A high-resolution rock glacier inventory of South Tyrol: Evaluating lithologic, topographic, and climatic controls

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Abstract

In South Tyrol, a comprehensive and homogeneous database of rock glaciers is missing. This is a critical shortcoming for the basic understanding of creeping permafrost in the region, as well as for geohazard assessment and planning, especially in relation to contemporary climate warming. To this purpose, we have: (1) compiled a regional inventory through visual inspection of optical and LiDAR-derived imagery; and (2) analyzed the spatial distribution of rock glaciers in relation to topography, lithology, and climate. Climatic attributes were drawn from regionally interpolated data of the 3PClim project. The inventory tallies 2798 rock glaciers that occupy a surface of 146 km^2. Of these, 502 were classified as active rock glaciers, 615 as inactive, and 1681 as relict. Median front elevation of the active landforms (2695 m) is 100 m and 440 m higher than that of the inactive and relict ones. This offset can vary over 200 m as a function of slope aspect. Median MAAT on active and inactive rock glaciers is respectively -2.3 and -1.6 °C, and above the melting point (+0.2 °C) on relict landforms. Despite such differences, we find that median days of snow cover is comparable in active and inactive landforms (310 and 302 respectively) and significantly lower in relict ones (273). Most of the rock glaciers develop(ed) on paragneiss, mica schists and phyllites (83%), followed by orthogneiss (21%), and limestones and dolostones (8%). Lithologic effects, except in calc schists, which score distinctively lower than schists and orthogneiss, are largely masked by interactions between topographic and climatic conditions across physiographic zones.

1 Introduction

The spatial distribution and activity of rock glaciers contain critical information on the past and present state of permafrost (Barsch 1996). In South Tyrol, Italy, a number of active rock glaciers are known for their interference with infrastructure, or as prospective sources of hazard, however, a comprehensive appraisal of their spatial distribution is missing. This is a critical shortcoming for geohazard assessment and regional planning, especially in relation to contemporary climate warming.

From a basic, process-oriented standpoint, the variety of physiographic settings across South Tyrol, in conjunction with available high-resolution topography, geological mapping, and gridded climate data, offer the opportunity to investigate possible controls on creeping permafrost occurrence, exerted by elevation, lithology and climate (e.g., mean annual temperature (MAAT) and precipitation (MAP)).

To address the foregoing needs, in this contribution we present a new rock glacier inventory of South Tyrol, compiled at high spatial-resolution. In particular, we (1) examine and characterize the spatial distribution of active, inactive and relict rock glaciers in South Tyrol; and (2) explore the spatial variability of rock glaciers across five physiographic zones, with respect to varying topography, lithology, and climate (Figures 1 and 2).

1.1 Geological setting and physiographic zones

South Tyrol, an autonomous province in the Central-Eastern Alps, lies south of the Alpine divide and encompasses three tectonic sub-regions, which, proceeding southward, include: the Pennidic, the Austroalpine, and the Southalpine domains (Schmid et al. 2004). The Pennidic domain, which belongs to the High Tauern mountain range, is located in the northeastern corner of the province and is characterized by the large extent of calc-silicate schist (> 50%; here for brevity termed calc schist), followed by orthogneiss, and by mica schist and paragneiss. The Austroalpine domain, which occupies more than half of the province (Figure 1a), is dominated by mica schist and paragneiss (> 85%), with lesser orthogneiss, granite, and dolostone. The Southalpine domain, bounded westward and northward by the Periadriatic Line, is underlain by sedimentary rocks (about 50%)—mainly limestone and dolostone, with lesser marl and sandstone—followed by mica schist and paragneiss, and by volcanics and granitoids.

In order to account for the spatial variability in precipitation (Figure 1b) and elevation (Figure 2), the broad Austroalpine domain has been further subdivided into three physiographic zones. Consequently, in this work we will consider the spatial distribution of rock glaciers across five physiographic zones: Western (WestAu), Central (CentrAu) and Eastern Austroalpine (EastAu), Pennidic (Penn), and Southalpine (SudAlp) (Figure 1). The altitudinal, lithologic and climatic characterizations of each zone (Table 1) and the relevant terrain distributions across elevations (Figure 2) refer to topography located above 1400 m a.s.l. This altitudinal cut-off is dictated by the elevation of the lowermost rock glacier mapped in the inventory.

