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INVENTORY, DISTRIBUTION AND TOPOGRAPHIC FEATURES OF ROCK GLACIERS IN THE SOUTHERN REGION OF THE EASTERN ITALIAN ALPS (TRENTINO)

ABSTRACT: SEPPI R., CARTON A., ZUMIANI M., DALL'AMICO M., ZAMPEDRI G. & RIGON R., *Inventory, distribution and topographic features of rock glaciers in the southern region of the Eastern Italian Alps (Trentino).* (IT ISSN 0391-9838, 2012).

A GIS-based rock glacier inventory was conducted in a region of about 6200 km^2 located in the southern sector of the Eastern Italian Alps (Trentino). The five major mountain groups of the region were investigated and a total of 705 rock glaciers, 25% of which are intact (i.e. containing permafrost), were identified. Their spatial distribution is rather inhomogeneous, which suggests that, in addition to climate, the bedrock lithology and structure are among the key factors controlling their genesis and development. The lowest density of rock glaciers was associated with carbonatic rock outcroppings (e.g. in the Brenta Group and in the Dolomites), whereas the highest density was observed in areas dominated by metamorphic rocks (e.g. Ortles Cevedale group). The rock glaciers cover a total area of 33.3 km^2, which is more than 1.4% of the area located above 1600 m a.s.l. and is comparable to the area covered by glaciers (38.3 km^2 in 2003). The rock glaciers are located at a mean elevation of 2282 ±289 m a.s.l. and are distributed in an elevation range of about 1440 m. Considering separately the two classes of intact and relict (i.e. with no permafrost) rock glaciers, the mean elevation is 2632 ±205 m a.s.l. and 2169 ±211 m a.s.l. respectively. Relict rock glaciers are found between 1650 and 2700 m a.s.l., whereas above 2800 m a.s.l. only intact rock glaciers exist. The mean aspect of all the inventoried rock glaciers is 43°. A dominant northern orientation does not emerge in the class of the intact forms, whereas the relict rock glaciers show a predominant northern orientation with a mean aspect of about 30°. According to the mean elevation of the intact rock glaciers, the lower boundary of permafrost in the studied region would be located at an elevation of approximately 2630 m a.s.l. This boundary varies significantly when considering the different exposures, and ranges from about 2510 m a.s.l. on north-facing slopes to about 2690 m a.s.l. on those exposed to the south. The lower boundary of permafrost existence in the past, as marked by the mean elevation of the relict rock glaciers, was located about 450 m lower than the modern one with variations included in a range of 230 m according to the exposure. This provides a rough estimation of the shift in elevation of the lower permafrost boundary between the present-day and the time when the relict rock glaciers were active. Accordingly, a MAAT increase of about 2.9°C can be calculated applying a standard vertical lapse rate (0.65°C/100 m) to this shift.

KEY WORDS: Rock glacier inventory; GIS; Rock glacier distribution; Permafrost; Eastern Italian Alps.

RIASSUNTO: SEPPI R., CARTON A., ZUMIANI M., DALL'AMICO M., ZAMPEDRI G. & RIGON R., *Catasto, distribuzione e caratteristiche topografiche dei rock glaciers nella regione meridionale delle Alpi orientali italiane (Trentino).* (IT ISSN 0391-9838, 2012).

Questo articolo presenta un catasto dei rock glacier realizzato nel settore meridionale delle Alpi orientali italiane (Trentino). Sono stati studiati i cinque principali gruppi montuosi ivi presenti, individuando e descrivendo un totale di 705 rock glacier, il 25% dei quali intatti (contenenti permafrost). La distribuzione spaziale dei rock glacier tra i cinque gruppi montuosi studiati è piuttosto disomogenea, suggerendo che, oltre al clima, la litologia e la struttura del substrato siano tra i fattori determinanti nel controllare la loro genesi e il loro sviluppo. La densità più bassa è stata osservata nelle aree dominate dall'affioramento di rocce carbonatiche (ad esempio nel Gruppo di Brenta e nelle Dolomiti s.s), mente la densità più elevata è caratteristica delle aree dove affiorano

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rocce metamorfiche (ad esempio nel gruppo Ortles Cevedale). I rock glacier coprono una superficie totale di 33.3 km^2, che corrisponde a più dell'1.4% dell'area situata sopra 1600 m s.l.m. di quota. La loro estensione totale è confrontabile con quella dei ghiacciai della stessa regione, che è di circa 38.3 km^2 (dato del 2003). La quota media dei rock glacier è pari a 2282 ±289 m s.l.m. e sono distribuiti in un intervallo altimetrico di 1440 m. La quota media delle forme intatte è di 2632 ±205 m s.l.m., quella delle forme relitte di 2169 ±211 m s.l.m. I rock glacier relitti raggiungono una quota minima di circa 1650 m s.l.m. e sono presenti fino alla quota massima di circa 2700 m s.l.m. Sopra i 2800 m s.l.m. esistono soltanto forme intatte. L'orientazione media dei rock glacier è a NE (pari a 43°), le forme intatte non mostrano una prevalente esposizione verso i quadranti settentrionali, mentre tra quelle relitte predomina l'esposizione a N. In accordo con la quota media dei rock glacier intatti, il limite inferiore del permafrost nella regione studiata sarebbe collocato ad una quota di circa 2630 m a.s.l. Tale quota varia tra 2510 m s.l.m. sui versanti esposti a Nord e 2690 m s.l.m. su quelli esposti a Sud. Il limite inferiore del permafrost nel passato, indicato dalla quota media dei rock glacier relitti, era collocato circa 450 m più in basso rispetto a quello attuale, con un valore che varia nell'intervallo di 230 m in funzione dell'esposizione. Questi dati possono fornire una stima della variazione di quota del limite inferiore del permafrost tra il presente e il periodo nel quale i rock glacier relitti erano attivi.

TERMINI CHIAVE: Catasto dei rock glacier; GIS; Distribuzione dei rock glacier; Permafrost; Alpi orientali italiane.

INTRODUCTION

Rock glaciers are prominent landforms in the cold environments of the Alps and consist of slowly creeping masses of debris and ice characterized by a distinctive surface topography (i.e. ridges, furrows and fluidal textures) (Wahrhaftig & Cox, 1959; Haeberli & *alii*, 2006). They exist and develop under periglacial conditions and are regarded as key geomorphological evidences of the permafrost presence in alpine environments (Barsch, 1996; Haeberli, 2000).

The genesis of rock glaciers has been debated for a long time and several authors claim that they are landforms of glacial origin, i.e. they essentially originate from the evolution of a debris-covered glacier (Whalley & Martin, 1992; Humlum, 1996; Whalley & Palmer, 1998; Clark & *alii*, 1998). In support of this statement, sedimentary (i.e. glacial) ice into landforms called «rock glacier» was observed and described, e.g. in the rock glacier Galena Creek (Colorado) (Potter & *alii*, 1998; Steig & *alii*, 1998) or, more recently, in the Alps (Krainer & Mostler, 2000; Guglielmin & *alii*, 2004; Ribolini & *alii*, 2007; Ribolini & *alii*, 2010). However, also the concept of «geomorphic continuum» is largely accepted to explain the genesis of rock glaciers (Berger & *alii*, 2004; Haeberli & *alii*, 2006; Krainer & *alii*, 2010). According to this concept, the two extremes of this continuum are «perennially frozen and ice-rich debris on non-glacierised mountain» and «debris-covered glaciers in permafrost-free areas» (Haeberli & *alii*, 2006).

