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Title: Rock glaciers, protalus ramparts and pronival ramparts in the southeastern Alps

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Abstract: Rock glaciers and protalus ramparts are characteristic landforms of the periglacial domain often used as markers for the occurrence of permafrost in mountain terrains. Therefore, relict rock glaciers can be used for paleoclimate reconstructions. We present here the first rock glacier inventory of the southeastern Alps (including the northeastern-most region of Italy and Slovenia), previously unreported, interpreted from use of high resolution orthophotos and high resolution digital terrain model interpolated from airborne laser scanning (LiDAR). We mapped 53 rock glaciers covering a total area of 3.45 km2. The majority of rock glaciers are classified as relict and distributed between 1,708-1,846 m asl with slope range between 19° and 27°. Besides rock glaciers we also observed 66 protalus (pronival) ramparts, having median elevation of 1,913 m asl and covering 0.48 km2. More than half of the inventoried protalus ramparts are located in the more maritime area of the Alps with higher precipitation compared to the location of rock glaciers. Using paleoclimate reconstruction based on the existing 1981-2010 climatology of the area, we infer that the rock glaciers formed during one of the dry and cold periods of the late Pleistocene and early Holocene (12.8±0.3-11.9 ka BP and/or 10.8±0.2 -10.1 ± 0.2 ka BP). Possible evolution of the active pronival forms observed in the most maritime area of this alpine sector is also discussed.

Reviewers' comments:

Reviewer #1: Thank you for your comprehensive edits and re-writing. In particular for the clarification of the features mapped. You have also clarified the terminology to a reasonable extent. However, there is still the assumption that all rock glaciers are permafrost-related features. And this is now extended by you to 'protalus ramparts', exemplified by the paper by Scapozza. However, it does confirm that the protalus ramparts looked at by Scarpozza are the'felsgirlande' of the older German Literature (eg Jäckli 1957, Jäckli, Heinrich. 1957. Gegenwartsgeologie des bündnerischen Rheingebietes: ein Beitrag zur exogenen Dynamik alpiner Gebirgslandschaften: Kümmerly & Frey, Geograph. Verlag.). Protalus ramparts as indicated would not be recognised by (most) geomorphologists in the UK and USA/Canada as 'protalus ramparts'. I agree this can be confusing but I think this should be indicated in your paper at least as a balance. If the features are 'relict' then it becomesdifficult to determine the proesees involved. Examples of protalus ramparts with and devoid of ice are given by Whalley and Azizi (Whalley, W Brian, and Fethi Azizi. 2003. "Rock glaciers and protalus landforms: Analogous forms and ice sources on Earth and Mars." Review of. Journal of Geophysical Research: Planets (1991-2012) 108 (E4)) This shows the difficulty of mapping via remotely sensed images.

Answering to suggestions given by the reviewer we added in the introduction the following sentence

"With regard to the relict forms is often difficult to be sure of the exact mode of formation of a rock glacier (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), Ttherefore, most of the authors recognize rock glaciers as climatic and paleoclimatic indicators of actual or past permafrost conditions and for this reason, rock glaciers are often used for paleoclimate reconstructions (e.g., Barsch and Updike, 1971; Kerschner, 1985; Harris and Pedersen, 1994; Hughes et al., 2003; Ribolini et al., 2007)." (see please page 2 lines 45 – 51 of the text version with track changes)

When considering protalus ramparts and pronival ramparts we updated two sentences as follow

"These could be considered as indicators of activity in case of pronival ramparts, while the presence of long-lasting summer snow fields in a protalus rampart could be indicator of permafrost presence. With regard to the relict forms, owing the difficulty in distinguishing the real origin of the two forms especially via remote sensing, we consider them all together." (see please page 8 lines 186 – 189 of the text version with track changes)

We also updated the references with the paper Whalley and Azizi (2008) and (Evin and Fabre, 1990)

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Editor's comments:

- Some grey figures are unacceptable.

Fig. 3. In d, e, and f, both high and low values have darker tones while middle values have lighter tones. Therefore it is impossible to know whether values are high or low for darker mapped areas.

This is absolutely true! We re-drawn figure 3 in d, e and f obtaining a much clearer result

Fig. 7. It is impossible to correlate tones with features (see the strange legend). It is unacceptable to write Blue, Purple and Yellow in a grey figure. Also it is hard to read some black text labels, both in the color and grey versions.

We agree with the Editor. We re-drawn figure 7 in order that now is much easier to read the text labels. We also changed the grey figure. Both the legend of the color and grey scale version has been drawn in a new version deleting the colours/grey tones of areas interested by permafrost at the highest degree of probability because not present in our study area and for this reason a bit confusing in our figure.

- For a figure with subfigures a, b, etc, its caption should begin with a general title of the whole figure. In this sense, the caption of Fig. 4 is OK, but the captions of Figs. 1, 2, and 3 should be corrected.

We followed suggestion given by the Editor adding a general introduction to the captures of figures 1, 2 and 3

- The blue color of Fig. 2b is rather strange. What does it mean?

We don't know, but certainly it was a mistake occured during the file conversion…we didn't notice during the submission. The figure has been corrected and figure 2b is now presented with more realistic colours.

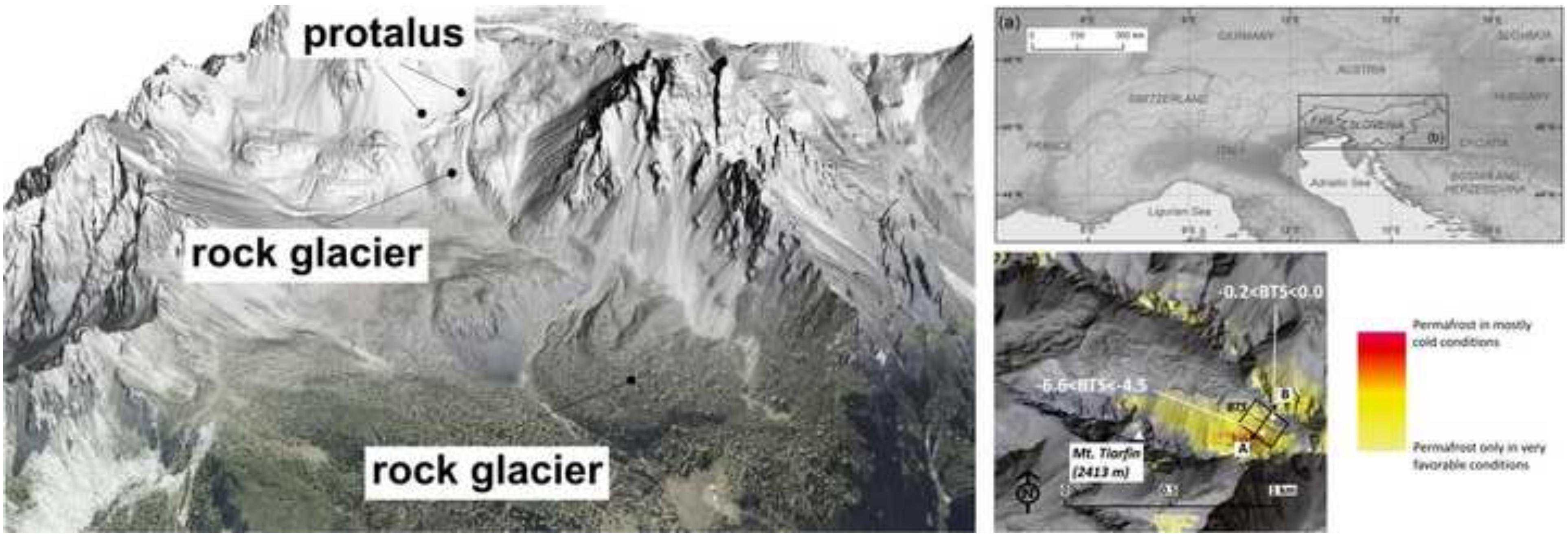
We also checked again the whole paper and corrected some very small and few mistakes. The recent publication of a paper related to sporadic permafrost occurrence in the area, gave also us the opportunity to add a sentence and a reference in the study area chapter (please see page 5, lines 106-109), We also added the author contributions before the acknowledgments.

Rock glaciers, protalus ramparts and pronival ramparts in the southeastern Alps

Highlights

- Rock Glacier distribution in the Southestern European Alps
- Onset of periglacial landforms based on speleothem paleoclimatic reconstruction
- protalus/pronival rampart distribution in the Southestern European Alps
- Identification of periglacial landforms by using high resolution LiDAR survey

Graphical Abstract



Rock glaciers, protalus ramparts and pronival ramparts in the southeastern Alps

Key words: rock glacier, protalus rampart, pronival ramparts, Alps, permafrost, LiDAR

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Abstract

Rock glaciers and protalus ramparts are characteristic landforms of the periglacial domain often used as markers for the occurrence of permafrost in mountain terrains. Therefore, relict rock glaciers can be used for paleoclimate reconstructions. We present here the first rock glacier inventory of the southeastern Alps (including the northeastern-most region of Italy and Slovenia), previously unreported, interpreted from use of high resolution orthophotos and high resolution digital terrain model interpolated from airborne laser scanning (LiDAR). We mapped 53 rock glaciers covering a total area of 3.45 km^2. The majority of rock glaciers are classified as relict and distributed between 1,708-1,846 m asl with slope range between 19° and 27°. Besides rock glaciers we also observed 66 protalus (pronival) ramparts, having median elevation of 1,913 m asl and covering 0.48 km^2. More than half of the inventoried protalus ramparts are located in the more maritime area of the Alps with higher precipitation compared to the location of rock glaciers. Using paleoclimate reconstruction based on the existing 1981-2010 climatology of the area, we infer that the rock glaciers formed during one of the dry and cold periods of the late Pleistocene and early Holocene (12.8±0.3-11.9 ka BP and/or 10.8±0.2 -10.1 ± 0.2 ka BP). Possible evolution of the active pronival forms observed in the most maritime area of this alpine sector is also discussed.

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 been long discussed and authors generally distinguish between rock glaciers of glacial (e.g., Martin and Whalley, 1987; Whalley and Martin, 1992) and periglacial (e.g., Haeberli, 1985; Barsch, 1988) origin. 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 the relict forms is often difficult to be sure of the exact mode of formation of a rock glacier (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), ~~T~~therefore, most of the authors recognize rock glaciers as climatic and paleoclimatic indicators of actual or past permafrost conditions and for this reason, rock glaciers are often used for paleoclimate reconstructions (e.g., Barsch and Updike, 1971; Kerschner, 1985; Harris and Pedersen, 1994; Hughes et al., 2003; Ribolini et al., 2007). Protalus ramparts are generally the result of ice reach ground creep and some authors are prone to consider them as embryonic rock glaciers (Haeberli, 1985; Barsch, 1996; Scapozza et al., 2011). Balch ventilation due to air convection through coarse talus slopes 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 summer long-lasting 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 rock fall boulders sliding, rolling or bouncing on it. However, the shape and development of such ridges are influenced even 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 or the change in 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 of ice and basal sliding (Ballantyne and Benn, 1994).