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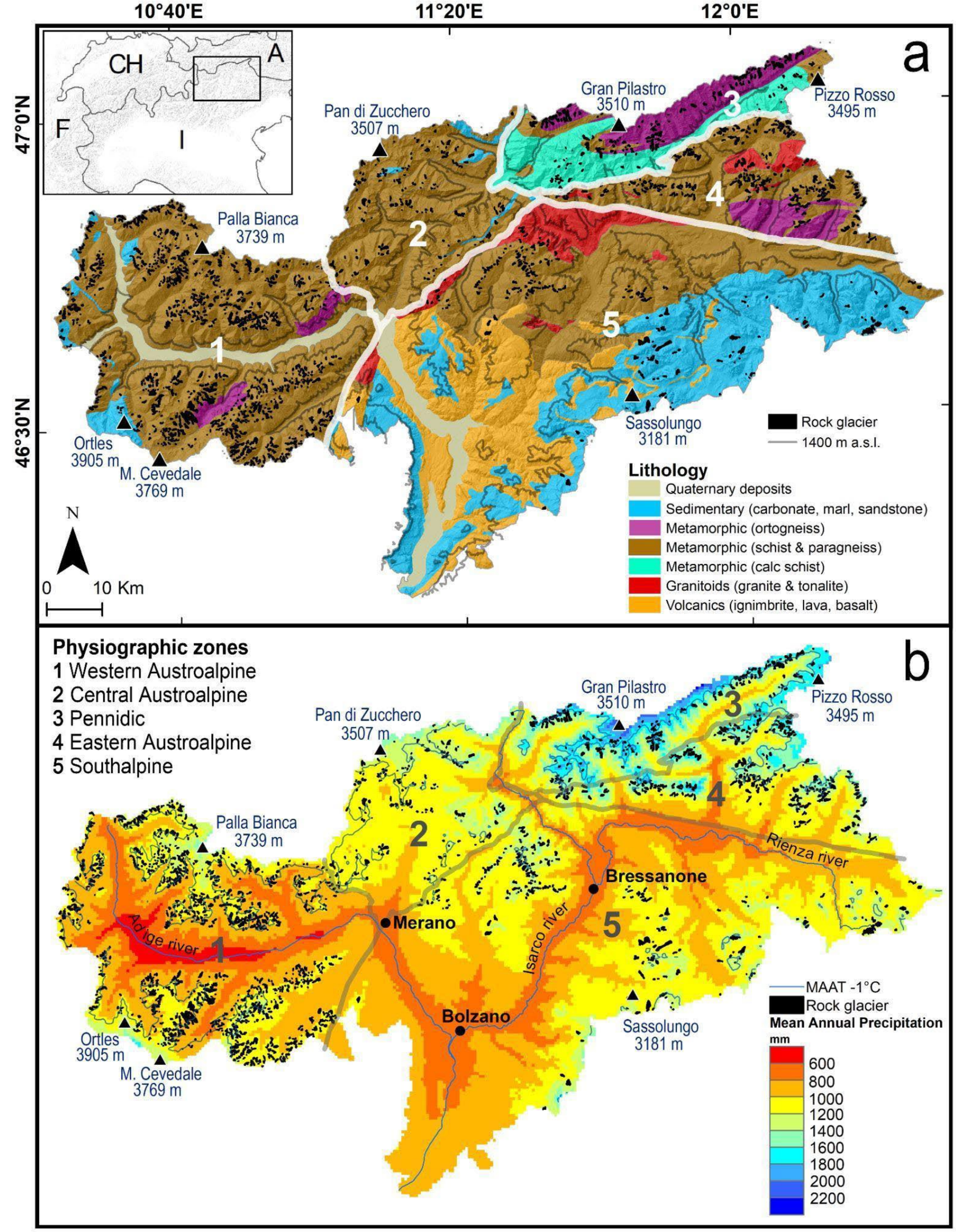

Figure 1. Rock glacier inventory map of South Tyrol superimposed on: (a) large-scale geology (after Keim et al. 2023); and (b) Mean Annual Precipitation (1981–2010; 3PClim 2023). In panel a), thick white linework separates the five physiographic zones constrained in this study (see numbering 1 through 5); dark grey linework marks the 1400 m contour line. In panel b), black linework marks the MAAT -1 °C isotherm.

Table 1. Main characteristics of the five physiographic zones. MAP refers to the mean value of precipitation, with standard deviation in brackets. MAAT refers to the mean elevation of Mean Annual Air Temperature. Lithologic categories are ranked by percent area. All values refer to terrain elevation > 1400 m a.s.l.

