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Spring-water temperature suggests widespread occurrence of Alpine permafrost in pseudo-relict rock glaciers

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Abstract. Runoff originating from ground ice contained in rock glaciers represents a significant water supply for lowlands. Pseudo-relict rock glaciers contain patchy permafrost but appear to be relict, and therefore they can be misinterpreted when using standard classification approaches. The permafrost content, spatial distribution and frequency of this type of rock glacier are poorly known. Therefore, identifying pseudo-relict rock glaciers that might still contain permafrost, and potentially ice, is crucial for understanding their hydrological role in a climate change context.

This work analyses rock–glacier spring-water temperature in a 795 km^2 catchment in the eastern Italian Alps to understand how many rock glaciers classified as relict could have spring-water temperatures comparable to active or transitional rock glaciers as possible evidence of their pseudo-relict nature. Spring-water temperature, often auxiliary to other approaches for specific sites, was used for a preliminary estimate of the permafrost presence in 50 rock glaciers classified as relict. In addition, we present electrical resistivity tomography (ERT) results on two relict rock glaciers with opposing spring-water temperature and surface characteristics to constrain spring-water temperature results at the local scale.

The results show that about 50 % of the rock glaciers classified as relict might be pseudo-relict, thus potentially containing permafrost. Both supposedly relict rock glaciers investigated by geophysics contain frozen sediments. The majority of the cold springs are mainly associated with rock glaciers with blocky and scarcely vegetated surfaces, but geophysics suggest that permafrost may also exist in rock glaciers below 2000 m a.s.l., entirely covered by vegetation and with a spring-water temperature of up to 3.7 °C. We estimate that pseudo-relict rock glaciers might contain a significant portion (20 %) of all the ice stored in the rock glaciers in the study area. These results highlight the relevance of pseudo-relict rock glaciers in periglacial environments. Even if not a conclusive method, spring-water temperature analyses can be used to preliminarily distinguish between relict and pseudo-relict rock glaciers in wide regions.

1 Introduction

The timings and magnitude of cryosphere runoff have high climatic sensitivity and are impacted by current changes in Earth's climate (Engelhardt et al., 2014; Zemp et al., 2015; Carturan et al., 2019). Moreover, a deterioration of the water quality has been reported for springs fed by melting permafrost (Thies et al., 2013; Ilyashuk et al., 2014). Due to glacier decline, in recent decades growing attention has been paid to other water reservoirs, such as subsurface ice, including debris-covered glacier ice and, in particular, ground ice stored in periglacial landforms such as rock glaciers and glacial–permafrost composite landforms (e.g. Brighenti et al., 2019; Jones et al., 2019; Schaffer et al., 2019; Seppi et al., 2019; Wagner et al., 2021). Projection of ice loss rates indicates that in the second half of the 21st century more subsurface ice may be preserved than glacier surface ice because of their different response times to atmospheric warming (Haeberli et al., 2017). Subsurface ice is therefore expected to significantly contribute to stream runoff under future climate warming (Janke et al., 2015, 2017).

Jones et al. (2018) assessed the importance of ice contained in rock glaciers at the global scale, estimating that 62.02 ± 12.40 Gt of ice is contained in intact rock glaciers. With the adjective "intact" we refer to the traditional categorization of rock glaciers, which distinguishes between intact rock glaciers (containing ice) and relict rock glaciers (not containing ice). According to the most up-to-date classification (RGIK, 2023), rock glaciers should be categorized as active, transitional and relict, referring exclusively to the efficiency of sediment conveyance (expressed by the surface movement) at the time of observation. This classification should not be used to infer any ground ice content.

Even though relict rock glaciers should not contain ice (Haeberli, 1985; Barsch, 1996), more recent studies showed that some relict rock glaciers can preserve permafrost and ice far below the regional lower limit of discontinuous permafrost (e.g. Delaloye, 2004; Strozzi et al., 2004; Lewkowicz et al., 2011; Bollati et al., 2018; Colucci et al., 2019). This evidence raises the question of whether a significant fraction of rock glaciers classified as relict should actually be considered "pseudo-relict", i.e. "rock glaciers which appear to be visually relict but still contain patches of permafrost" (Kellerer-Pirklbauer et al., 2012; Kellerer-Pirklbauer, 2008, 2019). This question is relevant because landforms classified as relict in some regions can be up to an order of magnitude larger and more numerous than active/transitional rock glaciers (e.g. Seppi et al., 2012; Scotti et al., 2013; Kofler et al., 2020), with potentially significant ecological and hydrological impacts (e.g. Brenning, 2005a; Millar and Westfall, 2019; Brighenti et al., 2021; Sannino et al., 2021). According to Jones et al. (2019), identifying and establishing the activity state of rock glaciers is an important initial step in determining their potential hydrological significance.