The distribution of rock glaciers around the world has been investigated in several mountains region and particularly in the European Alps both at regional-local scale (e.g., Seppi et al., 2012; Scotti et al., 2013) and at the national-regional scale (e.g., Guglielmin and Smiraglia, 1997; Kellerer-Pirklbauer et al., 2012; Rangecroft et al., 2014). Guglielmin and Smiraglia (1997) has been used as starting reference for the revision of the old inventory. Before this, very little was known about rock glacier distribution in the northeastern-most part 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 to conduct this analysis; the DTMs' high resolution, in fact, allow extremely accurate representations of terrain, the calculation of landforms geometry and spatial attributes with a detail previously unattainable. Furthermore, Colucci and Guglielmin (2015) while analysing climatology and the glacier's response to climate in the southeastern Alps, characterized by the highest precipitation amount of the European Alps, found a close correlation between winter precipitation and glacial evolution, with a lesser contribution given by summer temperature. This finding was a motivation to investigate the possible presence of periglacial forms in the area, so far unreported.

Therefore, the aims of this work are to: 1) update the knowledge about periglacial alpine landforms in this sector of the Alps with rock glaciers and protalus (pronival) ramparts distribution and; 2) estimate the onset 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 Friuli Venezia Giulia (FVG) region, the northeastern-most region of Italy and Slovenia. (Figure 1).The investigated area extends for 28,130 km^2, of which 4,150 km^2 are mountainous areas (> 1,000 m asl). 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), Karavanke and Slovenian Prealps (Komac, 2005). The Tagliamento Amphitheater (Figure 1) represents the most well-preserved easternmost end moraine system of the south-alpine foreland and is one of the larger of the southern Alps covering an area of 220 km^2. It represents the most evident feature of Quaternary glaciations in FVG (Monegato et al., 2007).

The higher peaks are represented by Mt. Coglians-Hohewarte (2,780 m a.s.l.) in the Carnic Alps, Mt. Triglav (2,864 m a.s.l.) in the Julian Alps and Mt. Grintovec (2,558 m a.s.l.) in the Kamnik-

Savinja Alps (Figure 1b). In the Julian Alps, there is evidence of 14 permanent snow/firn bodies covering at present (2012) a total area of 0.266 km^2 compared to the 1.559 km^2 during the Little Ice Age (LIA) maximum (Colucci, 2016, in press). They have northerly aspect and developed at the base of steep rock slopes which favour avalanche activity, snow blowing and summer shading. The presence of sporadic permafrost phenomena 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).

Mean Annual Precipitation (MAP) are at its highest in the Julian Alps with totals higher than 3,300 mm, representing one of the highest mean values for the European Alps (Norbiato et al., 2007). In the inner Alpine area MAP decrease to 1,600-1,800 mm because of the rain shadow effect of the southern ridges, while towards east MAP decrease down to less than 1,000 mm. 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 East in Slovenia. The spatialized 1981-2010 MAAT shows extremes ranging from ca. -2.6 °C of the highest peaks to ca. 15.2 °C of 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 2,370±90 m asl. The -2 °C isotherm, which defines environments where frost action is dominant (French, 2007), is estimated at 2,665 ±90 m asl.

Figure 1

Location of Friuli Venezia Giulia (FVG) region and Slovenia. (a) European Alps ~~(a)~~ and (b) detail of the study area ~~(b)~~. t=Tagliamento end moraine system during LGM, x = Tiarfin area (Figure 7), y = Valbinon area (Figure 3).

3 - Methods

3.1 Identification of the landforms and climatic analyses

The inventory has been compiled by the inspection of medium resolution (0.5 m pixel 1998, 2003, 2011, 2014) and high resolution (0.15 m pixel 2006-2009) aerial orthorectified photographs (orthophoto) (Civil Defense of Region Friuli Venezia Giulia and the Surveying and mapping authority of the Republic of Slovenia).

High resolution (1.0 m cell size) digital terrain model (DTM) interpolated from airborne laser scanning (LiDAR) acquired between September 2006 and September 2009 (Civil Defense of FVG) for FVG and between February 2011 and April 2015 for Slovenia (Open access data, Geodetic Institute of Slovenia) served as the basis for geomorphological mapping and morphometric analysis of the landforms. Hillshade derived from the DTM was crucial especially in the recognition of landforms buried by vegetation where orthophotos are poorly useful (Figure 3).

Maps of climate and paleoclimate conditions over FVG were computed using monthly temperature grids derived from OSMER dataset (1996-2005) recalculated following Colucci and Guglielmin (2015) over the 30 years period 1981-2010. Data has been interpolated by using *natural neighbours* method from a grid of 480x480 m. For the Slovenian side a 1x1 km grid of 1981-2010 MAAT (Slovenian Environment Agency) was used. For the little ice age (LIA; 1350-1850 A.D.), we used the same approach by processing the 30 yr period 1851-1880 (Colucci and Guglielmin, 2015), which is the oldest available one 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, which is in agreement with the average anomalies of -2°C during the early Holocene respect to late preindustrial time set by Mauri et al. (2015).

3.2 Rock Glaciers

Several landform attributes were assigned to rock glaciers (Table 1), which allowed making further analyses. It is acknowledged that the upper limit of a rock glacier (rooting zone) is far to be easy to determine (e.g., Krainer and Ribis, 2012) and sometime is chosen arbitrarily. Therefore consistent effort was put on determining where the rock glacier meets the input accumulation zone above it by looking at surface morphology (Figure 3). We further classified the rock glaciers according to their geometry where a tongue-shaped rock glacier present a length/width ratio >1 and a lobate rock glacier a length/width ratio <1, respectively (Wahrhaftig and Cox, 1959). The geomorphological location, such as talus or debris rock glacier (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/lack of ice and because no horizontal/vertical displacement of the landforms were available. Therefore, we subdivided the rock glaciers in active (likely with ice), relict (likely without ice), and of uncertain activity when the landforms where not fully supported by all the necessary characteristics of one of the two above mentioned classes. To avoid confusion 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. Accordingly, active rock glaciers are those having a steep front, mostly steeper than the angle of repose of the material (35°), a mean longitudinal convex relief and 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, it has been demonstrated as some species can be present even with relatively high movements (<35 cm/year; Cannone and Gerdol, 2003) so the use of vegetation as a proxy for landforms activity should be more cautious, done on the field and not from remote platforms. The surface topography is generally characterized by a system of pronounced furrows and ridges transversal to the flow of the rock glacier originated from over-thrusting of internal shear planes and differential movement of distinct layers under compressive flow (e.g., Wahrhaftig and Cox, 1959; Haeberli 1985; Kääb and Weber, 2004). Relict rock glaciers have 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).

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

3.3 Protalus and pronival forms

The inventory comprises also protalus ramparts and pronival ramparts. We characterize these landforms in respect to the activity according to a geomorphological approach looking at the steepness of the front, and in addition we highlight the contingent presence/absence of a perennial or semi-permanent snow/*firn* field. These could be considered as indicators of activity in case of pronival ramparts, while the presence of long-lasting summer snow fields in a protalus rampart could be indicator of permafrost presence. With regard to the relict forms, owing 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.

Figure 2

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

3.4 Field observations

In order to assess the reliability of the inventory, we conducted field surveys during summer and autumn in 2012 and 2013, and during autumn in 2015 to better characterize the vegetation cover, verify the presence/absence of active springs, and eventually to measure water temperature during late summer-early autumn. The temperature of the springs was measured between August and September with a Pt100 thermistor class A-1/10 operating in the range of -50°C to 250 °C having 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)

Figure 3

An example of the methodology used in this research:~~.~~ (a) p~~P~~seudo 3d image from high-resolution orthophoto, ~~(a)~~ and (b) hillshade. ~~(b); r~~Rock glaciers are indicated as rg1, rg2 and rg3. Down, from left to right and referred to rg1 in (b): (c) calculation of area, length and width; (d) calculation of morphometric parameters from the high resolution DTM; (e) slope analysis; (f) computation of front steepness; (g) section of the longitudinal profile drown in (c).

4 - Results

4.1 – Rock glaciers

We mapped 53 rock glaciers covering an area of 3.45 km^2 (Figure 5 and Figure 6). Rock glaciers are concentrated in the Carnic Alps (28 rock glacier, 53% of the total) and in the Carnic Prealps (14 rock glacier, 26%). Seven rock glaciers (13% of the total) exist in the Julian Alps, only 2 (4% of the total) in the Karavanke and the same number in the Kamnik-Savinja Alps. The largest rock glacier cover an area of 0.51 km^2. The tongue shaped geometry is predominant (53%) compared to the lobate one (47%). The mean slope of rock glaciers is 22.6° with the majority of them (72%) falling in the range 19°-27°.

Forty-nine rock glaciers (92%) have been classified as relict and only 4 (8%) of uncertain activity. In particular, we found: a) 1 rock glacier having a mean front slope equal to 35°; b) 2 rock glaciers having slightly convex longitudinal profiles; c) 1 rock glacier with a plentiful spring having rather constant temperature of 2.5°C. The regional median minimum elevation of rock glacier fronts has been placed at 1,778 m asl, with a standard deviation of 130 m, representing the lowest altitude of relict forms in the Italian Alps (Guglielmin and Smiraglia, 1997; Dramis et al., 2003). Rock glaciers mostly developed on north-facing aspect (NW, N and NE; Figure 4c) and they are predominantly distributed within the 1,708-1,846 m asl altitude range (I and III quartile; Figure4b) with a median elevation of 1,777 m. Rock glaciers having north-facing and east-facing aspects (NW to E sector) tend to develop at lower altitude with a mean elevation between 1,700 m and 1,800 m asl. (Figure 4b), while south-facing rock glaciers have mean elevation between 1,860 and 2,016 m asl, extending from roughly 1,800 m 2,100 m asl. This pattern is common in several 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 minimum elevation of rock glacier fronts. In fact, their fronts stopped on average at 1,076 m asl, which is very close to the LGM ELA set at ca. 1,200 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 scattered among the Carnic Prealps, Kamnik-Savinja Alps and Julian Prealps; the majority is distributed between 1,697 m and 2,007 m asl (I and III quartile) with a median elevation of 1,913 m asl. Seven were selected as possibly active protalus ramparts and separately considered in Figure 4b owing to the presence of long-lasting, but not permanent, snowfields as highlighted in the orthophotos and during field campaigns. This could indicate the presence of patches of permafrost allowing the surviving of the snow patch. They are located at the higher altitude ranging between 2,063 m and 2,442 m asl with a median elevation of 2,181 m asl. The possible presence of permafrost was also highlighted through BTS measurements performed in the Carnic Prealps at 2,258 m asl. The survey was performed on late February 2013, in an area occupied by 2 protalus ramparts that gave values ranging between -6.6°C/-4.5°C, largely sufficient to hypothesize the presence of permafrost (Figure 7). Our findings seem to be partially in agreement with evidence given by the available alpine permafrost index map (APIM, Figure 7) (Boeckli et al., 2012). Besides active protalus ramparts we also classified 9 active pronival ramparts, located in front of permanent snow/firn bodies and small glacierets, of which 7 in the Julian Alps (Colucci, 2016, in press) and 2 in the Kamnik-Savinja Alps. These ridges produce a damming effect for avalanches which enhance accumulation of winter snow, a significant impact to 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.

Figure 4

Main characteristics of the rock glacier and protalus rampart distribution: (a) regional distribution vs altitude: minimum, lower quartile, median, upper quartile and maximum are drawn respectively for relict rock glaciers and protalus ramparts (4 rock glaciers of uncertain activity and 7 protalus rampart selected on the basis of the presence of long-lasting snow patches are depicted only with median, minimum and maximum altitudes); (b) Altitudinal distribution vs glaciers and protalus ramparts aspect (bars indicate the 95% confidence interval); (c) polar diagrams with aspect distribution of both rock glaciers (RG) and protalus ramparts (PR). The 4 lowest rock glaciers located in the Julian Alps are not considered in the statistics.