Physio. zone	Area	MAP	MAAT -1°C	Lithologic categories			
	(km^2)	(mm/a)	(m a.s.l.)	I	II	III	IV
WestAu	1512	957 (±154)	2585	Schist 92%	Sedi 5%	Ortho 3%	-
CentrAu	629	1156 (±111)	2468	Schist 95%	Sedi 5%	-	-
Penn	545	1479 (±250)	2440	Calc-S 52%	Ortho 36%	Schist 12%	-
EastAu	602	1241 (±216)	2436	Schist 74%	Ortho 16%	Gran 10%	-
SudAlp	1855	1074 (±112)	2615	Sedi 48%	Schist 29%	Volc 16%	Gran 7%

Calc-S=calc schist; Gran=granitoids; Ortho=orthogneiss; Schist=mica schist and paragneiss; Sedi=Sedimentary, Volc=Volcanics

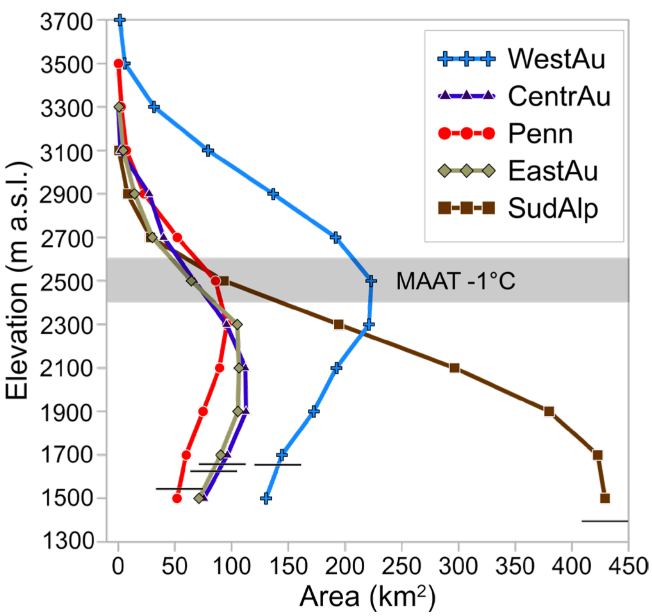

Figure 2. Terrain area as a function of elevation across the five physiographic zones. The -1 °C MAAT (1981–2010) represented as the range of variation in the five sectors, is a rough proxy for the altitudinal limit for contemporary permafrost occurrence (after Haeberli 1983 and Haeberli et al. 1989). Horizontal lines mark the elevation of the lowermost rock glacier front mapped in each zone.

The distribution of terrain area as a function of elevation shows comparable patterns across CentrAu, EastAu, and Pennidic zones, and differs greatly from that in WestAu and SudAlp. In particular, with respect to the first-order, altitudinal limit for contemporary permafrost occurrence, WestAu and SudAlp represent end members, as they contain respectively the largest and smallest extent of terrain above MAAT -1 °C (Figure 2).

Among the five zones, climate is driest in WestAu, with mean MAP = 957 mm. This figure increases progressively across SudAlp (1074 mm), CentrAu (1156 mm), EastAu (1241 mm), and the Pennidic zone (1479 mm; Table 1).

2 METHODOLOGY

Rock glacier detection, mapping and dynamic classification was conducted via visual inspection of gridded orthophotos with resolution between 0.2 and 0.5 m, acquired between 2008 and 2017, and LiDAR-derived hillshade raster of a 2.5-m Digital Terrain Model (DTM) surveyed between 2004 and 2006. Where available, information drawn from local reports on road closure or damage to infrastructure associated with the advance of rock glacier fronts was also used to complement the remotely based morphologic assessment on rock glacier activity.

Rock glacier delineation includes the extended footprint at the front and along the lateral margins, and excludes the topographic depression associated with the rooting zone (e.g., Brardinoni et al. 2019; RGIK 2023).

Following Barsch (1996), our geomorphologic inventory adopts the classification scheme that combines genetic (talus vs. debris), geometric (tongue-shaped vs. lobate), and dynamic (active, inactive and relict) attributes. Accordingly, active rock glaciers would contain an amount of permafrost sufficient to sustain downslope creep and/or shearing at depth over large parts of their surface, including front advance. Inactive (or transitional) rock glaciers, which would contain permafrost in a lesser amount, may exhibit subsidence but no frontal displacement. Relict rock glaciers, due to permafrost exhaustion, do not display any surface displacement.