More recently, Berthling (2011) suggests to reject the morphological definition of rock glacier, in support of a new genetic definition. Accordingly, a rock glacier is «the visible expression of cumulative deformation by long-term creep of ice/debris mixtures under permafrost condition» (Berthling, 2011).

From a morphodynamic point of view, rock glaciers are traditionally classified into three categories: i) active landforms that contain frozen material and are moving, ii) inactive landforms that contain ice but have stopped moving and iii) relict landforms that no longer contain ice and are completely stabilized. The first two categories indicate the present-day presence of permafrost, while the rock glaciers of the third category suggest the existence of past permafrost conditions (Frauenfeder & Kääb, 2000; Frauenfelder & *alii*, 2001). Inactive rock glaciers were further distinguished by Barsch (1996) into *dynamic* inactive and *climatic* inactive. Whereas the rock glaciers of the first category have stopped moving, for instance, because of a reduction of the debris input from the rockwalls behind them and can be located in areas of continuous permafrost, those of the second are stable because of a rapid melting of the frozen material, that can be confined under an active layer several metres deep. Therefore, the *climatic* inactive rock glaciers are not in equilibrium with the climatic conditions that allow the existence and preservation of permafrost. Active and inactive rock glaciers are frequently grouped together into the class of the «intact» rock glaciers (Haeberli, 1985).

The large-scale spatial distribution of rock glaciers is primarily dictated by climate, in particular by Mean Annual Air Temperature (MAAT) and precipitation. On a local scale, however, their distribution is under the control of local factors such as bedrock lithology and structure, debris input, slope exposure, heat budget of the ground, shading, and snow thickness and persistence (Humlum, 1998; Aoyama, 2005).

The availability of digital, high-resolution remote data (orthophotos and LiDAR DEMs) has recently disclosed the possibility to create large-scale rock glacier inventories and databases. These inventories, as well as being an essential knowledge base of an alpine environment, can be taken into account by local authorities in the territorial planning and in the construction of infrastructures in mountain areas (e.g. roads, buildings and tourist facilities).

Moreover, as field evidence of permafrost presence, intact rock glaciers are largely used for creating and validating permafrost distribution models and maps (Imhof, 1996; Lambiel & Reynard, 2001; Gruber & Hoelzle, 2001; Janke, 2005). In the context of the Alpine Space PermaNET project (Mair & *alii*, 2011), for example, a Permafrost Evidence Database (PED) has been developed for the whole European Alps. In addition to point type evidences such as surface and sub-surface ground temperatures, geophysical prospecting, rockfall scars and surface movements, this database includes seven rock glaciers inventories from France, Italy, Austria and Switzerland, with a total of 4795 landforms (Cremonese & *alii*, 2011). In addition, a new statistical model and an alpine-scale permafrost index map are partly based on the rock glacier inventories carried out within the project (Boeckli & *alii*, 2012). The inventory presented in this paper was also completed in the framework of this alpine-wide project.

In this paper, we present a GIS-based rock glacier inventory of a large region located in the southern sector of the Eastern Italian Alps (Trentino). The topographic parameters (elevation, aspect, slope) and the morphological characteristics of 705 intact and relict rock glaciers are presented and briefly discussed. The spatial distribution of the rock glaciers is analysed in relation to the large variability of the lithology occurring in the study area. On the basis of the intact and relict rock glaciers distribution, the present and past lower boundaries of permafrost existence are also inferred.

STUDY REGION

The study area includes a large sector of the Eastern Italian Alps, extends from 10° 26' to 11° 58' E and from 45° 39' to 46° 32' N, and corresponds with the administrative border of the province of Trento (fig. 1). The highest elevations of this area exceed 3500 m a.s.l., and about 20% of the territory lies over an elevation of 2000 m a.s.l. Our investigation focused on the five major mountain groups of the area, i.e. the Ortles-Cevedale (OC), Adamello-Presanella (AP), the Brenta (BRE), the Dolomiti (DOL) and the Lagorai (LAG) (fig. 1). While BRE and the LAG are entirely located in the investigated area, the other groups extend beyond its border and consequently were not fully investigated.

Different rock types characterize these mountain groups. The OC is located north of the Periadriatic Lineament, the major fault system separating the alpine chain from the Southern Alps sector, and belongs to the Austroalpine nappes of the Alps. The part of this group that lies in our study region is mainly composed by metamorphic rocks such as micaschists, gneiss, phyllites and migmatites. The other mountain groups entirely belong to the Southern Alps domain and are thus located south-central (AP) and southeast (BRE, DOL and LAG) of the Periadriatic Lineament. The AP consists mainly of intrusive rocks such as tonalites, granodiorites, quartz-diorites and trondhjemites. In marginal sectors of this group, the metamorphic basement (composed of micaschists, phyllites and paragneiss) and the Permo-Triassic sedimentary cover (made up of clastic and carbonate rocks) crop out the BRE group is entirely composed of sedimentary rocks, mostly limestones and dolomites, spanning in age from the Triassic to the Upper Cretaceous. In the eastern part of the study region, very different types of rocks crop out in the DOL. The part of this group that is located in our study area is composed of volcanic rocks (dacites, rhyodacites and basalts) and siliciclastic and calcareous sedimentary rocks, both of Permian and Triassic age. The LAG group is characterized by three main lithologies: pre-Permian metamorphic rocks (micaschists and phyllites) and Permian effusive (rhyolites, rhyodacites and andesites) and intrusive (granite) rocks.