5-Discussion

5.1 Rock glaciers distribution and estimated age of formation

The altitudinal range of rock glaciers analysed here is the lowest for the southern Alps and comparable with what has been found for relict rock glaciers in the Northern Alps of Austria (1,798 m) and in the Austrian Niedere Tauern Range (1,823-1,850 m) (Kellerer-Pirklbauer et al., 2012).

Rock glaciers are widespread periglacial landforms in the Alps and the active modern ones are generally seen as indicators of the presence of discontinuous mountain permafrost in areas where the MAAT is < -2 °C (Haeberli, 1985; Barsch, 1996; French, 2007). At present climate, having as reference the spatialized MAAT 1981-2010 (Figure 5 and Figure 6) and the topographic setting, the current distribution of rock glaciers in the Carnic Alps and Prealps entirely falls in areas with MAAT<3 °C and MAP<1,700 mm 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>1,700 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), although it is well known that rock glaciers may reach lower altitudes compared to the climatic permafrost boundaries (Harris and Pedersen, 1998). Considering that for this alpine sector the results of the study on speleothems reported in Belli et al. (2013) and Frisia et al. (2005) are the best paleoclimatic proxies for the last 16,000 years, it is possible to recognize 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 that time, no periods with considerable colder and drier conditions compared to present days were detected in the southeastern Alps. Therefore, it is reasonable to speculate that these two periods could be the most favorable to have permafrost conditions in our study area and form the rock glaciers. Despite the low number of dated rock glaciers (e.g., Dramis et al., 2003; Stenni et al., 2007, Scapozza et al., 2010) a Younger Dryas (YD) or a Holocenic age of the relict rock glaciers has been suggested (Frauenfelder et al., 2001; Lambiel and Reynard, 2001). Moreover, in the Alps, active rock glaciers are about 400-500 m higher in elevation respect to the relict forms, which correspond to a temperature drop of ca. 2.6-3.3 °C (Frauenfelder et al., 2001). Sector S1, highlighted in Figure 5, showed the lowest averaged MAAT (-1.9±0.7 °C) during the YD and the higher rock glaciers fronts altitude (1,822±163 m asl). Here, the highest rock glacier (Tiarfin, Figure 1 and Figure 7) had a MAAT of -2.6 °C with 5 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 at the YD event. The YD mean annual 0 °C-isotherm is estimated at about 1,400 m asl (Figure 5 and Figure 6). If we still believe that MAAT < -2 °C is valid we can hypothesize: i) the south-eastern Alps MAAT cooling during the YD was higher than the assumed -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 (i.e. balch ventilation , e.g., Harris and Pedersen, 1998) or low radiation conditions (shady positions); iii) these rock glaciers were formed in cold and dry periods older than the YD.The high MAAT for the lowest lying rock glaciers located 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) and therefore we hypothesize that these rock glaciers were formed during the LGM.

Figure 5

Maps of MAAT in FVG calculated for the 30 years period 1981-2010, for the LIA and for the YD. Numbers in the legend (upper left) respectively refer to: 1) protalus rampart; 2) rock glacier; 3) 1,700 mm w.e.; 4) 1961-2000 MAP contour line (step of 100 mm w.e.); 5) 1,400 m asl contour line; 6) MAAT <-2 °C; 7) -2 °<MAAT <0 °C; 8) 0 °<MAAT<3 °C; 9) MAAT>3 °C. S1 is commented in the discussions. (DEM derived by LiDAR survey performed between 2006 and 2009 by Civil Defense of Region FVG; For colour interpretation, please refer to the web version of the article)

Figure 6

Maps of MAAT in Slovenia calculated for the 30 years period 1981-2010, for the LIA and for the YD. Numbers in the legend (upper left) respectively refer to: 1) protalus rampart; 2) rock glacier; 3) 1,700 mm w.e.; 4) 1981-2010 MAP contour line (step of 100 mm w.e.); 5) 1,400 m asl contour line; 6) MAAT <-2 °C; 7) -2 °<MAAT <0 °C; 8) 0 °<MAAT<3 °C; 9) MAAT>3 °C. Climate data (1 km x 1 km grid data of MAAT and MAP for the period 1981-2010) was provided by Slovenian Environment Agency. DEM 12.5 m (The Surveying and Mapping Authority of the Republic of Slovenia) was used as a base layer. (For colour interpretation, please refer to the web version of the article)

5.2 Protalus and Pronival Ramparts

In this inventory, a comparable number of protalus ramparts respect to rock glaciers were recognized, which is uncommon if we look at what was found in other inventories from the Alps (e.g. Scapozza, 2015), where the number of rock glaciers largely prevails. Protalus ramparts situated in the Carnic Alps and Prealps (47% of the total), the drier sector of the examined area, generally follow the same geographical distribution of rock glaciers, whereas more than half of the inventoried protalus ramparts are located in a more maritime area of the Alps where higher precipitation is recorded, but still < 2500 mm yr^{-1}. Active protalus ramparts are located in the driest areas with a present MAAT between -0.4°C and 2.0°C. The possible presence of permafrost on some of them as enhanced by BTS results should be more related to the local conditions than the regional climate pattern, or even related to the LIA when regional MAAT were 1.7 °C lower. The active pronival ramparts observed in the Julian Alps (Figure 2b), on the contrary, at present develop in climatic conditions far to be defined as periglacial, especially owing the high precipitation amount of the area always > 2,500 mm a^{-1}. They formed at a distance from the talus foot slope < 30–70 m, which is consistent with the definition given by Ballantynes 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 according to Matthews et al. (2011). This fits well with the very high snow precipitation regime (c. 7.0 m of winter snow accumulation at 1,800 m asl) and the high snow avalanche frequency of the analysed area.

Moreover, Matthews et al. (2011), analysing a subset of avalanche-derived pronival ramparts in the maritime southwestern area of Norway, found ages for active ramparts ranging from <2,900 BP years and <1,550 BP years, with the oldest ones of YD age. They concluded that these features likely suggest a continued development throughout the Holocene, modulated by variations in 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 southeastern Alps.

Figure 7

~~(a)~~ Tiarfin area (“x” in Figure 1b) with the area where BTS measurements have been performed (rectangle) and the range of BTS measurements. The composite rock glacier flowing SE to NW is contoured by a black thin line. Some protalus ramparts possibly active 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 to the hillshade of Tiarfin area. The legend on the right indicates the probability of permafrost occurrence (For colour interpretation, please refer to the web version of the article).

6 Conclusions

The revised inventory of rock glaciers in the southeastern Alps accounts for 53 such landforms. They cover a total area of 3.45 km^2 and have been classified as mostly relict, with only 4 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 (present periglacial domain). The relict rock glaciers seem to be related to the YD cold phase, but we cannot exclude an older age for some. The inventory of protalus and pronival ramparts shows the occurrence of 66 landforms. Seven protalus ramparts, characterized by the presence of long-lasting snow fields, highlighted the possible presence of permafrost patches. Nine active pronival ramparts, owing the presence of still existing permanent ice patches and glacierets, are located in the more 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 and from the YD, modulated by the normal climate variability affecting the size and the shape of the glacierets. The exact chronology of the beginning and evolution of such periglacial forms in the southeastern Alps is still not well known, and there are only some working hypotheses that need to be clarified in the coming years. The 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 authomatic routines for the morphometric analysis. RRC, MG and MŽ interpreted the results and recognized the landforms in GIS environment. RRC, CB and MŽ made the field observations. RRC made the BTS measures. RRC, CB and MŽ prepared and analyzed the climatological and palaeoclimatological maps. RRC, MG and MŽ wrote the manuscript.

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Rock glaciers, protalus ramparts and pronival ramparts in the southeastern Alps

Key words: rock glacier, protalus rampart, pronival ramparts, Alps, permafrost, LiDAR

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Abstract

Rock glaciers and protalus ramparts are characteristic landforms of the periglacial domain often used as markers for the occurrence of permafrost in mountain terrains. Therefore, relict rock glaciers can be used for paleoclimate reconstructions. We present here the first rock glacier inventory of the southeastern Alps (including the northeastern-most region of Italy and Slovenia), previously unreported, interpreted from use of high resolution orthophotos and high resolution digital terrain model interpolated from airborne laser scanning (LiDAR). We mapped 53 rock glaciers covering a total area of 3.45 km^2. The majority of rock glaciers are classified as relict and distributed between 1,708-1,846 m asl with slope range between 19° and 27°. Besides rock glaciers we also observed 66 protalus (pronival) ramparts, having median elevation of 1,913 m asl and covering 0.48 km^2. More than half of the inventoried protalus ramparts are located in the more maritime area of the Alps with higher precipitation compared to the location of rock glaciers. Using paleoclimate reconstruction based on the existing 1981-2010 climatology of the area, we infer that the rock glaciers formed during one of the dry and cold periods of the late Pleistocene and early Holocene (12.8±0.3-11.9 ka BP and/or 10.8±0.2 -10.1 ± 0.2 ka BP). Possible evolution of the active pronival forms observed in the most maritime area of this alpine sector is also discussed.

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 been long discussed and authors generally distinguish between rock glaciers of glacial (e.g., Martin and Whalley, 1987; Whalley and Martin, 1992) and periglacial (e.g., Haeberli, 1985; Barsch, 1988) origin. 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 the relict forms is often difficult to be sure of the exact mode of formation of a rock glacier (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, most of the authors recognize rock glaciers as climatic and paleoclimatic indicators of actual or past permafrost conditions and for this reason, rock glaciers are often used for paleoclimate reconstructions (e.g., Barsch and Updike, 1971; Kerschner, 1985; Harris and Pedersen, 1994; Hughes et al., 2003; Ribolini et al., 2007). Protalus ramparts are generally the result of ice reach ground creep and some authors are prone to consider them as embryonic rock glaciers (Haeberli, 1985; Barsch, 1996; Scapozza et al., 2011). Balch ventilation due to air convection through coarse talus slopes 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 summer long-lasting 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 rock fall boulders sliding, rolling or bouncing on it. However, the shape and development of such ridges are influenced even 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 or the change in 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 of ice and basal sliding (Ballantyne and Benn, 1994).

The distribution of rock glaciers around the world has been investigated in several mountains region and particularly in the European Alps both at regional-local scale (e.g., Seppi et al., 2012; Scotti et al., 2013) and at the national-regional scale (e.g., Guglielmin and Smiraglia, 1997; Kellerer-Pirklbauer et al., 2012; Rangecroft et al., 2014). Guglielmin and Smiraglia (1997) has been used as starting reference for the revision of the old inventory. Before this, very little was known about rock glacier distribution in the northeastern-most part 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 to conduct this analysis; the DTMs' high resolution, in fact, allow extremely accurate representations of terrain, the calculation of landforms geometry and spatial attributes with a detail previously unattainable. Furthermore, Colucci and Guglielmin (2015) while analysing climatology and the glacier's response to climate in the southeastern Alps, characterized by the highest precipitation amount of the European Alps, found a close correlation between winter precipitation and glacial evolution, with a lesser contribution given by summer temperature. This finding was a motivation to investigate the possible presence of periglacial forms in the area, so far unreported.