Additional attributes include vegetation cover (as evaluated from optical imagery), rock glacier area, and a number of topographic variables extracted from the LiDAR DTM, such as elevation (front, mean, and maximum), mean slope gradient, and slope aspect of the main flow line.

Climatic characterization of each rock glacier is conducted through data extraction from 0.5-km climatic grids of the Austria-Italy Interreg project 3PClim, which refer to the 1981–2010 period. Attributes, extracted at the centroid of each landform, include mean annual air temperature (MAAT, °C), mean annual precipitation (MAP, mm), mean annual snowfall (SF, cm), and mean annual snow cover duration (SCD, day). In addition, mean annual incoming solar radiation (ISR, Wh/m^2) is drawn from a 25-m grid (Solar Tirol 2023).

Dominant rock glacier lithology is extracted from the general geologic map of South Tyrol (Keim et al. 2023), the compilation of which relies on published and unpublished results of the 1:50,000 Geological Cartography Project of Italy and the Basiskarte project, the 1:100,000 Italian Geological Map, the 1:500,000 Structural Model of Italy 1:500,000 (Bigi et al. 1990), the 1:50,000 geological map of the Geologische Bundesanstalt (Wien) and the Geological Overview map of Tyrol (Brandner 1980).

The simplified classification of the rock units into six lithologic classes (Figure 1a) provides a first-order characterization of the conditioning that lithology would exert on mechanical weathering, and especially on frost cracking as a supplier of debris for rock glacier development. Obviously, a similar broad-scale approach cannot capture the spatial heterogeneity in rock resistance within and across lithologies, for example, layer thickness, orientation, and dipping (e.g., sedimentary rocks and some volcanics), joint spacing and compaction.

In this work, starting from a regional lithologic ranking of resistance to fracturing (e.g., in decreasing order: granitoids, orthogneiss, volcanics, mica schist and paragneiss, calc schist, and sedimentary rocks; Grill 2014), we evaluate the actual number of rock glaciers (#) per unit lithologic area (i.e., rock glacier density, expressed as #/km^2), while considering covariation in climatic and topographic characteristics. To reduce noise, we limit our comparative analysis to the regional altitudinal belt that hosts rock glaciers, that is, above 1400 m a.s.l.

Given the uncertainty that typically characterizes the dynamic classification of rock glaciers in traditional geomorphologic inventories (Brardinoni et al. 2019), possible lithologic effects on rock glacier density will be explored on the entire inventory, without distinguishing among active, inactive and relict landforms. Uncertainty may be greatly reduced through InSAR-based kinematic classification of rock glaciers (Strozzi et al. 2004), as shown in western South Tyrol by Bertone et al. (2024).

3 Results

The inventory encompasses 2798 rock glaciers, for a combined area of 146 km^2, out of 5143 km^2 of terrain that lies above 1400 m a.s.l. (2.8%). Most rock glaciers are of the talus type (2605, 93%), with only 193 qualifying as debris type (Table 2). Following the morphologically-based dynamic classification of rock glaciers, about 60% are assessed as relict (n = 1681), 615 as inactive (22%), and 502 as active (18%). Accordingly, about 40% of the mapped polygons would qualify as intact, permafrost-bearing features.

Table 2. Rock glacier count by genetic and dynamic type.

RG type count (%)	Active	Inactive	Relict	Total
Talus	444 (17)	580 (22)	1581 (61)	2605 (93)
Debris	58 (30)	35 (18)	100 (52)	193 (7)
Combined	502 (18)	615 (22)	1681 (60)	2798 (100)

Despite the above-mentioned uncertainty involved in the assessment of rock glacier activity conducted via visual interpretation of optical imagery, examination of climatic characteristics across activity classes is helpful. MAAT increases progressively from active through inactive to relict rock glaciers (Figure 3a), with interquartile separation between relict and the other two categories. Median values of the two intact categories plot below the melting point (i.e., active = -2.3 °C; inactive = -1.6 °C), whereas the relict counterpart is significantly higher (+0.2 °C). Distributions of mean annual ISR do display the same pattern of increase, but inter-categorical differences are subtle (Figure 3b), suggesting that this variable is rather insensitive to rock glacier activity and would not represent an effective predictor.