Previous investigations of the "possible" permafrost content of relict rock glaciers looked at individual case studies or small groups of landforms (e.g. Delaloye, 2004; Kellerer-Pirklbauer et al., 2014; Popescu, 2018; Colucci et al., 2019; Pavoni et al., 2023). Studies considering a larger number of relict rock glaciers, at the regional scale, were mainly focused on the past distribution of mountain permafrost and on the reconstruction of related palaeoclimatic conditions (e.g. Frauenfelder et al., 2001; Seppi et al., 2010; Charton et al., 2021; Dlabáčková et al., 2023).

As a result, the actual distribution, frequency and ice content of pseudo-relict rock glaciers might be underestimated, with the last one being essential for implementing worldwide estimates of water resources stored in periglacial landforms (e.g. Jones et al., 2018). Detailed geophysical investigation of selected landforms is certainly suitable as a first step towards better knowledge of pseudo-relict rock glaciers and their ice content. However, due to logistical constraints, this approach cannot be applied to a large number of rock glaciers at the catchment or regional scale. A recent and commendable advance on this topic was achieved by the proposition of operational guidelines on the interferometric synthetic aperture radar (InSAR)-based kinematic characterization of rock glaciers (Bertone et al., 2022), which can be used for thorough studies of wide areas. However, this approach is not suitable for distinguishing between relict and pseudo-relict rock glaciers, because their surface has no movement or the movement is very slow and in the same range as the uncertainty of the method.

One possible way of investigating the presence of permafrost in these landforms over large areas is by analysing spring-water temperature measured downslope of rock glaciers. Haeberli (1975) proposed monitoring of spring-water temperature in late summer as useful evidence of permafrost, and various authors used this method as auxiliary permafrost evidence (e.g. Frauenfelder et al., 1998; Scapozza, 2009; Imhof et al., 2000; Strozzi et al., 2004; Cossart et al., 2008). Carturan et al. (2016) demonstrated that this method can be used successfully for mapping permafrost distributions at the catchment scale. All these works are based on the evidence that, in late summer, spring water affected by permafrost has a lower temperature compared to those unaffected, with upper thresholds ranging between 0.9 and 1.1 °C for probable permafrost and between 1.8 and 2.2 °C for possible permafrost.

In this work, we analyse the spatial variability of spring-water temperature in a 795 km^2 catchment located in the eastern Italian Alps, where 338 rock glaciers were inventoried (Seppi et al., 2012), to better understand the permafrost distribution. We hypothesize that a significant portion of rock glaciers classified as relict have spring-water temperatures comparable to those of active/transitional rock glaciers, which is possible evidence of their permafrost content and their pseudo-relict nature. The specific objectives of this study are as follows:

i. Analyse the influence of topographic and geomorphological factors on spring-water temperature.

ii. Investigate the main controls on water temperature for springs downslope of rock glaciers, and particularly relict rock glaciers.

iii. Investigate via geophysical analyses the presence of permafrost in two rock glaciers selected for their different spring-water temperature and surface characteristics to constrain spring-water temperature results at the local scale.

iv. Preliminarily estimate and compare the ice content of rock glaciers and glaciers in the study area.

2 Study area

The Val di Sole is located in the upper part of the Noce River catchment, a tributary of the Adige River, which is the main river system in north-eastern Italy (Fig. 1). The catchment is 795 km^2 wide, with elevation ranging between 520 m a.s.l. at the outlet (Mostizzolo) and 3769 m a.s.l. at the summit of Monte Cevedale, averaging 1705 m a.s.l. (Fig. 1). Metamorphic rocks (mica schists, paragneiss and orthogneiss) prevail on the northern side of the valley, whereas tonalite is found in the south-western part and dolomites and limestones prevail in the south-eastern part (Dal Piaz et al., 2007; Martin et al., 2009; Chiesa et al., 2010; Montrasio et al., 2012).

The catchment includes a glacierized area of 16 km^2 (in 2006; Salvatore et al., 2015). Bare bedrock and debris are found outside the glaciers down to an elevation of 2700 m, which is the lower regional limit of discontinuous permafrost (Boeckli et al., 2012). Discontinuous cover of Alpine meadows and shrubs is present between 2200 and 2700 m, while below 2000–2200 m forests are dominant. The valley bottom is covered by cultivation and settlements.