Therefore, the aims of this work are to: 1) update the knowledge about periglacial alpine landforms in this sector of the Alps with rock glaciers and protalus (pronival) ramparts distribution and; 2) estimate the onset 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 Friuli Venezia Giulia (FVG) region, the northeastern-most region of Italy and Slovenia. (Figure 1).The investigated area extends for 28,130 km^2, of which 4,150 km^2 are mountainous areas (> 1,000 m asl). 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), Karavanke and Slovenian Prealps (Komac, 2005). The Tagliamento Amphitheater (Figure 1) represents the most well-preserved easternmost end moraine system of the south-alpine foreland and is one of the larger of the southern Alps covering an area of 220 km^2. It represents the most evident feature of Quaternary glaciations in FVG (Monegato et al., 2007).

The higher peaks are represented by Mt. Coglians-Hohewarte (2,780 m a.s.l.) in the Carnic Alps, Mt. Triglav (2,864 m a.s.l.) in the Julian Alps and Mt. Grintovec (2,558 m a.s.l.) in the Kamnik-

Savinja Alps (Figure 1b). In the Julian Alps, there is evidence of 14 permanent snow/firn bodies covering at present (2012) a total area of 0.266 km^2 compared to the 1.559 km^2 during the Little Ice Age (LIA) maximum (Colucci, 2016, in press). They have northerly aspect and developed at the base of steep rock slopes which favour avalanche activity, snow blowing and summer shading. The presence of sporadic permafrost phenomena 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).

Mean Annual Precipitation (MAP) are at its highest in the Julian Alps with totals higher than 3,300 mm, representing one of the highest mean values for the European Alps (Norbiato et al., 2007). In the inner Alpine area MAP decrease to 1,600-1,800 mm because of the rain shadow effect of the southern ridges, while towards east MAP decrease down to less than 1,000 mm. 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 East in Slovenia. The spatialized 1981-2010 MAAT shows extremes ranging from ca. -2.6 °C of the highest peaks to ca. 15.2 °C of 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 2,370±90 m asl. The -2 °C isotherm, which defines environments where frost action is dominant (French, 2007), is estimated at 2,665 ±90 m asl.

Figure 1

Location of Friuli Venezia Giulia (FVG) region and Slovenia. (a) European Alps and (b) detail of the study area. t=Tagliamento end moraine system during LGM, x = Tiarfin area (Figure 7), y = Valbinon area (Figure 3).

3 - Methods

3.1 Identification of the landforms and climatic analyses

The inventory has been compiled by the inspection of medium resolution (0.5 m pixel 1998, 2003, 2011, 2014) and high resolution (0.15 m pixel 2006-2009) aerial orthorectified photographs (orthophoto) (Civil Defense of Region Friuli Venezia Giulia and the Surveying and mapping authority of the Republic of Slovenia).
High resolution (1.0 m cell size) digital terrain model (DTM) interpolated from airborne laser scanning (LiDAR) acquired between September 2006 and September 2009 (Civil Defense of FVG) for FVG and between February 2011 and April 2015 for Slovenia (Open access data, Geodetic Institute of Slovenia) served as the basis for geomorphological mapping and morphometric analysis of the landforms. Hillshade derived from the DTM was crucial especially in the recognition of landforms buried by vegetation where orthophotos are poorly useful (Figure 3).
Maps of climate and paleoclimate conditions over FVG were computed using monthly temperature grids derived from OSMER dataset (1996-2005) recalculated following Colucci and Guglielmin (2015) over the 30 years period 1981-2010. Data has been interpolated by using *natural neighbours* method from a grid of 480x480 m. For the Slovenian side a 1x1 km grid of 1981-2010 MAAT (Slovenian Environment Agency) was used. For the little ice age (LIA; 1350-1850 A.D.), we used the same approach by processing the 30 yr period 1851-1880 (Colucci and Guglielmin, 2015), which is the oldest available one 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, which is in agreement with the average anomalies of -2°C during the early Holocene respect to late preindustrial time set by Mauri et al. (2015).

3.2 Rock Glaciers

Several landform attributes were assigned to rock glaciers (Table 1), which allowed making further analyses. It is acknowledged that the upper limit of a rock glacier (rooting zone) is far to be easy to determine (e.g., Krainer and Ribis, 2012) and sometime is chosen arbitrarily. Therefore consistent effort was put on determining where the rock glacier meets the input accumulation zone above it by looking at surface morphology (Figure 3). We further classified the rock glaciers according to their geometry where a tongue-shaped rock glacier present a length/width ratio >1 and a lobate rock glacier a length/width ratio <1, respectively (Wahrhaftig and Cox, 1959). The geomorphological location, such as talus or debris rock glacier (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/lack of ice and because no horizontal/vertical displacement of the landforms were available. Therefore, we subdivided the rock glaciers in active (likely with ice), relict (likely without ice), and of uncertain activity when the landforms where not fully supported by all the necessary characteristics of one of the two above mentioned classes. To avoid confusion 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. Accordingly, active rock glaciers are those having a steep front, mostly steeper than the angle of repose of the material (35°), a mean longitudinal convex relief and 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, it has been demonstrated as some species can be present even with relatively high movements (<35 cm/year; Cannone and Gerdol, 2003) so the use of vegetation as a proxy for landforms activity should be more cautious, done on the field and not from remote platforms. The surface topography is generally characterized by a system of pronounced furrows and ridges transversal to the flow of the rock glacier originated from over-thrusting of internal shear planes and differential movement of distinct layers under compressive flow (e.g., Wahrhaftig and Cox, 1959; Haeberli 1985; Kääb and Weber, 2004). Relict rock glaciers have 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).

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

3.3 Protalus and pronival forms

The inventory comprises also protalus ramparts and pronival ramparts. We characterize these landforms in respect to the activity according to a geomorphological approach looking at the steepness of the front, and in addition we highlight the contingent presence/absence of a perennial or semi-permanent snow/*firn* field. These could be considered as indicators of activity in case of pronival ramparts, while the presence of long-lasting summer snow fields in a protalus rampart could be indicator of permafrost presence. With regard to the relict forms, owing 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.

Figure 2

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 on late October 2014.

3.4 Field observations

In order to assess the reliability of the inventory, we conducted field surveys during summer and autumn in 2012 and 2013, and during autumn in 2015 to better characterize the vegetation cover, verify the presence/absence of active springs, and eventually to measure water temperature during late summer-early autumn. The temperature of the springs was measured between August and September with a Pt100 thermistor class A-1/10 operating in the range of -50°C to 250 °C having 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)

Figure 3

An example of the methodology used in this research: (a) pseudo 3d image from high-resolution orthophoto, and (b) hillshade.Rock glaciers are indicated as rg1, rg2 and rg3. Down, from left to right and referred to rg1 in (b): (c) calculation of area, length and width; (d) calculation of morphometric parameters from the high resolution DTM; (e) slope analysis; (f) computation of front steepness; (g) section of the longitudinal profile drown in (c).

4 - Results

4.1 – Rock glaciers

We mapped 53 rock glaciers covering an area of 3.45 km^2 (Figure 5 and Figure 6). Rock glaciers are concentrated in the Carnic Alps (28 rock glacier, 53% of the total) and in the Carnic Prealps (14 rock glacier, 26%). Seven rock glaciers (13% of the total) exist in the Julian Alps, only 2 (4% of the total) in the Karavanke and the same number in the Kamnik-Savinja Alps. The largest rock glacier cover an area of 0.51 km^2. The tongue shaped geometry is predominant (53%) compared to the lobate one (47%). The mean slope of rock glaciers is 22.6° with the majority of them (72%) falling in the range 19°-27°.

Forty-nine rock glaciers (92%) have been classified as relict and only 4 (8%) of uncertain activity. In particular, we found: a) 1 rock glacier having a mean front slope equal to 35°; b) 2 rock glaciers having slightly convex longitudinal profiles; c) 1 rock glacier with a plentiful spring having rather constant temperature of 2.5°C. The regional median minimum elevation of rock glacier fronts has been placed at 1,778 m asl, with a standard deviation of 130 m, representing the lowest altitude of relict forms in the Italian Alps (Guglielmin and Smiraglia, 1997; Dramis et al., 2003). Rock glaciers mostly developed on north-facing aspect (NW, N and NE; Figure 4c) and they are predominantly distributed within the 1,708-1,846 m asl altitude range (I and III quartile; Figure4b) with a median elevation of 1,777 m. Rock glaciers having north-facing and east-facing aspects (NW to E sector) tend to develop at lower altitude with a mean elevation between 1,700 m and 1,800 m asl. (Figure 4b), while south-facing rock glaciers have mean elevation between 1,860 and 2,016 m asl, extending from roughly 1,800 m 2,100 m asl. This pattern is common in several 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 minimum elevation of rock glacier fronts. In fact, their fronts stopped on average at 1,076 m asl, which is very close to the LGM ELA set at ca. 1,200 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 scattered among the Carnic Prealps, Kamnik-Savinja Alps and Julian Prealps; the majority is distributed between 1,697 m and 2,007 m asl (I and III quartile) with a median elevation of 1,913 m asl. Seven were selected as possibly active protalus ramparts and separately considered in Figure 4b owing to the presence of long-lasting, but not permanent, snowfields as highlighted in the orthophotos and during field campaigns. This could indicate the presence of patches of permafrost allowing the surviving of the snow patch. They are located at the higher altitude ranging between 2,063 m and 2,442 m asl with a median elevation of 2,181 m asl. The possible presence of permafrost was also highlighted through BTS measurements performed in the Carnic Prealps at 2,258 m asl. The survey was performed on late February 2013, in an area occupied by 2 protalus ramparts that gave values ranging between -6.6°C/-4.5°C, largely sufficient to hypothesize the presence of permafrost (Figure 7). Our findings seem to be partially in agreement with evidence given by the available alpine permafrost index map (APIM, Figure 7) (Boeckli et al., 2012).
Besides active protalus ramparts we also classified 9 active pronival ramparts, located in front of permanent snow/firn bodies and small glacierets, of which 7 in the Julian Alps (Colucci, 2016, in press) and 2 in the Kamnik-Savinja Alps. These ridges produce a damming effect for avalanches which enhance accumulation of winter snow, a significant impact to 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.

Figure 4

Main characteristics of the rock glacier and protalus rampart distribution: (a) regional distribution vs altitude: minimum, lower quartile, median, upper quartile and maximum are drawn respectively for relict rock glaciers and protalus ramparts (4 rock glaciers of uncertain activity and 7 protalus rampart selected on the basis of the presence of long-lasting snow patches are depicted only with median, minimum and maximum altitudes); (b) Altitudinal distribution vs glaciers and protalus ramparts aspect (bars indicate the 95% confidence interval); (c) polar diagrams with aspect distribution of both rock glaciers (RG) and protalus ramparts (PR). The 4 lowest rock glaciers located in the Julian Alps are not considered in the statistics.

5-Discussion

5.1 Rock glaciers distribution and estimated age of formation

The altitudinal range of rock glaciers analysed here is the lowest for the southern Alps and comparable with what has been found for relict rock glaciers in the Northern Alps of Austria (1,798 m) and in the Austrian Niedere Tauern Range (1,823-1,850 m) (Kellerer-Pirklbauer et al., 2012).