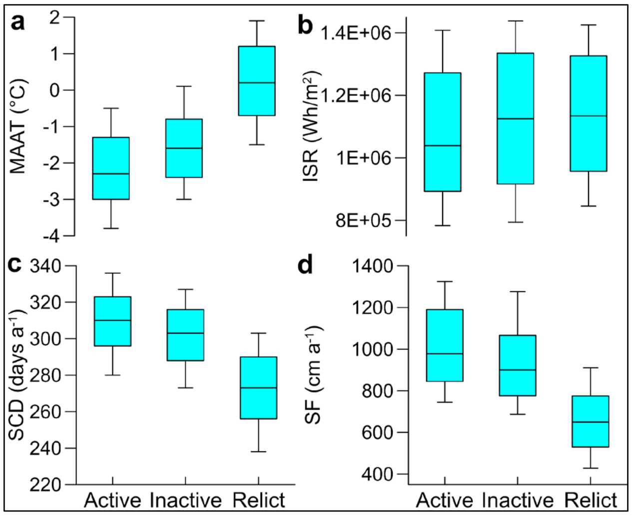

Figure 3. Climatic and topographic characterization of active, inactive, and relict rock glaciers. Variability of mean annual: (a) air temperature (MAAT), (b) incoming solar radiation (ISR), (c) snow cover duration (SCD), and (d) snowfall (SF). Climate data refer to the average from 1981–2010. Whiskers indicate respectively the 10th and the 90th percentiles; boxes enclose interquartile ranges and the horizontal lines represent median values.

By contrast, both variables related to snow, namely snow cover duration (SCD), and (d) snowfall (SF), decline systematically as one proceeds from active to relict landforms. Specifically, median SCD values decline from 310 days in active landforms, to 303 days and 273 days in inactive and relict counterparts, respectively (Figure 3c). Median SF sets at 978 cm a^{-1} and declines to 900 and 650 cm a^{-1} for inactive and relict landforms, respectively (Figure 3d).

Overall, median front elevation of active rock glaciers (2690 m) is respectively 95 m and 435 m higher than that of the inactive (2595 m) and relict ones (2255 m; i.e., Comb in Figure 4). By modulating incoming solar radiation, slope aspect appears to significantly affect the elevation of a given activity class, with values gradually increasing from north- through south-facing aspects. The maximum offset ranges from 212 m for intact to 286 m for relict landforms. Despite the general predictability of rock glacier distribution in the aspect-

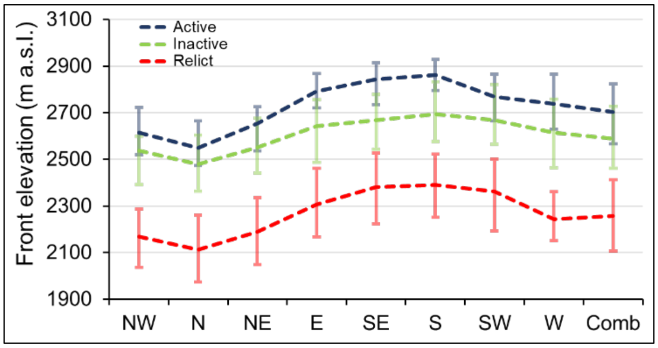

Figure 4. Rock glacier front elevation as a function of slope aspect. Dashed linework connects median values; whiskers enclose interquartile ranges. Comb = combined.

elevation space, active rock glacier fronts facing east and southeast reach elevations similar to those facing south, and plot significantly higher than the west and southwest counterparts (Figure 4). The same pattern, albeit less pronounced, is visible across relict rock glaciers.

With respect to rock glacier occurrence across lithologies (Figure 5), highest densities are observed in mica schists and paragneiss (0.76 #/km^2)—here termed *schists* for simplicity—and orthogneiss (0.63 #/km^2), followed by granitoids (0.27 #/km^2), which exhibit a 3-fold drop, calc schists (0.21 #/km^2), sedimentary rocks (mainly dolostone and limestone with lesser marl and sandstone; 0.15 #/km^2), and finally by volcanics (ignimbrite, lava, and basalts; 0.02 #/km^2).