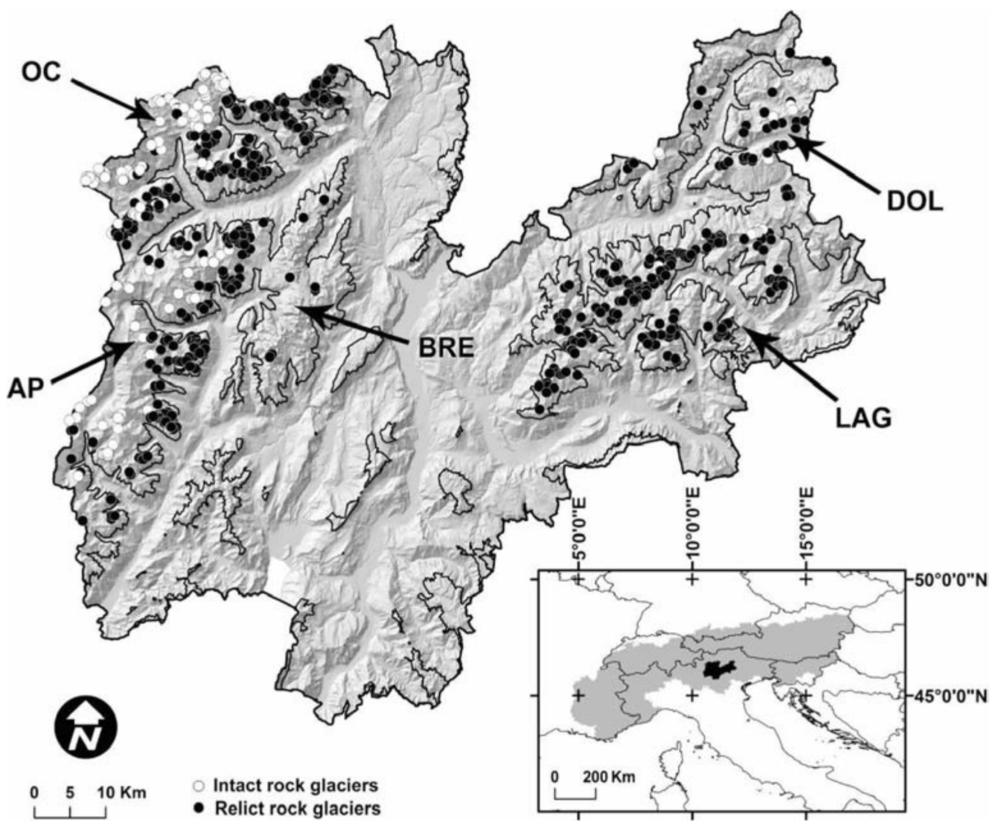

FIG. 1 - Location of the study area and spatial distribution of the 705 rock glaciers. The five investigated mountain groups and the 1600 m a.s.l. contour are shown. OC: Ortles-Cevedale; AP: Adamello-Presanella; BRE: Brenta; DOL: Dolomiti; LAG: Lagorai.

Glaciers are in a phase of continuous shrinkage, as showed by mass balance measurements of representative glaciers (Carturan & *alii*, 2005; Carturan & Seppi, 2007; 2009), and covered 38 km^2 of the study area in 2003 (Provincia autonoma di Trento, unpublished data).

Unlike the research on glaciers, the investigations on permafrost and periglacial landforms in this area are relatively sparse. A rock glacier inventory was completed for the whole Adamello-Presanella massif (Baroni & *alii*, 2004), and topographic surveys are in progress since 2001 on two active landforms of this mountain area, in order to measure their surface displacement (Seppi & *alii*, 2011a; 2011b). More recently, the relict rock glaciers of the same mountain group were used to estimate the distribution of permafrost in the past (Seppi & *alii*, 2010). Rock glaciers and other periglacial landforms (e.g. gelifluction lobes) were reported in large-scale geomorphological maps (Gruppo Nazionale Geografia Fisica e Geomorfologica, 1986; Baroni & Carton, 1996; Seppi, 1999) and in recent geological maps of the Italian Geological Survey (CARG project). Two active rock glaciers were recently described and carefully investigated by Krainer & *alii* (2010) in the Dolomites. In the same area, an active rock glacier developed from a debris-covered glacier is under investigations since a couple of years (Zanoner & *alii*, 2012).

METHODS AND DATA

The rock glacier inventory is based on analyses carried out in a GIS using orthophotos (resolution of 0.5 m) and a Digital Elevation Model (DEM), both of 2006. In particular, the DEM was generated from an airborne LiDAR flight and has a ground resolution of 1x1 m below the elevation of 2000 m a.s.l., and of 2x2 m above 2000 m a.s.l. First, the rock glaciers were identified using the orthophotos and a hillshade (light source: azimuth 315°, elevation 45°) derived from the DEM; then, the outlines of the rock glaciers were digitized as polygons in the GIS. The hillshade was particularly helpful in defining the correct perimeter of the rock glaciers and in identifying the forms where the orthophotos are unsuitable, such as in shaded north-exposed slopes and in areas covered by a dense tree vegetation (fig. 2). The polygon shapes of the rock glaciers were digitized using the more suitable scale, depending on the size of the form under investigation. Therefore, no fixed scale was used for digitizing the shapes. The data on rock glaciers reported in published papers (Baroni & *alii*, 2004) and maps (Gruppo Nazionale Geografia Fisica e Geomorfologia, 1986; Baroni & Carton, 1996; Seppi, 1999) were carefully collected and taken into account to build the inventory.

The rock glaciers are described by several parameters, both quantitative and qualitative, including those requested by the PermaNET project for implementing the Permafrost Evidence Database of the entire Alps (Cremonese & *alii*, 2011). However, in order to achieve a more complete description of the landforms, we used a number of supplementary parameters, partially derived from our previous works (Baroni & *alii*, 2004; Seppi & *alii*, 2005).

Each rock glacier is described by the following main parameters: location (mountain group and coordinates), perimeter, area, length, width, mean elevation, mean slope and mean orientation. Other parameters describe qualitative characteristics, such as: geometry (lobate or tongue shape), general morphology (simple, complex), (micro) morphology of the surface (presence of ridges, furrows and hollows), lithology of the source area, type of debris that feeds the rock glacier (e.g. talus, till), occurrence and extent of the vegetation cover, and relationships with the local vegetation boundaries and with the glaciers/perennial snowfields located above the rock glacier.

The quantitative data (i.e. area, perimeter, length and width) were directly calculated in the GIS. Mean elevation and mean slope were calculated by a zonal statistic procedure on the rock glacier polygons using the DEM and the slope raster derived from the DEM, respectively. For calculating the mean orientation, the aspect raster was created from the DEM and a statistic procedure developed for circular data was applied on each polygon (Davis, 2002). Then, the mean aspect values were indexed assigning the value 9 to south, 7 to south-west and south-east, 5 to east and west, 3 to north-west and north-east, and 1 to north. These classes were chosen by attributing less weight to the most favorable aspect (north) and vice versa and are regarded as a proxy of the solar radiation received by the rock glaciers.

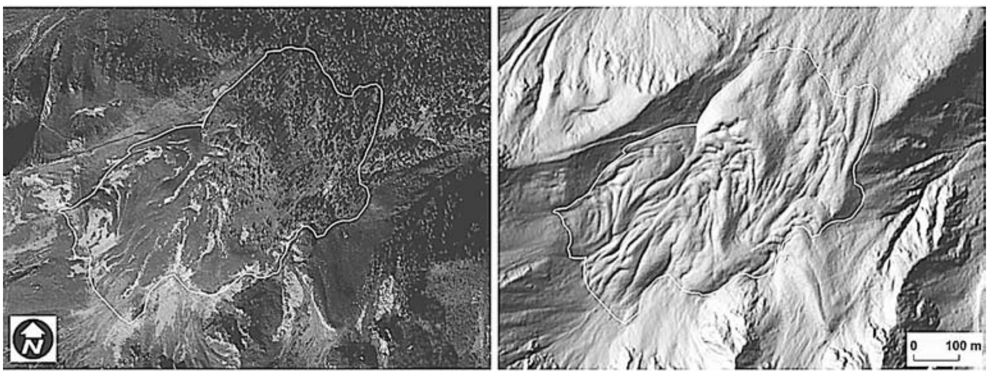

FIG. 2 - A relict rock glacier located in the Ortles Cevedale massif (ID 182 of the inventory) that is hidden by vegetation can be seen in the orthophoto (left). The same rock glacier is shown in the hillshade derived from the DEM (right).

In order to highlight the differences between the classes of intact and relict rock glaciers, t-tests at the 95% confidence level were applied on elevation, area and slope. The same test was applied on the indexed mean aspect.