Rock glaciers are widespread periglacial landforms in the Alps and the active modern ones are generally seen as indicators of the presence of discontinuous mountain permafrost in areas where the MAAT is < -2 °C (Haeberli, 1985; Barsch, 1996; French, 2007). At present climate, having as reference the spatialized MAAT 1981-2010 (Figure 5 and Figure 6) and the topographic setting, the current distribution of rock glaciers in the Carnic Alps and Prealps entirely falls in areas with MAAT<3 °C and MAP<1,700 mm 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>1,700 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), although it is well known that rock glaciers may reach lower altitudes compared to the climatic permafrost boundaries (Harris and Pedersen, 1998). Considering that for this alpine sector the results of the study on speleothems reported in Belli et al. (2013) and Frisia et al. (2005) are the best paleoclimatic proxies for the last 16,000 years, it is possible to recognize 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 that time, no periods with considerable colder and drier conditions compared to present days were detected in the southeastern Alps. Therefore, it is reasonable to speculate that these two periods could be the most favorable to have permafrost conditions in our study area and form the rock glaciers. Despite the low number of dated rock glaciers (e.g., Dramis et al., 2003; Stenni et al., 2007, Scapozza et al., 2010) a Younger Dryas (YD) or a Holocenic age of the relict rock glaciers has been suggested (Frauenfelder et al., 2001; Lambiel and Reynard, 2001). Moreover, in the Alps, active rock glaciers are about 400-500 m higher in elevation respect to the relict forms, which correspond to a temperature drop of ca. 2.6-3.3 °C (Frauenfelder et al., 2001). Sector S1, highlighted in Figure 5, showed the lowest averaged MAAT (-1.9±0.7 °C) during the YD and the higher rock glaciers fronts altitude (1,822±163 m asl). Here, the highest rock glacier (Tiarfin, Figure 1 and Figure 7) had a MAAT of -2.6 °C with 5 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 at the YD event. The YD mean annual 0 °C-isotherm is estimated at about 1,400 m asl (Figure 5 and Figure 6). If we still believe that MAAT < -2 °C is valid we can hypothesize: i) the south-eastern Alps MAAT cooling during the YD was higher than the assumed -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 (i.e. balch ventilation , e.g., Harris and Pedersen, 1998) or low radiation conditions (shady positions); iii) these rock glaciers were formed in cold and dry periods older than the YD.The high MAAT for the lowest lying rock glaciers located 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) and therefore we hypothesize that these rock glaciers were formed during the LGM.

Figure 5

Maps of MAAT in FVG calculated for the 30 years period 1981-2010, for the LIA and for the YD. Numbers in the legend (upper left) respectively refer to: 1) protalus rampart; 2) rock glacier; 3) 1,700 mm w.e.; 4) 1961-2000 MAP contour line (step of 100 mm w.e.); 5) 1,400 m asl contour line; 6) MAAT <-2 °C; 7) -2 °<MAAT <0 °C; 8) 0 °<MAAT<3 °C; 9) MAAT>3 °C. S1 is commented in the discussions. (DEM derived by LiDAR survey performed between 2006 and 2009 by Civil Defense of Region FVG; For colour interpretation, please refer to the web version of the article)

Figure 6

Maps of MAAT in Slovenia calculated for the 30 years period 1981-2010, for the LIA and for the YD. Numbers in the legend (upper left) respectively refer to: 1) protalus rampart; 2) rock glacier; 3) 1,700 mm w.e.; 4) 1981-2010 MAP contour line (step of 100 mm w.e.); 5) 1,400 m asl contour line; 6) MAAT <-2 °C; 7) -2 °<MAAT <0 °C; 8) 0 °<MAAT<3 °C; 9) MAAT>3 °C. Climate data (1 km x 1 km grid data of MAAT and MAP for the period 1981-2010) was provided by Slovenian Environment Agency. DEM 12.5 m (The Surveying and Mapping Authority of the Republic of Slovenia) was used as a base layer. (For colour interpretation, please refer to the web version of the article)

5.2 Protalus and Pronival Ramparts

In this inventory, a comparable number of protalus ramparts respect to rock glaciers were recognized, which is uncommon if we look at what was found in other inventories from the Alps (e.g. Scapozza, 2015), where the number of rock glaciers largely prevails. Protalus ramparts situated in the Carnic Alps and Prealps (47% of the total), the drier sector of the examined area, generally follow the same geographical distribution of rock glaciers, whereas more than half of the inventoried protalus ramparts are located in a more maritime area of the Alps where higher precipitation is recorded, but still < 2500 mm yr^{-1}. Active protalus ramparts are located in the driest areas with a present MAAT between -0.4°C and 2.0°C. The possible presence of permafrost on some of them as enhanced by BTS results should be more related to the local conditions than the regional climate pattern, or even related to the LIA when regional MAAT were 1.7 °C lower. The active pronival ramparts observed in the Julian Alps (Figure 2b), on the contrary, at present develop in climatic conditions far to be defined as periglacial, especially owing the high precipitation amount of the area always > 2,500 mm a^{-1}. They formed at a distance from the talus foot slope < 30–70 m, which is consistent with the definition given by Ballantynes 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 according to Matthews et al. (2011). This fits well with the very high snow precipitation regime (c. 7.0 m of winter snow accumulation at 1,800 m asl) and the high snow avalanche frequency of the analysed area.

Moreover, Matthews et al. (2011), analysing a subset of avalanche-derived pronival ramparts in the maritime southwestern area of Norway, found ages for active ramparts ranging from <2,900 BP years and <1,550 BP years, with the oldest ones of YD age. They concluded that these features likely suggest a continued development throughout the Holocene, modulated by variations in 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 southeastern Alps.

Figure 7

Tiarfin area ("x" in Figure 1b) with the area where BTS measurements have been performed (rectangle) and the range of BTS measurements. The composite rock glacier flowing SE to NW is contoured by a black thin line. Some protalus ramparts possibly active 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 to the hillshade of Tiarfin area. The legend on the right indicates the probability of permafrost occurrence (For colour interpretation, please refer to the web version of the article).

6 Conclusions

The revised inventory of rock glaciers in the southeastern Alps accounts for 53 such landforms. They cover a total area of 3.45 km^2 and have been classified as mostly relict, with only 4 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 (present periglacial domain). The relict rock glaciers seem to be related to the YD cold phase, but we cannot exclude an older age for some. The inventory of protalus and pronival ramparts shows the occurrence of 66 landforms. Seven protalus ramparts, characterized by the presence of long-lasting snow fields, highlighted the possible presence of permafrost patches. Nine active pronival ramparts, owing the presence of still existing permanent ice patches and glacierets, are located in the more 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 and from the YD, modulated by the normal climate variability affecting the size and the shape of the glacierets. The exact chronology of the beginning and evolution of such periglacial forms in the southeastern Alps is still not well known, and there are only some working hypotheses that need to be clarified in the coming years. The 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 authomatic routines for the morphometric analysis. RRC, MG and MŽ interpreted the results and recognized the landforms in GIS environment. RRC, CB and MŽ made the field observations. RRC made the BTS measures. RRC, CB and MŽ prepared and analyzed the climatological and palaeoclimatological maps. RRC, MG and MŽ wrote the manuscript.

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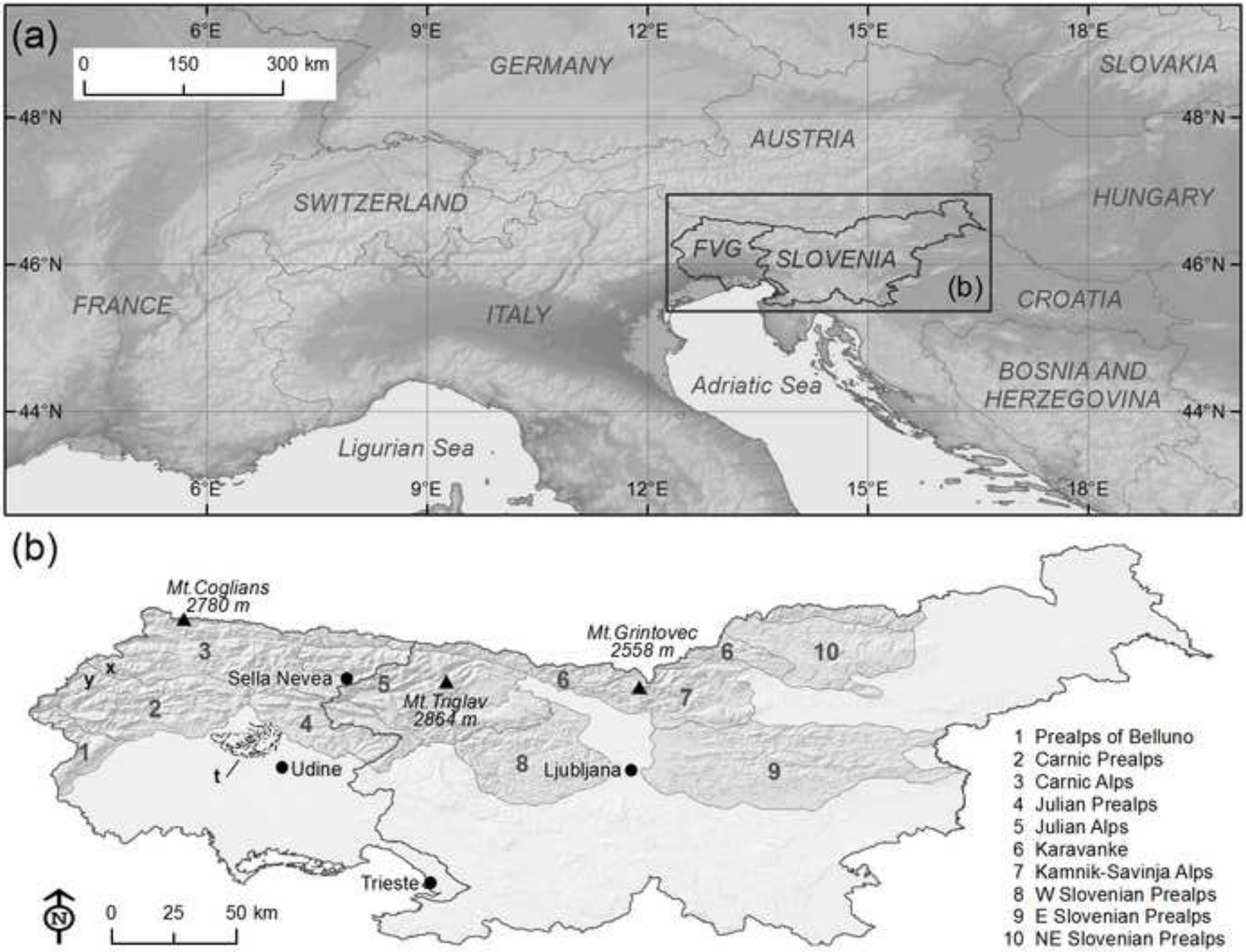