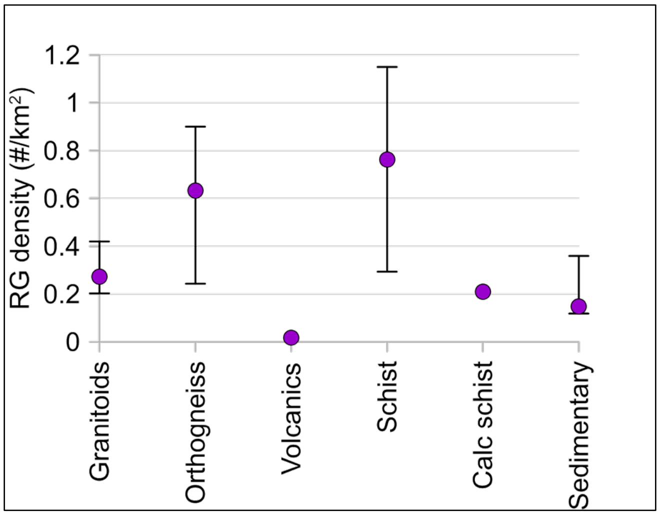

Figure 5. Overall rock glacier density by lithology in South Tyrol (filled circles). Whiskers indicate the minimum and maximum density values across the five physiographic zones. Terrain area refers to topography located at elevations > 1400 m a.s.l.

4 Discussion and Conclusions

4.1 Rock Glacier Types and Activity

Regarding rock glacier genetic classification, our inventory displays proportions of talus and debris rock glaciers that are in line with those reported in inventories compiled elsewhere in the European Alps, such as in Swiss Ticino (Scapozza and Mari 2010), the Austrian Tyrolean Alps (Krainer and Ribis 2012), and the Italian central Alps (i.e., Lombardy, Scotti et al. 2013). Albeit heavily affected by inter-operator variability, a limitation that makes direct comparison of rock glacier activity among different inventories problematic, similarities apply also to the relative abundance of intact (40%) and relict (60%) rock glaciers, considering the percentages documented in Ticino (intact 45% and relict 55%), in Lombardy (42% and 58%), and in the Tyrolean Alps (45.5% and 54.5%). By contrast, in Trentino (Italy) and in the Eastern Alps (Austria) relict rock glaciers appear to be more prevalent, accounting respectively for 75% and 79% (Kellerer-Pirklbauer et al. 2012; Seppi et al. 2012). We interpret this discrepancy as the effect of broad, low-lying, pre-alpine terrain (e.g., the Lagorai in Trentino), which today largely host relict landforms.

Mean front elevations of active, inactive and relict rock glaciers in South Tyrol mimic closely those of the neighbouring Tyrolean Alps in Austria (Krainer and Ribis 2012), for which the main discrepancy is represented by the mean elevation of the active fronts (2628 m), located just 62 m below.

As shown in Figure 3, stratification into active, inactive and relict rock glaciers aids identifying a number of useful climatic and altitudinal dependences. Considering the -1 °C to -2 °C threshold for discontinuous permafrost in the Alps (Haeberli 1983; Haeberli et al. 1989), a median MAAT around the melting point—even if partly affected by post-industrial climate warming—today could not sustain permafrost occurrence. This observation suggests that significantly cooler conditions, compared to the average of the Holocene, must have promoted the development of currently relict rock glaciers (mean MAAT +0.2 °C). Indeed, going farther back from the Holocene, summer temperature during the Younger Dryas was 3 to 5 °C lower than today (Ivy-Ochs et al. 2023), thus supporting the likely onset of rock glacier development during the latest and slightly milder phases of this stadial (e.g., Frauenfelder et al. 2001; Böhlert et al. 2011; Kellerer-Pirklbauer et al. 2012; Scotti et al. 2017).

Rock glacier stratification by activity further shows that increasing snow persistence on the ground may have an important role in the thermal insulation of blocky debris, as annual snow free conditions, on average, decline progressively from active (55 days), to inactive (62 days), and especially to permafrost devoid rock glaciers (92 days; Figure 3c). A similar altitudinal transition across active, inactive and relict landforms is also observed in terms of annual snowfall (Figure 3d) and should not surprise, since all snow-related climatic parameters depend directly on elevation. The lack of spatially-distributed climatic data in other inventories, makes it difficult to evaluate the significance of the correlations shown in Figure 3, also in relation to prospective scenarios of climate change.

4.2 Lithologic Effects and Interactions with Topo-climatic Characteristics

The question of lithologic controls on rock glacier formation and growth is a challenging one. On one hand, rock glaciers require a high supply of debris to induce and support over time creep and shearing at depth, a supply that in principle would increase with decreasing rock strength of the source walls. On the other hand, to favour thermal ventilation and permafrost persistence, a coarse blocky supply of debris is needed (as opposed to fine-grained material), a condition that would require greater rock strength, as well as outcrops characterized by thick bedding planes and high joint spacing.