Particular attention was paid to the definition of the activity status of the rock glaciers. According to the definition of Haeberli (1985) and Barsch (1996), they were classified as intact (containing frozen material) or relict (with no frozen material). Our assessment was based on several visible evidences from the orthophotos and the DEM, and on field observations and data (i.e. topographic surveys and ground surface temperature measurements). The category of «intact rock glacier», which includes active (i.e. moving) and inactive (i.e. containing permafrost but no moving) landforms, is rather general, but this classification was chosen because of the investigation method we adopted (based on aerial imagery interpretation) and because of the lack of data on the flow of the rock glaciers. This classification was used in other inventories carried out elsewhere, e.g. in the Alps (Lambiel & Reynard, 2001), in Norway (Lilleøren & Etzelmüller, 2011), in Sierra Nevada (Millar & Westfall, 2008) and in the northern Japanese Alps (Aoyama, 2005). In our inventory, only two rock glaciers, for which the movement was measured (Seppi & *alii*, 2011a; 2011b), could be defined as «active».

Intact rock glaciers normally have a bulging appearance, a steep frontal slope, well-defined ridges and furrows and no vegetation cover (fig. 3). Relict rock glaciers show a subdued topography, gentle frontal and lateral slopes, and an extensive vegetation cover, frequently consisting of shrubs and trees (fig. 4).

FIG. 3 - One of the largest intact (active) rock glaciers of the inventory (ID 788) located in the Ortles Cevedale massif. The front has an elevation of about 2800 m a.s.l. The person in the white circle serves as scale.

FIG. 4 - A relict rock glacier (ID 208 of the inventory) located in the Ortles Cevedale massif. The elevation of the front is about 2150 m a.s.l.

RESULTS AND DISCUSSION

Rock glaciers distribution

A total of 705 rock glaciers were identified in the five mountain groups of the study area over about half a degree of latitude (fig. 1). After a preliminary investigation that showed the occurrence of rock glaciers only above 1600 m a.s.l., we decided to restrict the analysis to the area above this elevation. This area covers a surface of 387 km^2 in the OC, 540 km^2 in the AP, 238 km^2 in the BRE, 377 km^2 in the DOL, and 556 km^2 in the LAG (tab. 1). The five investigated areas have a mean elevation ranging from about 1970 m a.s.l. (LAG) to more than 2300 m a.s.l. (OC). The distribution of area versus elevation is shown in figure 5.

On the total number of rock glaciers (705), 173 (25%) were classified as intact, the others as relict. This ratio can be compared with that observed in other regions of the Alps, although in most cases different criteria for the morphodynamic classification of the landforms were adopted. In the Bagnes-Hérémence region (Western Swiss Alps), for example, on a total of 239 landforms, 130 (54%) are active/inactive (i.e. intact) and the remainder are relict

TABLE 1 - Characteristics of the five investigated mountain groups and distribution of rock glaciers among them. OC: Ortles-Cevedale; AP: Adamello-Presanella; BRE: Brenta; DOL: Dolomiti; LAG: Lagorai

		OC	AP	BRE	DOL	LAG
Area above 1600 m a.s.l (km^2)		387	540	238	377	556
Mean elevation (m a.s.l.)		2319	2212	2082	2088	1969
Total n of RG		303	178	7	44	173
RG density (RG/km^2)		0.78	0.33	0.03	0.12	0.31
% of area covered by RG		3.6	1.2	0.1	1.2	1.5
Intact RG	n	104	47	-	7	15
	%	34.3	26.4	-	15.9	8.7

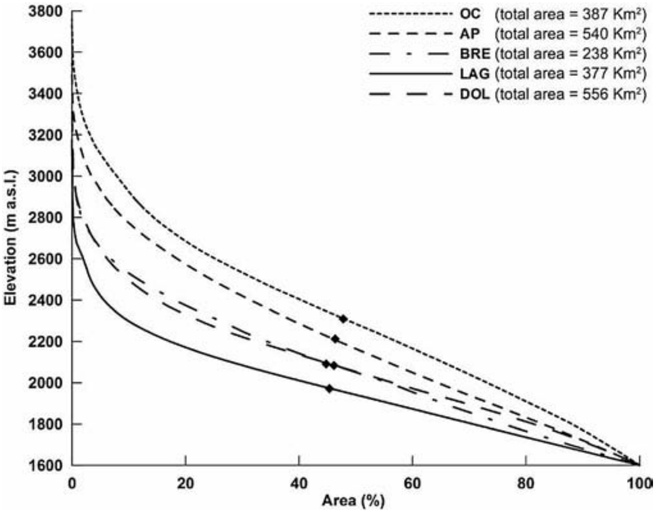

FIG. 5 - Hypsographic curves of the five investigated mountain areas. The curves refer to the areas located above an elevation of 1600 m a.s.l. The black diamonds indicate the mean elevation of each area.

(Lambiel & Reynard, 2001). Six inventories compiled in all the Swiss Alps include a total of 741 rock glaciers, 456 of them (62%) are classified as active or inactive, the others as relict (Frauenfelder & Kääb, 2000). Krainer & Mostler (2000) report data from an existing inventory of the eastern Austrian Alps and indicate a total number of 1451 rock glaciers, 282 (19%) of which are intact and 1169 (81%) are relict. Therefore, the ratio of intact and relict rock glaciers observed in our work is in an intermediate position between these two neighbouring regions of the Alps.

In the rock glacier inventory of the Italian Alps (Guglielmin & Smiraglia, 1997), the activity status of the landforms was defined using rather different criteria than in our work, thus making comparison difficult. However, a crude comparison could be performed considering the «active» landforms of that inventory as the «intact» of our work and the «inactive» as the «relict». In the entire Italian Alps, 1594 rock glaciers were observed, 59% of which were classified as inactive and 19% as active. The remaining were classified as of uncertain activity (18%) or complex (4%). In the southernmost region of the Italian Alps (Argentera Massif), a recent study (Ribolini & Fabre, 2006) showed the existence of 134 rock glaciers, 22% of which are active, 26% inactive, and the remainder are relict.

The spatial distribution of rock glaciers among the five investigated mountain groups is rather inhomogeneous. The total number ranges from more than 300 landforms in the OC to only 7 in the BRE. The percentage of intact rock glaciers ranges from 34% in the OC to 0% in the BRE (tab.1; fig. 6). Despite a similar number of rock glaciers was observed in the AP and LAG (178 versus 173), the fraction of intact landforms is considerably higher in the first group (26% versus 9%). The two mountain groups have a similar amount of area above 1600 m a.s.l. (540 versus 556 km^2), even though the mean elevation of the first is significantly higher than the second (2210 versus 1970 m a.s.l.) (tab. 1). The reduced availability of large areas at high elevation can partly give explanation for the nearly exclusive occurrence of relict rock glaciers in the LAG (fig. 5). Nevertheless, such a large number of relict forms suggest that permafrost was rather widespread in the past in this mountain group, reaching a lower elevation slightly higher than 1600 m a.s.l. In the other mountain groups, the rock glaciers reach a lower elevation of respectively 1840 m a.s.l. (OC), 1690 m a.s.l. (AP), 1950 m a.s.l. (BRE) and 1900 m a.s.l. (DOL).