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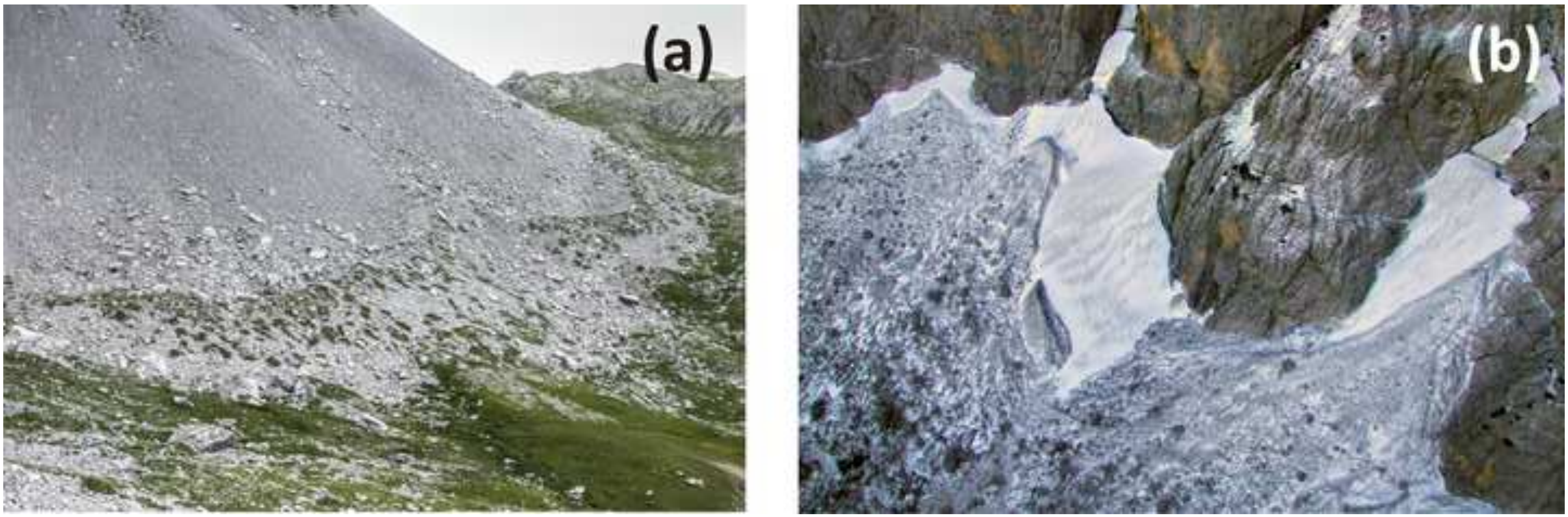

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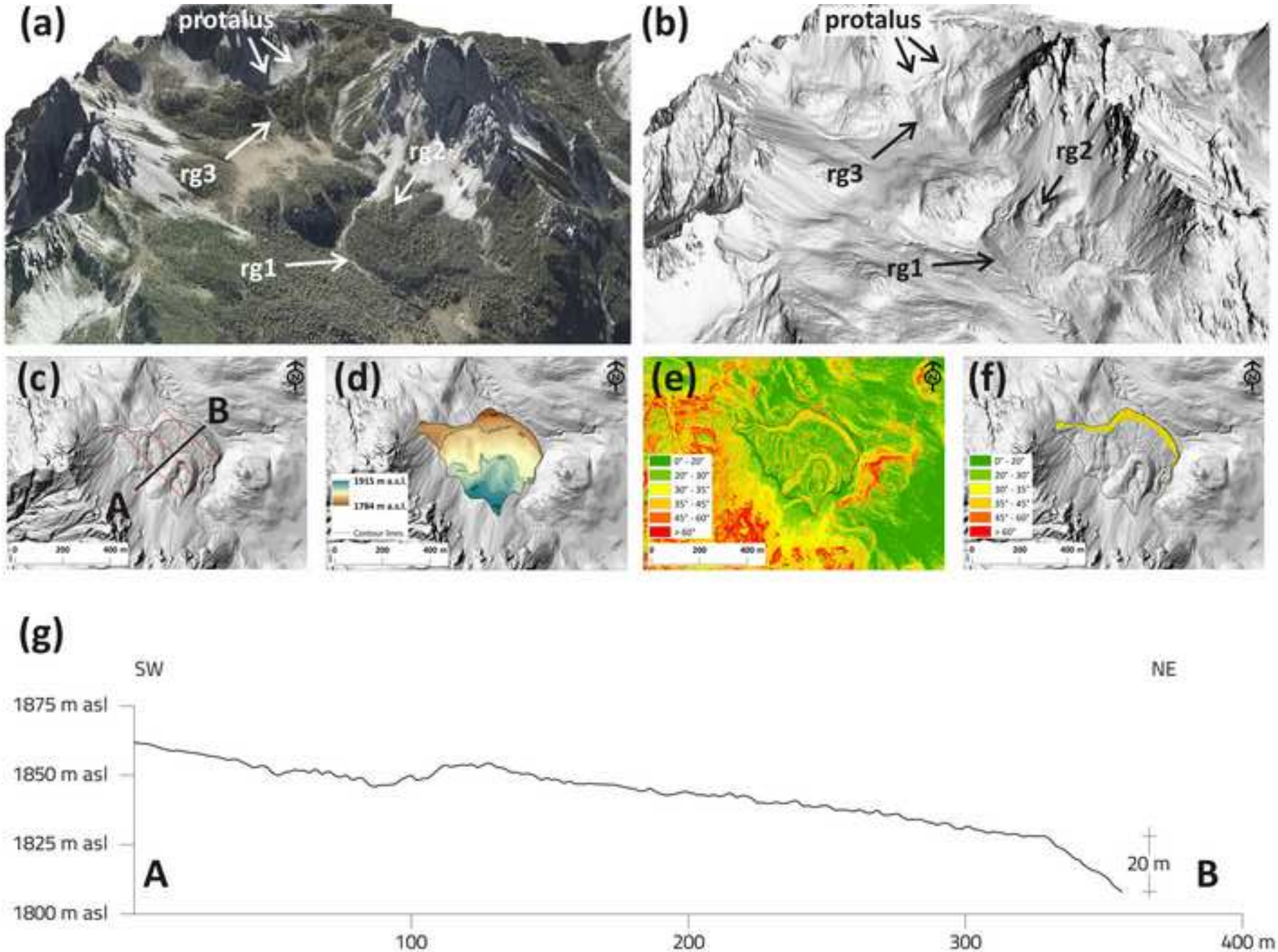

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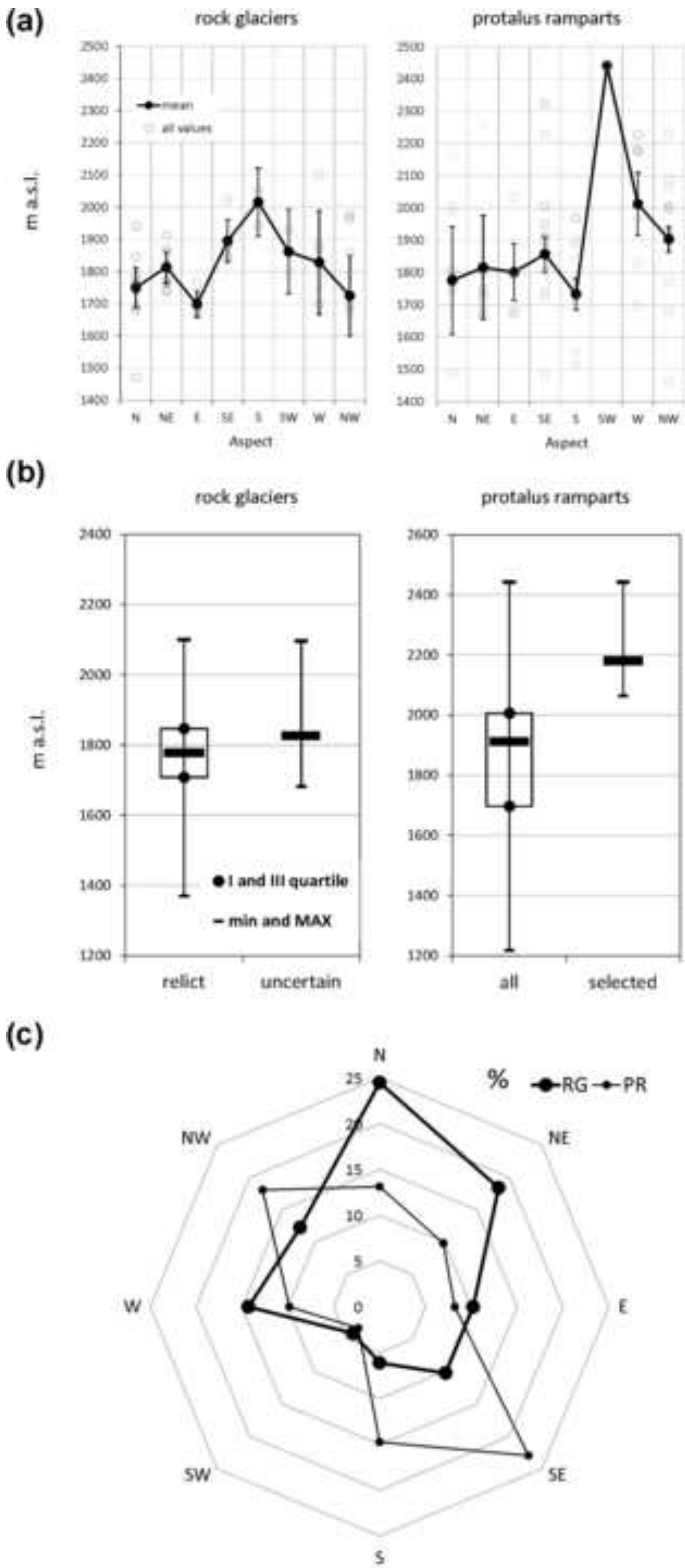

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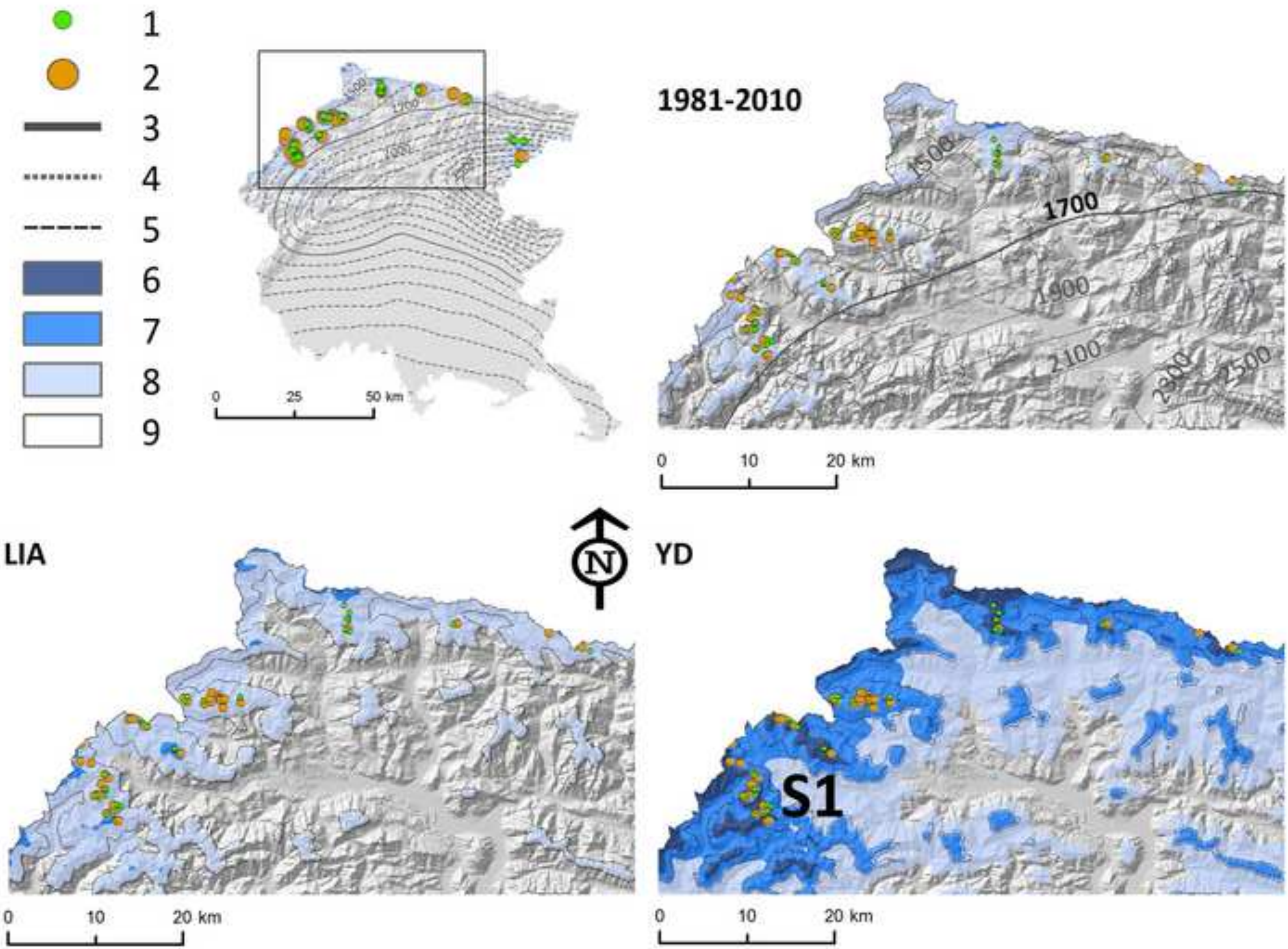