The Val di Sole lies in a transition zone between the "inner dry alpine zone" in the north (Frei and Schär, 1998) and the wetter area under the influence of the Mediterranean Sea in the south. At the valley floor, the mean annual precipitation in the period between 1971 and 2008 is ~ 900 mm. Precipitation increases with elevation and in the southern part, with a maximum of 1500 mm in the Adamello-Presanella Group (Carturan et al., 2012; Isotta et al., 2014). The mean annual 0 °C isotherm is located at 2500 m. The mean annual air temperature variability is dominated by elevation, whereas latitudinal and longitudinal variations are negligible.

Seppi et al. (2012) mapped 338 rock glaciers in the Val di Sole. Based on evidence visible in the orthophotos and digital elevation models (DEMs), the majority of the rock glaciers were classified as relict (229, 68 % of the total), whereas only 42 of the remaining 109 could be classified as active based on the multi-temporal high-resolution DEMs and the other 67 could be considered transitional. Most of the rock glaciers (302, 89 % of the total) are composed of deposits of metamorphic rocks on the orographic left side of the valley.

3 Materials and methods

3.1 Experimental design

We focused our investigations on the northern part of the Val di Sole because it has a rather homogeneous lithology (metamorphic rocks with predominant mica schists) and a mean annual precipitation of 1233 mm at 2600 m (Carturan et al., 2016). This was done to minimize the effects of different lithologies and annual precipitation on the spatial variability of spring-water temperature and to highlight the role of other variables in their catchment, upslope area or upslope rock glaciers.

To obtain statistically meaningful and generalizable results, we designed a sampling scheme for rock glacier spring-water temperature considering the variability of permafrost-related characteristics in the study area, i.e. vegetation cover (related to ground temperature and fine debris infill), size (length and area), elevation, slope, aspect and lithology (Barsch, 1996; Haeberli, 1985; Lambiel and Reynard, 2001; Boeckli et al., 2012).

We inspected these variables, reported for each rock glacier of the Val di Sole in the database of Seppi et al. (2012), using a correlation matrix and principal component analysis. The aim was to evaluate their possible covariance and to optimize the number of variables to be included in the sampling scheme. The analysis revealed high positive covariance between length and area (both related to size). Negative covariance was found between elevation and vegetation cover and between slope and length or area.

Based on these outcomes and considering the accessibility of springs, we built a sampling scheme around four variables: (i) rock glacier activity, (ii) length, (iii) mean elevation and (iv) vegetation cover. The last two variables are correlated because active/transitional rock glaciers are at high elevations and are almost free of vegetation, and the opposite is true for relict rock glaciers. Vegetation cover is probably one of the few variables that may aid in identifying rock glacier activity (Ikeda and Matsuoka, 2002; Strozzi et al., 2004; Kofler et al., 2020), and it can vary greatly among rock glaciers at similar elevations. For this reason, we kept both elevation and vegetation, applying a modification to the vegetation cover classification proposed by Seppi et al. (2012). We distinguish between two classes, i.e. "vegetated" and "non-vegetated", for active, transitional and relict rock glaciers (see Table 1 for the threshold values). The vegetation cover was visually estimated in the field and in orthophotos for each rock glacier. Our sampling scheme ensured that at least one rock glacier was sampled for each combination of variables (Table 2). The frequency distribution of rock glacier length and mean elevation was used to identify three terciles, employed for grouping them into short, medium and long rock glaciers and low-, mid- and high-elevation rock glaciers. Frequency distributions and terciles of active, transitional and relict rock glaciers were calculated separately (Table 2).

3.2 Data collection

Water temperature was measured at 220 springs, 133 of which are located downslope of rock glaciers (multiple springs were often measured downslope of the same rock glacier), 81 downslope of other deposits and 8 in bedrock. Springs were sampled from mid-August to mid-October, after the end of the snowmelt. Most springs were measured once a year from 2018 to 2020, and a small group of them

Table 1. Classification of active, transitional and relict rock glaciers in two different classes of vegetation cover.

Rock glacier category	Vegetation cover class	Meaning
Active or transitional	Vegetated	Vegetation cover $> 10\,\%$
	Non-vegetated	Vegetation cover $< 10\,\%$
Relict	Vegetated	Vegetation cover $> 50\,\%$
	Non-vegetated	Vegetation cover $< 50\,\%$

Table 2. Sampling scheme used for water temperature measurements at rock glacier springs.