The mean density of rock glaciers in the five mountain groups is about 0.34/km^2, corresponding to around 1.59% of the total area. This value is higher than that observed in the Niedere Tauern (Austrian Alps), where in the area above an elevation of 1500 m a.s.l. a density of 0.27/km^2 was recorded (Kellerer-Pirklbauer, 2007). Focusing on the various mountain groups of our study, the rock glacier density is highly variable, ranging from 0.78/km^2 in the OC (3.6% of the area) to 0.03/km^2 in the BRE (0.1% of the area) (tab. 1).

The lowest densities were observed in the areas dominated by sedimentary rocks such as the BRE, which is entirely composed of carbonate rocks (limestones and dolomites). The largest number of rock glaciers was observed in the OC, although the amount of area above 1600 m is

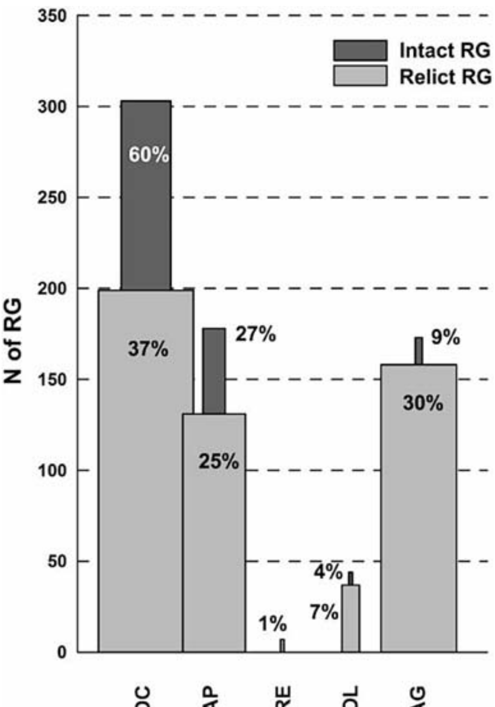

FIG. 6 - Number of intact and relict rock glaciers for the five mountain groups included in the inventory. The bars width represents the percentage of intact and relict rock glacier in each mountain group. Percentages refer to the total number of rock glaciers. Percentages are also indicated by the numbers. OC: Ortles-Cevedale; AP: Adamello-Presanella; BRE: Brenta; DOL: Dolomiti; LAG: Lagorai.

not the largest among the five mountain groups. In this area, the distribution is controlled by geology, since only metamorphic rocks (micaschists, gneiss, phyllites and migmatites) crop out.

The large difference in rock glaciers density seems to be related to the different lithologies that characterize the mountain groups of our study area. Type of rock and bedrock structure have been shown to affect rock glaciers development at a local scale in several alpine areas. For example, in a large area of the Austrian Alps, Kellerer-Pirklbauer (2007) observed that the most suitable lithologies for rock glaciers development are granites and granitic gneisses, followed by paragneiss, amphibolite, quartzite and micaschists. The less suitable are carbonate rocks (including marble). Matsuoka & Ikeda (2001) collected worldwide data from literature on the distribution of talus-derived rock glaciers in relation to the bedrock lithology. They observed that rock glaciers are more common in areas with rocks having large joint spacing and therefore producing large blocks (up to 5 m in diameter). The major rock types having these characteristics are granite (including granodiorite), gneiss, sandstone and limestone (including dolomite). On the contrary, rock types unfavorable for rock glaciers development are those producing fine material (e.g. schists, shale, rhyolite). Moreover, the same authors highlighted the importance of the geology (lithology and structure) of the source rockwall in producing debris of different size and, consequently, in determining the development of two types of rock glaciers (bouldery or pebbly) (Ikeda & Matsuoka, 2006). In the Spanish Pyrenees, Chueca (1992) performed statistical tests on a group of 170 rock glaciers in an area of 6500 km^2 and found a non-random distribution pattern. Most rock glaciers (65 %) develop in areas with crystalline lithologies (i.e. granites) characterized by a linear fracturing density of 6-12 km/km^2. In the Lemhi Range (central Idaho, USA), Johnson & *alii* (2007) demonstrated a strong control of lithology on rock glaciers distribution. Here, most rock glaciers develops on metasedimentary bedrock (massive sandstone and quartzite), while a small number of landforms are present on carbonate-dominated areas. It is suggested that karst hydrology in carbonate rocks does not allow snowmelt water to be stored and refrozen in debris deposits, thus hindering the development of rock glaciers.

Our data are consistent with the literature regarding the low rock glacier density observed in areas dominated by carbonate and dolomitic rocks (e.g. in BRE and DOL), whereas the large number of landforms observed in areas dominated by rocks producing small-size debris (e.g. micaschists and phyllites in OC, pre-Permian metamorphic and effusive rocks in LAG) is in some contrast to what is reported in the literature (Matsuoka & Ikeda, 2001). Therefore, bedrock lithology and structure (e.g. the faulting system affecting the bedrock at a local scale) help to explain the inhomogeneous distribution of rock glaciers in our study area.

Rock glacier characteristics and topographic features

The rock glaciers included our inventory show a mean area of 0.047 ±0.066 km^2 (tab. 2). The sum of all rock glaciers areas is 33.3 km^2 and is comparable to the whole area covered by glaciers (38.3 km^2 in 2003, Provincia autonoma di Trento, unpublished data).

The mean area of the relict rock glaciers is larger than that of the intact (0.052 ±0.073 versus 0.032 ±0.029 km^2) (fig. 7a; tab. 2). The largest is a relict «polymorphic rock glacier» (*sensu* Frauenfelder & Kääb, 2000) located in the DOL (ID 295 in the inventory), which has an area of 1.05 km^2. Its area is nearly double than that of the second largest (ID 296, 0.56 km^2), which is located about one kilometre away. The difference in size between the two groups of rock glaciers (intact and relict) is statistically significant, as confirmed by the t-test at the 0.05 significance level (p=0.00) (tab. 3).

Relict rock glaciers in the Alps developed in the Lateglacial, both in the Older and in the Younger Dryas, and started to decay during the Holocene climatic amelioration

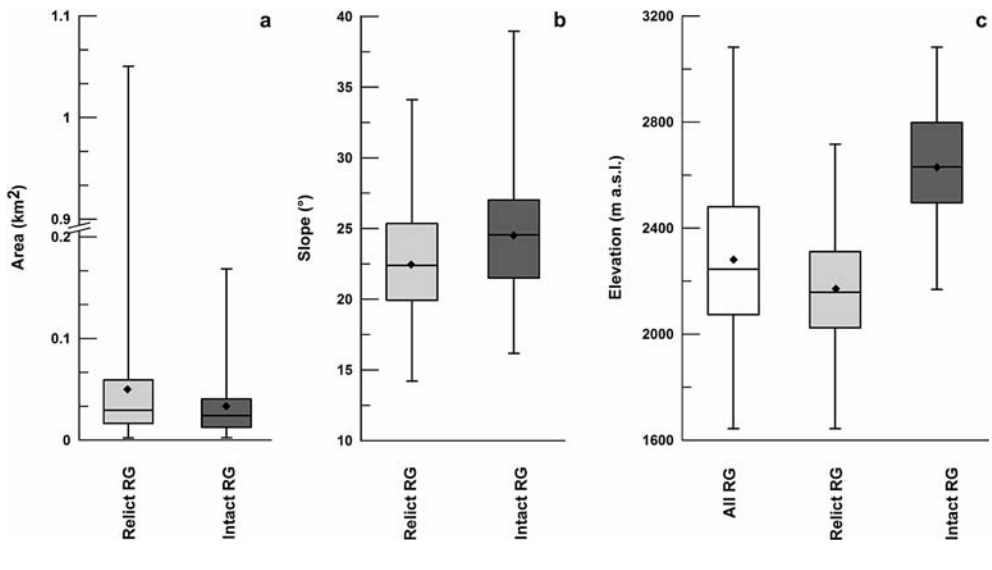

FIG. 7 - Box plots showing area (a), slope (b) and elevation (c) of the rock glaciers. The caps at the end of the vertical bars indicate the minimum and maximum values. The box is defined by the lower and upper quartiles. The line in the center of the box is the median, while the black diamond indicates the mean. Note that in (a) the y-axis is broken.