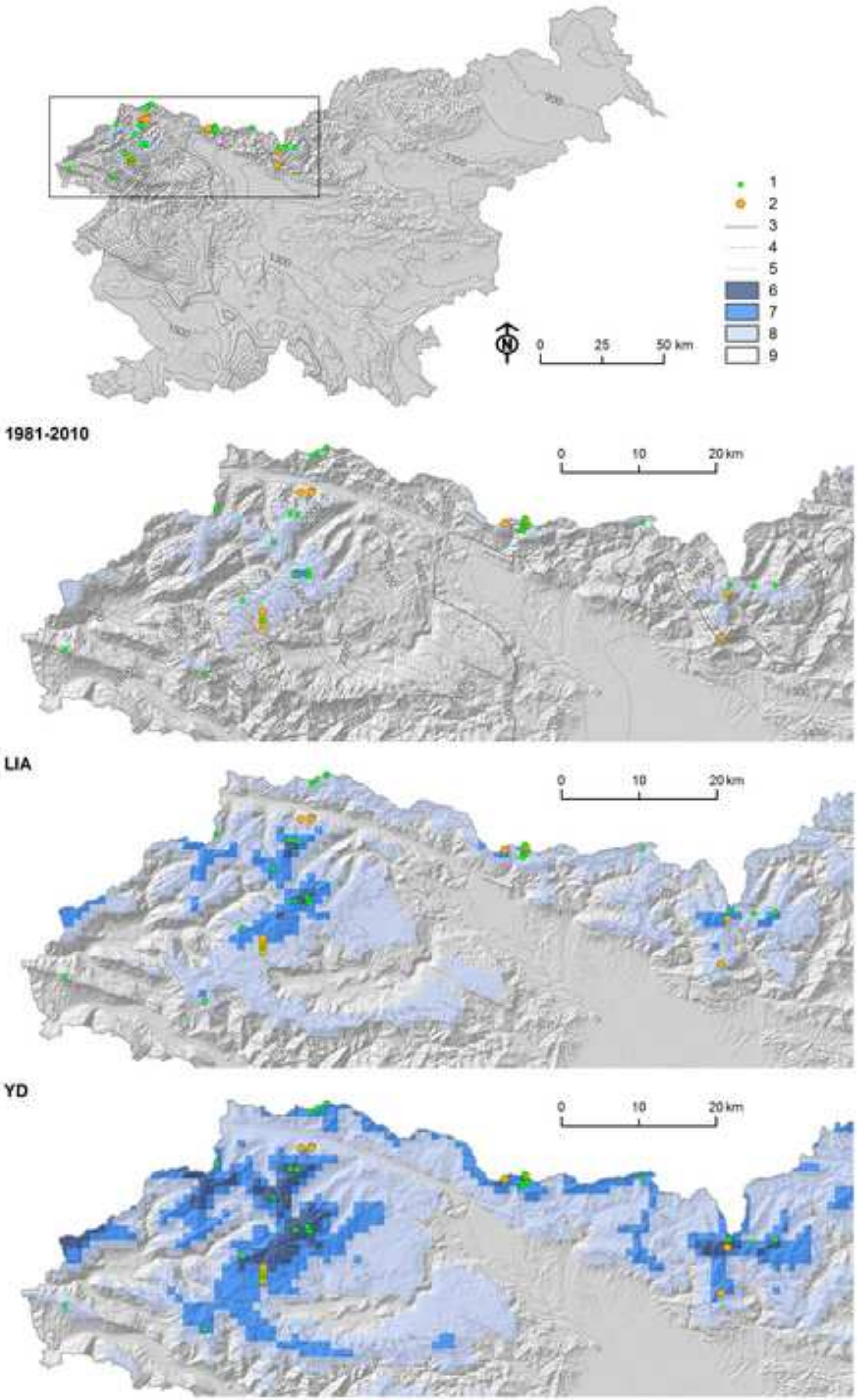
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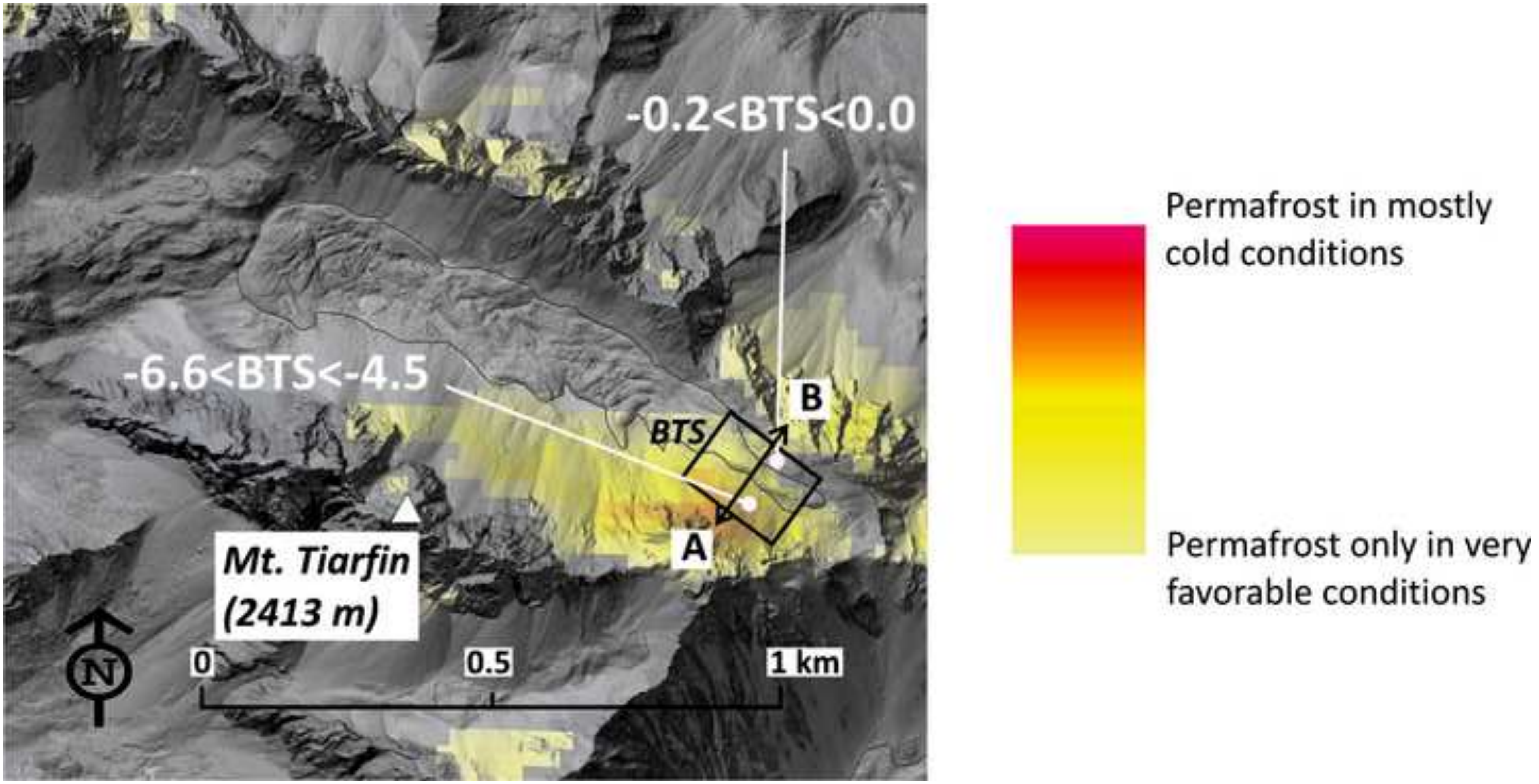

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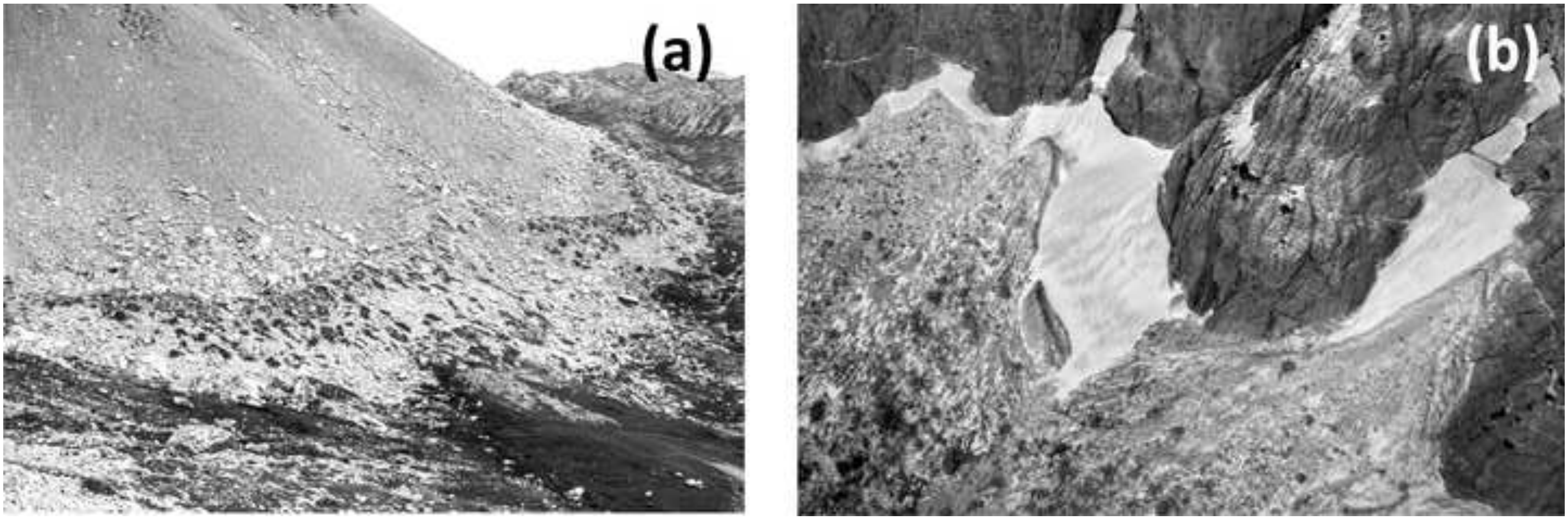