Our results show that rock glacier density varies across lithologies in a complex way (Figure 5), which does not follow an intuitive ranking related to rock strength, or its opposite, thus suggesting that efficient interactions with other factors may be involved, including the variety of weathering mechanisms in cold regions (Hall et al. 2002). For example, rock glacier density in orthogneiss scores second highest—although regarded as one of the most resistant rock types—and much higher than granitoids, which one would expect to bear at least comparable resistance. Likewise, densities in granitoids and sedimentary rocks are surprisingly very similar.

Table 3. Rock glacier count, combined area, and density across physiographic zones. RG densities are computed on mountain terrain located above 1400 m a.s.l.

Physiographic zone	RG count	RG combined area (km^2)	RG density ($\#/km^2$)
WestAu	**1642**	70.4	1.08
CentrAu	**208**	10.0	0.33
Penn	**265**	17.2	0.48
EastAu	**385**	24.9	0.64
SudAlp	**298**	23.5	0.16
Combined	**2798**	146.1	0.54

Examination of rock glacier density across physiographic zones, each characterized by different combinations of climatic, topographic and lithologic boundary conditions, helps provide better context to the integrated environmental conditions that may favour rock glacier development (Figure 1; Tables 1 and 2). WestAu stands out—both within the Austroalpine domain and among all the physiographic zones—for showing, by far, the highest rock glacier densities (Table 3). Given comparable lithologic composition among the three Austroalpine sub-zones (Table 1), this outcome suggests that more continental climatic conditions, in conjunction with a comparably greater portion of terrain located above 2300 m a.s.l., foster rock glacier formation (Figures 2 and 6). On the opposite end, in SudAlp, similar continental conditions (Figure 6b), but a topography distribution heavily skewed towards lower (< 2300 m) elevation (Figure 6a) and a dominance of sedimentary rocks (Table 1), yields an order-of-magnitude lower rock glacier density (Table 3).

In part, the scarcity of rock glaciers associated with sedimentary rocks (i.e., mainly limestone and dolostone) agrees with Johnson et al. (2007), according to whom, compared with metasedimentary rocks, water loss to subsurface in limestones could be the cause of unfavourable conditions for permafrost development and creep onset. This interpretation, although based on limited proportions of terrain within each physiographic zone (i.e., ~5%), is further supported by consistently low rock glacier densities across sedimentary rocks of WestAu and CentraAu (i.e., ~0.31 $\#/km^{2;}$ Figure 6).

Among metamorphic lithologies, rock glacier scarcity is particularly evident in calc schist (Figure 6), especially when looking at and around the Pennidic domain. Here, high rock glacier clustering on orthogneiss (violet) and on schist and paragneiss (brown), contrasts sharply with calc schist (cyan), where very few rock glaciers were mapped (Figure 7). This finding agrees with prior studies indicating that lithologies disintegrating into fine and platy debris would not favour rock glacier development (Wahrhaftig and Cox 1959; Evin 1987; Matsuoka et al. 1997; Haeberli et al. 2006).