TABLE 2 - Main statistics of elevation, area, slope and aspect of all the inventoried rock glaciers and of the two separate groups of intact and relict forms

		All RG	Intact RG	Relict RG
	n	705	173	532
Elevation (m a.s.l.)	Mean	2282	2632	2169
	St. dev.	289	205	211
	Median	2245	2631	2158
	Range	1439	914	1072
	Min	1644	2169	1644
	Max	3082	3082	2716
Area (km²)	Mean	0.047	0.032	0.052
	St. dev.	0.066	0.029	0.073
	Median	0.028	0.024	0.029
	Range	1.048	0.166	1.048
	Min	0.002	0.002	0.002
	Max	1.050	0.168	1.050
Slope (°)	Mean	23.2	24.6	22.7
	St. dev.	3.8	3.9	3.7
	Median	22.9	24.5	22.4
	Range	24.7	22.8	19.9
	Min	14.2	16.2	14.2
	Max	39.0	39.0	34.1
Aspect (°)	Mean vector	42.8	107.1	29.6
	Circ. Var.	0.83	0.83	0.79
	Circ. St. dev.	107.3	108.3	101.1

(Kerschner, 1978; 1985; Sailer & Kerschner, 1999; Frauenfelder & Kääb, 2000; Finsinger & Ribolini, 2001; Frauenfelder & *alii*, 2001; Lambiel & Reynard, 2001; Ribolini & Fabre, 2006). This long development may partly explain their larger size if compared to the intact landforms, which are of Holocene age (Kääb & *alii*, 1997; Haeberli & *alii*, 1999; Konrad & *alii*, 1999; Dramis & *alii*, 2003; Frauenfelder & *alii*, 2004). In some cases, active rock glaciers i) became inactive before the Little Ice Age (Scapozza & *alii*, 2010), ii) are located in cirques occupied by glaciers during the Little Ice Age or iii) are in close relationship with glacial deposits of the same age, such as in the Adamello Presanella massif (Baroni & *alii*, 2004) or in the Maritime Alps (Ribolini & *alii*, 2007).

The mean slope of all the inventoried rock glaciers is 23.2 ±3.8°. The class of intact landforms shows a slightly higher mean slope than the relict class, with values of 24.6 ±3.9° and 22.7 ±3.7° respectively (fig. 7b and tab. 2). This difference is statistically significant, as showed by the t-test performed at the 0.05 significance level (p=0.00) (tab. 3).

TABLE 3 - Results of the t-test comparing elevation, area, slope, and the indexed aspect for the two groups of intact and relict rock glaciers

	t	t critical 2-tailed (α= 0.05)	Probability
Elevation (m)	25.23	1.96	0.00
Area (km²)	–3.62	1.96	0.00
Slope (°)	5.60	1.96	0.00
Indexed aspect	3.74	1.96	0.00

The rock glaciers are located at a mean elevation of 2282 ±289 m a.s.l. and are distributed in an elevation range of 1439 m. The lowest is a relict landform located in the LAG at 1644 m a.s.l., while the highest is an intact one located in the OC at 3082 m a.s.l. Considering separately the two classes of intact and relict rock glaciers, the mean elevation is 2632 ±205 m a.s.l. and 2169 ±211 m a.s.l. respectively (fig. 7c and tab. 2). The t-test performed at the 0.05 significance level confirmed that the difference in elevation between the two classes is statistically significant (p=0.00) (tab. 3).

The number of intact and relict rock glaciers grouped into classes of 100 m of elevation is displayed in figure 8. Above 2800 m a.s.l. only intact rock glaciers exist, while below 2100 m a.s.l. only relict landforms can be observed. Intact and relict forms mainly coexist in the elevation belt between 2200 and 2700 m a.s.l. The elevation classes of the relict rock glaciers show a normal distribution and most of them (n=100) are in the class between 2100 and 2200 m a.s.l. The intact rock glaciers show a more asymmetrical distribution and most of them (n=32) are located between 2500 and 2600 m a.s.l. The analysis of the altitudinal distribution has shown that the different pattern among the two classes of rock glaciers may be due to the very large difference in their number (532 relict versus 173 intact).

The mean difference in elevation between intact and relict rock glaciers is about 460 m. This figure is rather

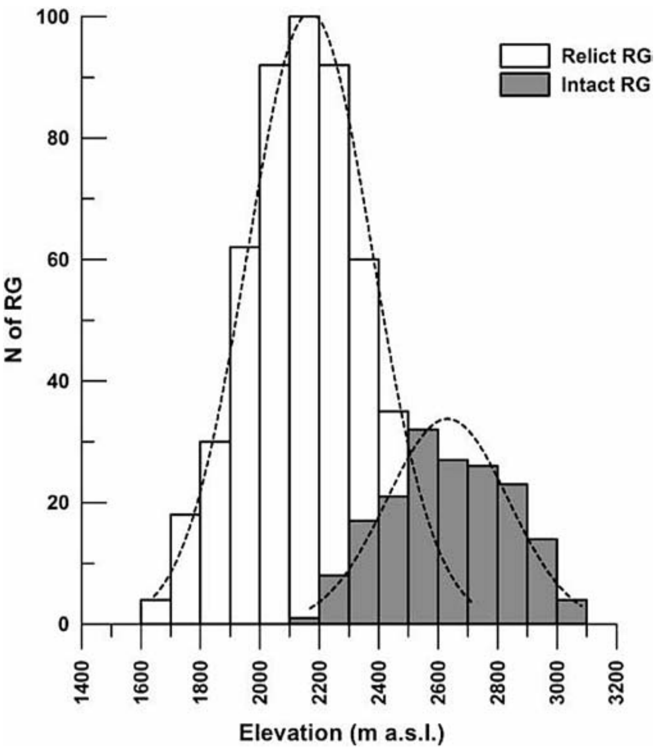

FIG. 8 - Number of intact and relict rock glaciers grouped into classes of 100 m of elevation. The fitting lines (dashed) represent a normal (Gaussian) distribution.

variable when considering the mean elevation for each aspect, ranging from about 330 m at SW to about 580 m at E (fig. 10). The intact rock glaciers having an overall northern exposure (N, NE and NW) are located at a mean elevation of 2510 m a.s.l., about 180 m lower than that having a southern exposure (S, SE and SW). In the group of relict rock glaciers, the difference in elevation is about the same.