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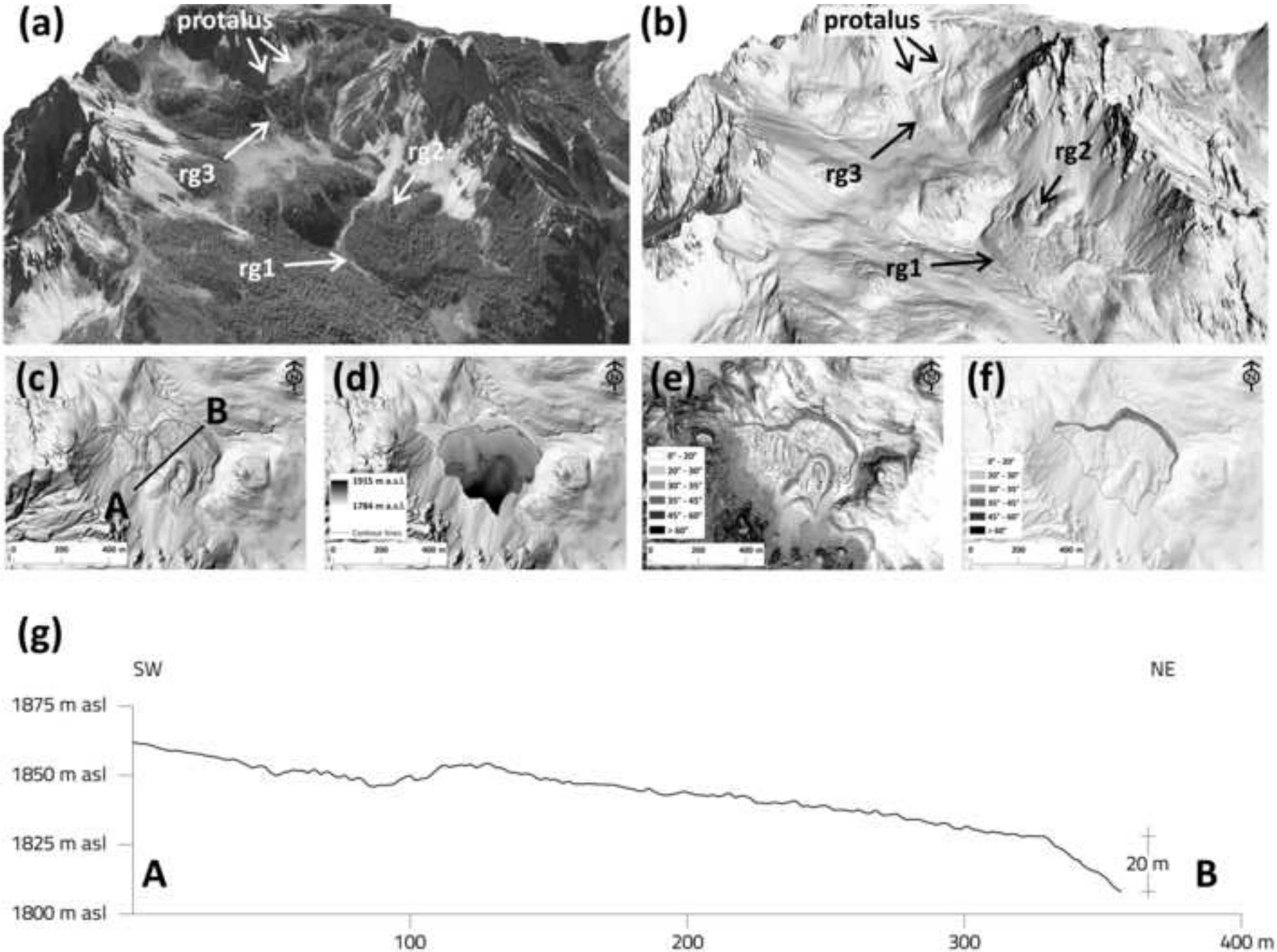

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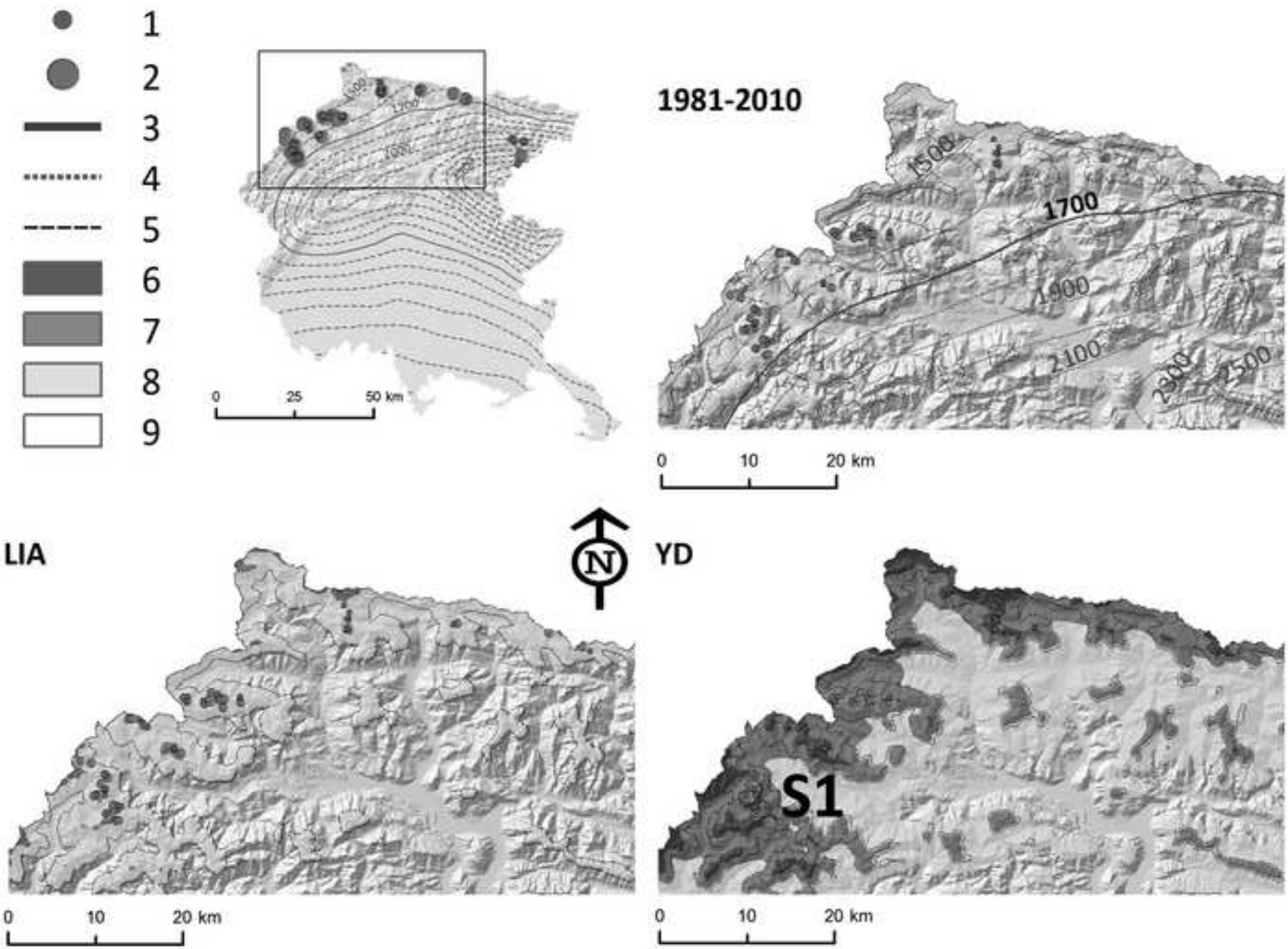

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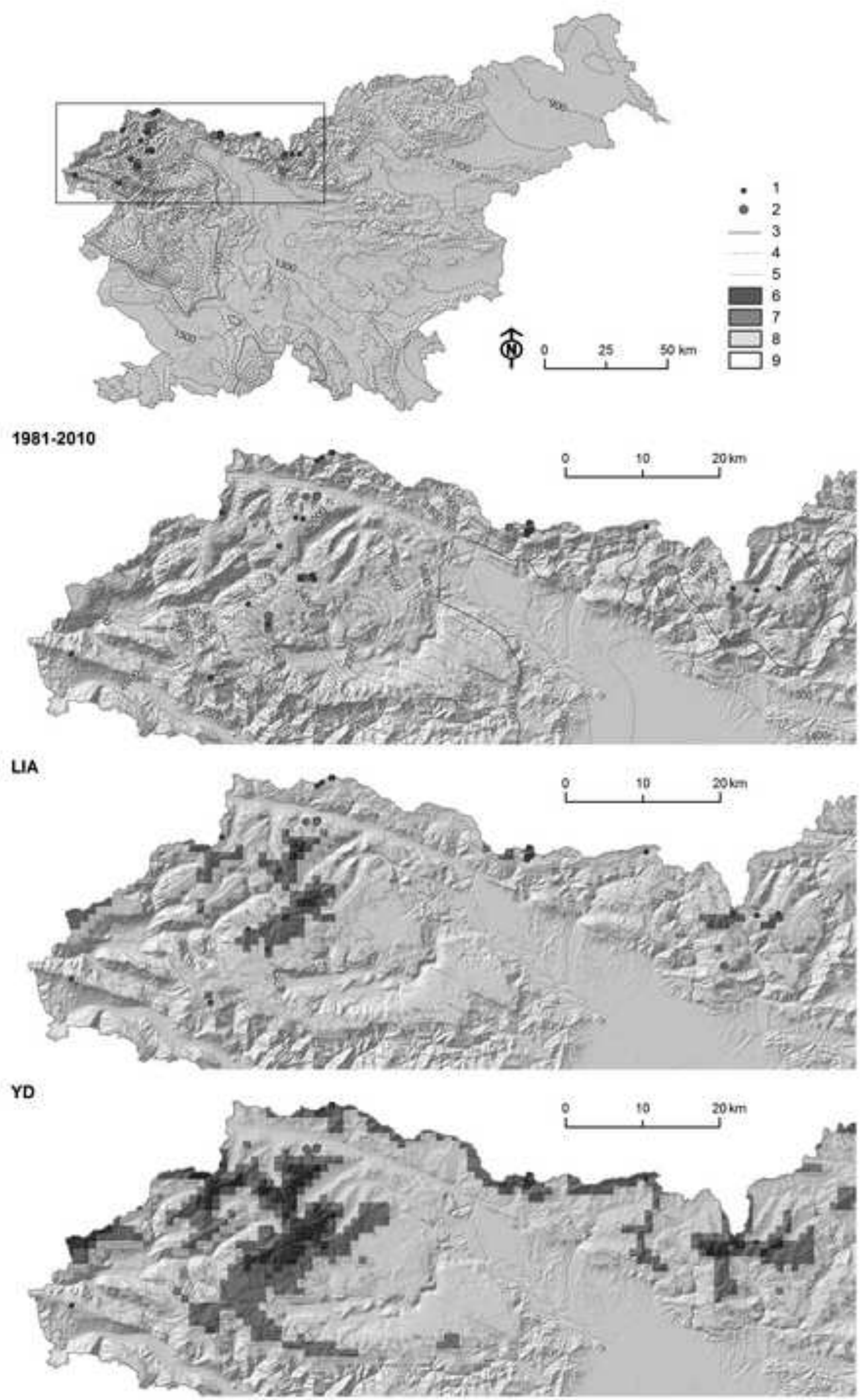

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