps (e.g. Scapozza, 2015) in which rock glaciers are more abundant than protalus ramparts. The protalus ramparts in the Carnic Alps and Prealps (47% of the total), the drier sector of the examined area, generally follow the distribution of rock glaciers, whereas more than half of the inventoried protalus ramparts are located in a more maritime area of the Alps with higher precipitation but still <2500 mm yr^{-1}. Active protalus ramparts are located in the driest areas with present *MAAT* values between −0.4 °C and 2.0 °C. The possible presence of permafrost on some of the ramparts, as supported by the *BTS* results, should be more related to the local conditions (e.g. shading, Balch ventilation) than the regional present climate pattern, or even related to degrading permafrost from the LIA when regional *MAAT* was 1.7 °C lower. On the contrary, the active pronival ramparts observed in the Julian Alps (Fig. 3b) develop in climatic conditions far to be defined as periglacial, especially owing the high precipitation amount of the area > 2500 mm yr^{-1}. They formed at a distance from the talus foot <30–70 m, which is consistent with the definition by Ballantyne and Benn (1994) in not considering such landforms as moraines. Based on the observed clast roundness of the ridges examined in the field, it is likely that the formation and development of these features is driven by dominating snow-avalanche processes (Matthews et al., 2011). This fits well with the very high snow precipitation regime (c. 7.0 m of winter snow accumulation at 1800 m a.s.l.) and the high snow avalanche frequency of the study area.

Moreover, Matthews et al. (2011), who analysed avalanche-derived pronival ramparts in the maritime southwestern area of Norway, found ages for active ramparts ranging from 2900 or 1550 BP years to the oldest ones of YD age. They concluded that these features most likely continuously developed throughout the Holocene, modulated by variations in the snow-avalanche frequency reflecting decadal to millennial-scale climatic variations. Similar features observed in the Julian Alps could thus possibly represent a sort of "average limit" of existence of the already existing glacierets, partially modified in the shape by firn/ice pushing, and modulated by small long-scale climate variability throughout the Holocene, as highlighted by Frisia et al. (2005) and Belli et al. (2013) for the south-eastern Alps.

6. Conclusions

The revised inventory of rock glaciers in the south-eastern Alps accounts for 53 such landforms. They cover a total area of 3.45 km^2 and most of them have been classified as relict, with only four rock glaciers of uncertain activity. Under the present climate, they are mainly located in the dryer area of this alpine sector where *MAAT* < 3 °C. The relict rock glaciers seem to be related to the YD cold phase, but we cannot exclude older ages for some. A total of 66 protalus and pronival ramparts were inventoried. Seven protalus ramparts, characterized by the presence of long-lasting snow fields, highlighted the possible presence of permafrost patches. Nine active pronival ramparts, with existing permanent ice patches and glacierets, are located in the maritime area of the region with high *MAP*. While the onset and decay of rock glaciers seem to be related to the YD cold phase and the subsequent climate amelioration of the early Holocene, the pronival ramparts of the Julian and Kamnik-Savinja Alps could have continuously developed during the entire Holocene, modulated by the normal climate variability affecting the size and shape of the glacierets. The exact chronology of the evolution of such periglacial forms in the south-eastern Alps is still not well known, and there are only some working hypotheses that need to be clarified in future. The

Fig. 6. Maps of *MAAT* in Slovenia calculated for the 30-yr period 1981–2010, for the LIA and the YD. Numbers in the legend (upper right) respectively refer to: 1) protalus rampart; 2) rock glacier; 3) 1700 mm w.e.; 4) 1981–2010 *MAP* contour line (interval of 100 mm w.e.); 5) 1400 m a.s.l. contour line; 6) *MAAT* < −2 °C; 7) *MAAT* = −2–0 °C; 8) *MAAT* = 0–3 °C; 9) *MAAT* > 3 °C. °C. Climate data (1 × 1 km grid data of *MAAT* and *MAP* for the period 1981–2010) were provided by the Slovenian Environment Agency. A DEM with 12.5 m resolution provided by the Surveying and Mapping Authority of the Republic of Slovenia was used as a base layer.


900
1100
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1900
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1700
1500
1
2
3
4
5
6
7
8
9
N
0 25 50 km
1981-2010
0 10 20 km
1900
1800
2000
2100
1800
1900
1800
2400
2800
2700
2900
3100
2300
2600
3000
2500
2200
1900
1700
1600
1500
1400
LIA
0 10 20 km
YD
0 10 20 km

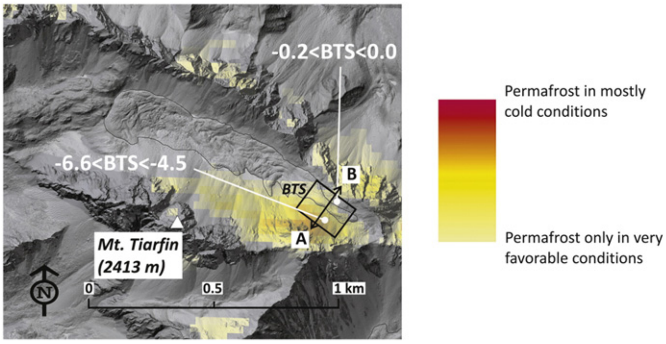

Fig. 7. Tiarfin area ("x" in Fig. 1b). *BTS* measurements have been performed in the rectangle. The range of *BTS* measurements is shown. The composite rock glacier flowing SE to NW is contoured by a black thin line. Some protalus ramparts converge towards the rock glacier, two of them in the *BTS* area. The Alpine permafrost index map (APIM) of the study area, freely available at http://www.geo.uzh.ch/microsite/cryodata/ (last accessed on 6 October 2015), is superimposed on the hillshade map of the Tiarfin area. The legend on the right indicates the probability of permafrost occurrence.

presence of patches of permafrost in equilibrium with the present climate is another important aspect that is currently under investigation.

Author contribution

RRC and MG initiated this research. CB elaborated the raw LiDAR data and set the semi-automatic routines for the morphometric analysis. RRC, MG and MŽ interpreted the results and recognized the landforms in the GIS environment. RRC, CB and MŽ made the field observations. RRC made the *BTS* measurements. RRC, CB and MŽ prepared and analysed the climatological and palaeoclimatological maps. RRC, MG and MŽ wrote the manuscript.

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