The difference in elevation between intact and relict rock glaciers measured in our inventory can not be directly compared with the inventories from other regions of the Alps. In fact, in such inventories different criteria were used for defining the activity status of the landforms and their elevation was defined using the mean frontal elevation rather than the mean elevation of the whole landform. A rough comparison could be done with the rock glacier inventory of the Italian Alps, in which a difference in elevation of ca 380 m between the fronts of active and inactive rock glaciers was reported for the Rethian Alps, the alpine region where our study area is located (Guglielmin & Smiraglia, 1997).

The rock glaciers of our inventory show a mean aspect of about 43°, with a circular variance of 0.83 (tab. 2). Circular variance indicates the dispersion of the individual values around the mean and can ranges from 0 to 1; values close to 1 indicate low dispersion (Davis, 2002). The aspect of all the inventoried rock glaciers and of the intact and relict subsets, grouped in class of 10 degree, is shown in figure 9. With reference to all the rock glaciers, half of them (50.3%) have a northern exposure, i.e. their aspect ranges from 292.5 to 67.5°, while 35.2% face south (i.e. their aspect ranges from 112.5 to 247.5°).

The mean aspect of intact rock glaciers is about 107°, with a circular variance of 0.83. In this class, only 39.3% of the total landforms face north, while 43.5% has a southern exposure. Hence, a dominant northern orientation does not emerge in the class of intact rock glaciers, as commonly observed in other areas of the Alps (Guglielmin & Smiraglia, 1997; Kellerer-Pirklbauer, 2007) and elsewhere (Janke, 2007; Lilleøren & Etzelmüller, 2011). This pattern may be due to the uneven distribution of the intact rock glaciers among the five investigated mountain groups. Indeed, the largest percentage of them (60%) is located in the OC, which is not completely included in the province of Trento and therefore was not fully investigated. In particular, the valleys of this group that were investigated have an overall north-south orientation, with several south-facing slopes in their highest areas. This could partly explain the absence of a dominant northern orientation in the class of the intact rock glaciers.

The relict rock glaciers show a predominantly northern orientation, with a mean aspect of about 30° (circular variance: 0.79). Most landforms of this class (53.8%) are exposed to N, NE or NW and 32.6% are exposed to S, SE or SW. The t-test at the 0.05 significance level showed a statistically significant difference (p=0.00) of the indexed aspect among the two classes of rock glaciers (tab. 3).

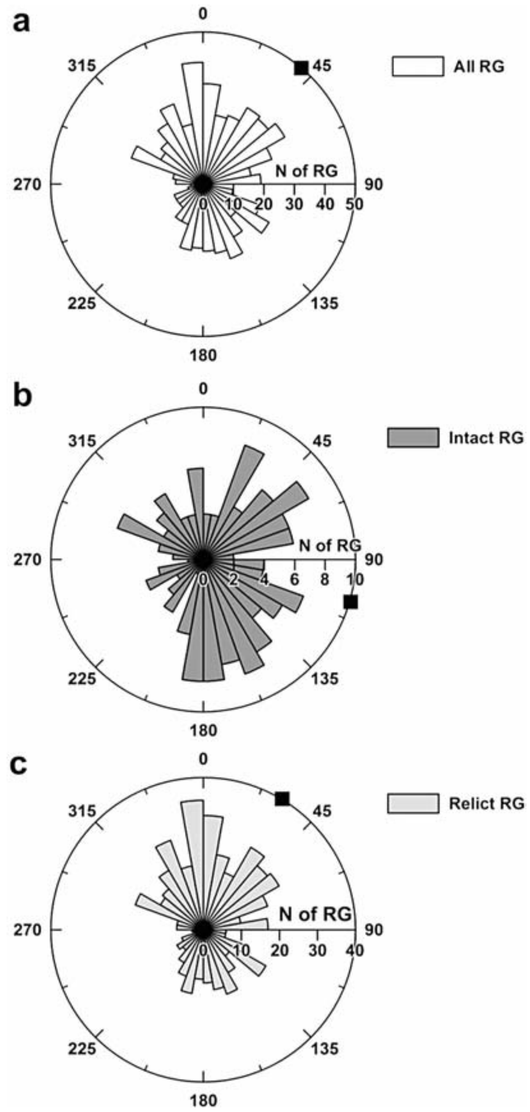

FIG. 9 - Rose diagrams showing the aspect of all the inventoried rock glaciers (a), the intact ones (b) and the relict ones (c). The angular interval is 10°. The black square indicates the mean aspect. Note that the radial axes have different scales.

The distribution of intact and relict rock glaciers as a function of orientation and elevation is shown in figure 10. In both classes, the north-facing landforms reach the lowest elevation, which is 2490 ±122 m a.s.l. for the intact forms and 2070 ±146 m a.s.l. for the relict ones. In contrast, the rock glaciers showing southern orientation are located at the highest elevation, both for the intact (2780 ±132 m a.s.l.) and the relict (2300 ±152 m a.s.l.). In general, the standard deviation is higher among the aspect classes of relict rock glaciers than in that of the intact.

Current and past permafrost boundaries

The spatial distribution of rock glaciers may provide a rough estimation of the permafrost distribution in a re-

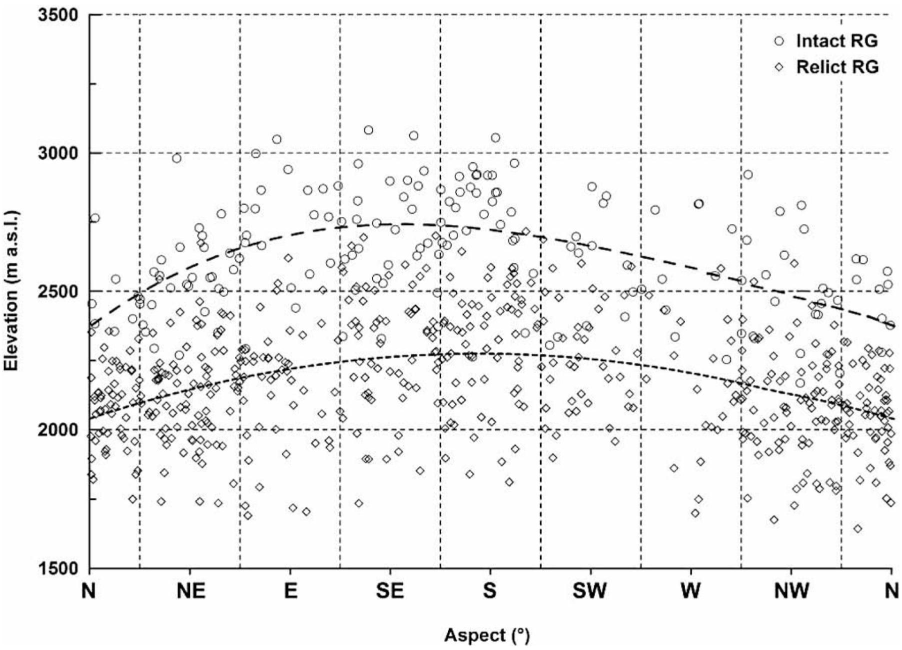

FIG. 10 - Scatterplot of aspect against elevation for intact and relict rock glaciers. The two dashed lines are 3rd order polynomial fit (upper line: intact rock glaciers; lower line: relict rock glaciers).