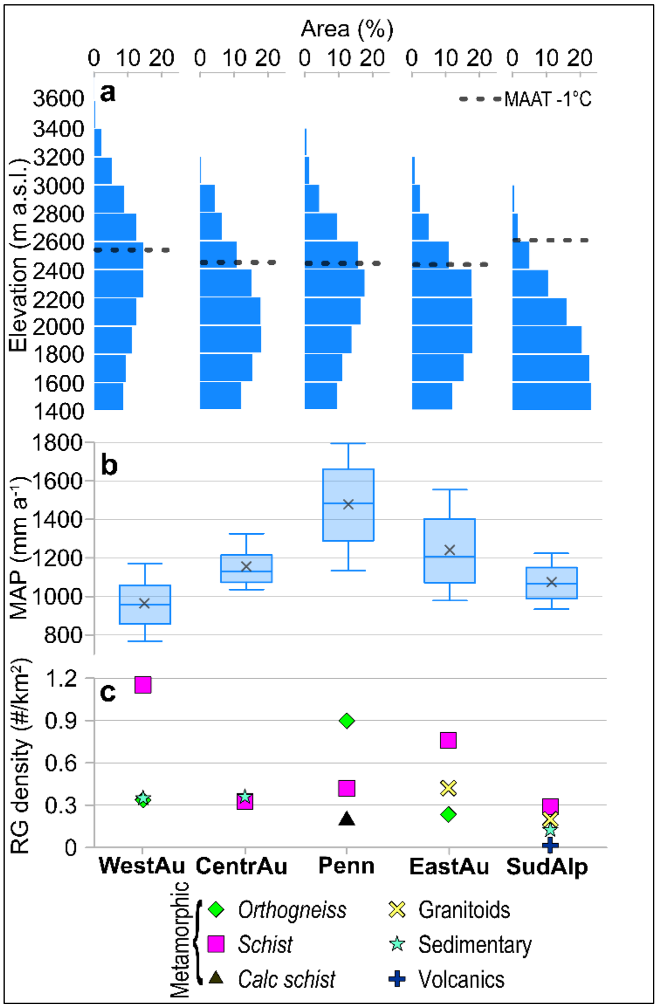

Figure 6. Rock glacier occurrence in the five physiographic zones, and relevant topographic and climatic conditions. (a) Percent terrain area as a function of elevation above 1400 m a.s.l.; (b) Frequency distribution of gridded Mean Annual Precipitation (1981–2010); and (c) rock glacier density by lithology. In panel (a), -1 °C MAAT is reported as a first-order proxy of the lower altitudinal limit for permafrost occurrence. In panel (b), horizontal lines and Xs represent median and mean values respectively. Whiskers mark the 10th and 90th percentiles; boxes bound the interquartile range.

Aside from the calc schist case, lithologic effects in the study region appear heavily masked by inter-zonal variation of climatic and topographic conditions, and possibly by additional confounding exerted by the spatial distribution of glacial till. Our interpretation is exemplified by the most common lithologies in South Tyrol, such as mica schist, paragneiss and orthogneiss. By encompassing a broad range of topo-climatic settings, these lithologies are also characterized by highest inter-zonal variability (Figure 6). While in some instances the direction and magnitude of this variability may be justified by the different positioning of a given lithology within alpine valleys (cf., spatial distribution of orthogneiss in Penn and WestAu), in other cases—at the coarse spatial scale of this work—explanation remains elusive. For example, with respect to rock glacier density in orthogneiss, we explain the 3-fold increase observed in Penn, compared to EastAu, with the altitudinal position that this lithology occupies within the landscape. Specifically, while in Penn orthogneiss outcrops at high elevations along the main Alpine divide, in EastAu it lies on mid to lower slopes and along tributary valley bottoms (Figure 1a).

To reduce uncertainty and improve the reliability of the rock glacier inventory presented in this contribution, especially with respect to the dynamic discrimination among active, inactive, and relict landforms, a regional effort is underway to integrate geomorphologic mapping and characterization with InSAR-based kinematic information (i.e., Bertone et al. 2022).

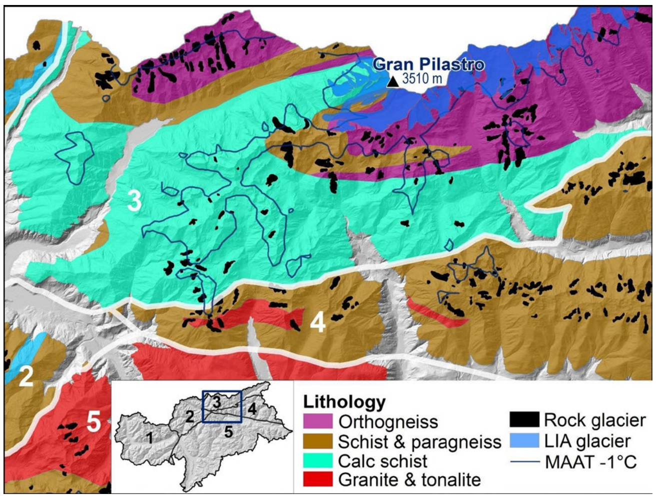

Figure 7. Map showing lithology above 1400 m a.s.l. and the rock glacier distribution in the upper Val d'Isarco area. Note rock glacier clustering in orthogneiss and in schist-paragneiss, as opposed to the sparse pattern in calc schist. 2 = Central Austroalpine; 3 = Pennidic; 4 = Eastern Austroalpine; 5 = SouthAlpine. Little Ice Age glacier extent from Knoll et al. (2009).

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