gion, in particular about the elevation of its lower limit. The present-day lower limit of permafrost can be estimated from the mean elevation of the intact rock glaciers (Barsch, 1996, Frauenfelder & Kääb, 2000). The relict forms may give information about the paleo-permafrost distribution of an area (Hughes & *alii*, 2003; Aoyama, 2005). However, it should be emphasized that permafrost can be preferentially preserved in rock glaciers with respect to the surrounding fine-grained or bedrock areas, due to the negative thermal anomaly (i.e. balch effect, chimney effect and other physical phenomena, Harris & Pedersen, 1998) that characterizes their openwork, blocky surface layer (Humlum, 1997; Sawada & *alii,* 2003; Juliussen & Humlum, 2008). Consequently, rock glaciers can develop even in areas that are permafrost free elsewhere, and permafrost within it can be present at considerably lower elevation than in bedrock or in fine debris. This may lead to a downward overestimation of the lower limit of permafrost if, for example, permafrost models are developed using the rock glaciers distribution (Imhof & *alii*, 2000). Moreover, using the comprehensive category of «intact» rock glaciers for estimating the current distribution of permafrost may introduce a further inaccuracy because this category includes also the climatic inactive rock glaciers, which are not in equilibrium with the present climate.

According to the distribution of intact rock glaciers the lower boundary of permafrost in our investigation area is currently located at a mean elevation of approximately 2630 m a.s.l. This boundary varies significantly when considering the different exposure of intact rock glaciers, and ranges from about 2510 m a.s.l. on north-facing slopes to about 2690 m a.s.l. on those exposed to the south (fig. 11). These estimations are conservative because in our inventory the elevation of each individual rock glacier has been calculated as the mean of the DEM fraction included in the polygon representing the landform, and therefore it does not correspond to the minimum elevation of the front. In fact, depending on the shape of the rock glacier and its overall slope, the elevation of the front may be several tens or hundreds meters lower than the mean elevation of the rock glacier.

In comparison to the entire study area, the present-day lower limit of permafrost is about 100 m higher in the OC, where, regardless of their exposition, the intact rock glaciers are located at a mean elevation of about 2720 m a.s.l. The limit is significantly lower in the AP, where a mean elevation of about 2530 m a.s.l. has been observed. In the LAG, the subset of intact rock glaciers is too small to make analogous considerations, but the lowest of them is located at an elevation of about 2260 m a.s.l.

The lower boundary of permafrost existence in the past, as marked by the mean elevation of the relict rock

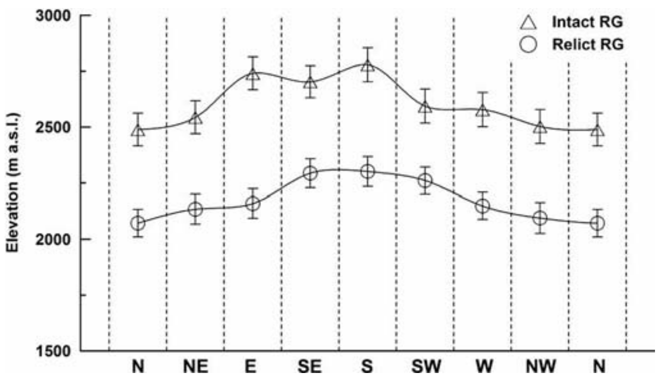

FIG. 11 - Mean elevation versus orientation of intact and relict rock glaciers. The vertical bars indicate the standard deviation. The two lines are spline smoothing fits.

glaciers, is about 450 m lower than the modern one, with variations included in a range of 230 m, according to the exposure (fig. 11). This difference in elevation can provide a rough estimation of the increase of the lower permafrost boundary, according to the climatic amelioration occurred between the Lateglacial and the Holocene. In the western Austrian Alps, for example, the fronts of the relict rock glaciers, which have been dated to the late Younger Dryas (Egesen III), were about 400 m lower than the present-day, suggesting an increase of the Mean Annual Air Temperature (MAAT) of about 3°C (Sailer & Kerschner, 1999). In the Swiss Alps (Err-Julier area), a lowering of about 500/600 m of the lower permafrost boundary in the Younger Dryas has been inferred from the relict rock glaciers distribution, corresponding to a MAAT from 3 to 4°C lower than the present (Frauenfelder & *alii*, 2001). In the Italian Alps, a difference in elevation of about 400 m between the fronts of active and inactive rock glaciers was observed, suggesting a MAAT increase of about 2.4°C calculated applying a vertical lapse rate of 0.6°C/100 m (Belloni & *alii*, 1993). Using the same lapse rate in our study region, a MAAT increase of about 2.7°C can be calculated, whereas applying a standard lapse rate (0.65°C/100 m) the increase is slightly higher (about 2.9°C). These values are therefore comparable to those calculated elsewhere.

CONCLUSIONS

This inventory has shown that in Trentino rock glaciers are one of the major landform of the periglacial environment, covering about 1.6% of the surface located above 1600 m a.s.l. of elevation. Their total area (33.3 km^2) is comparable to that of glaciers (38.3 km^2 in 2003). The inventory includes 705 landforms, 25% of which are intact. The distribution of the intact landforms indicates the presence of permafrost above an elevation of 2500 m a.s.l. on north exposed slopes.

The spatial distribution of rock glaciers among the five investigated mountain groups is rather inhomogeneous. Lower densities were observed in areas where carbonate rocks dominate (i.e. BRE and DOL). This distribution pattern seems mostly related to the different lithologic outcrops in the region, rather than to differences in the climatic conditions. Indeed, the limited range of latitude covered by rock glaciers (~30") does not seem to reasonably justify such a large difference in climate to determine this uneven distribution. Therefore, our study has confirmed that factors other than climate can dictate the overall distribution of rock glaciers at a local scale in alpine environments.

The majority of intact rock glaciers are located in the two highest mountain groups of the region (i.e. OC and AP), where they are the 34% and 26% of the total number respectively. Interestingly, almost exclusively relict rock glaciers are present in the LAG, where they reach the lowest elevation and have a large density. This indicates that in this mountain region, permafrost was very widespread in the past and at present has almost completely disappeared at each exposure.

The comparison between the mean elevation of the intact and relict rock glaciers allowed us to estimate the shift in elevation of the lower permafrost limit between the present-day and the time when the presently relict rock glaciers were active. This shift is in the order of 450 m and varies in a range of about 230 m among the different exposures.

Although no data exist about the age of the relict rock glaciers of our study region, we can tentatively assume that they are of Lateglacial age. Applying a standard lapse rate, a MAAT increase of about 2.9°C can be calculated from the difference in elevation between relict and intact rock glaciers. Therefore, this is the order of magnitude of the climatic amelioration occurred in our region from the Lateglacial to the modern time. However, these estimations are tentative and should be taken with particular caution, because we assessed the current lower limit of permafrost using the general category of intact rock glacier. Indeed, at a local scale it would be essential improving the definition of the morphodynamic state of the rock glaciers, in order to exclude the landforms indicating the presence of permafrost that is not in equilibrium with the current climatic conditions.

We are confident that, in a context of changing climate, using rock glacier inventories in territorial planning would improve the risks prevention in high altitude alpine environments. This is especially true when considering the current processes of degradation that affect permafrost and active rock glaciers in the Alps, often inducing a rapid change in their dynamics.

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