Activity state	Length	Elevation	Vegetation cover	Number of sampled rock glaciers
Active/transitional	Short (< 142 m)	Low (< 2634 m)	Non-vegetated	2
			Vegetated	None
		Mid (> 2634 and < 2811 m)	Non-vegetated	2
			Vegetated	None
		High (> 2811 m)	Non-vegetated	1
			Vegetated	None
	Mid (> 142 and < 251 m)	Low (< 2596 m)	Non-vegetated	1
			Vegetated	None
		Mid (> 2596 and < 2817 m)	Non-vegetated	1
			Vegetated	3
		High (> 2817 m)	Non-vegetated	2
			Vegetated	None
	Long (> 251 m)	Low (< 2655 m)	Non-vegetated	None
			Vegetated	1
		Mid (> 2655 and < 2779 m)	Non-vegetated	1
			Vegetated	None
		High (> 2779 m)	Non-vegetated	3
			Vegetated	None
Relict	Short (< 180 m)	Low (< 2267 m)	Non-vegetated	3
			Vegetated	4
		Mid (> 2267 and < 2453 m)	Non-vegetated	1
			Vegetated	2
		High (> 2453 m)	Non-vegetated	2
			Vegetated	2
	Mid (> 180 and < 340 m)	Low (< 2255 m)	Non-vegetated	3
			Vegetated	4
		Mid (> 2255 and < 2425 m)	Non-vegetated	1
			Vegetated	2
		High (> 2425 m)	Non-vegetated	2
			Vegetated	3
	Long (> 340 m)	Low (< 2222 m)	Non-vegetated	1
			Vegetated	4
		Mid (> 2222 and < 2388 m)	Non-vegetated	3
			Vegetated	5
		High (> 2388 m)	Non-vegetated	5
			Vegetated	3
			Total:	67

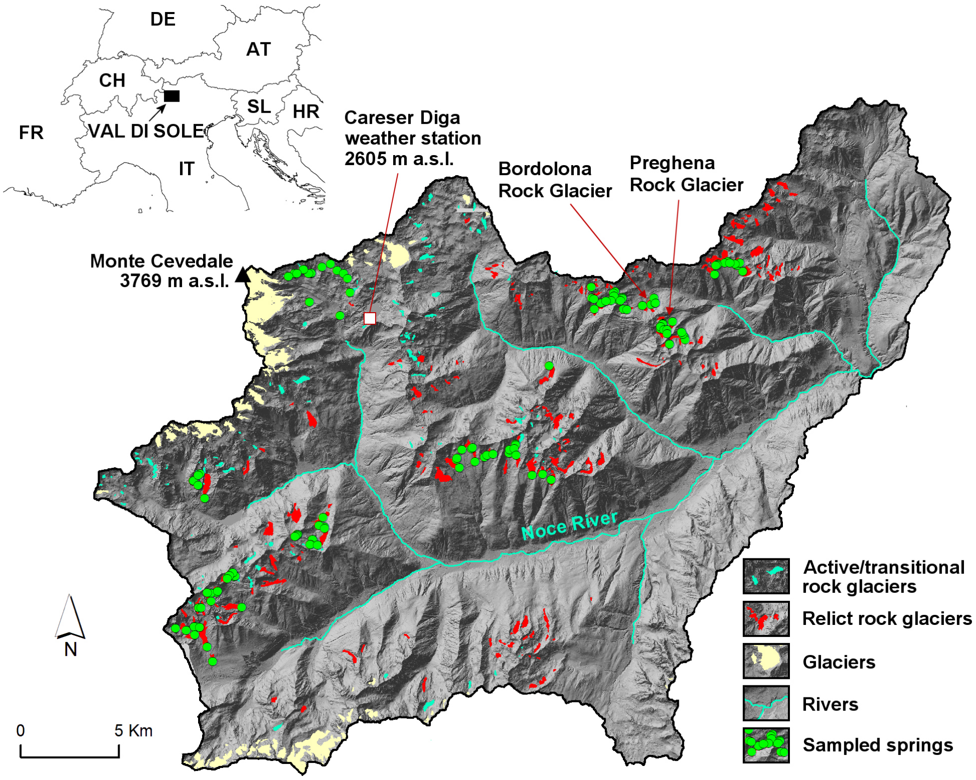

Figure 1. Geographic location of the study area and the sampled springs. The background is the hill-shaded 2014 lidar DEM surveyed by the Autonomous Province of Trento (https://siat.provincia.tn.it/stem/, last access: 30 November 2024).

was also measured in 2021. In these 4 years, the total number of single measurements was 540.

Based on the sampling scheme (Table 2), we measured spring-water temperature at 17 active/transitional rock glaciers and 50 relict rock glaciers, which corresponds to 22 % of all the rock glaciers in the study area. All variable combinations defined for relict rock glaciers have been sampled, whereas several combinations for active/transitional rock glaciers lack samplings. This was due to the non-existence of single combinations (e.g. there are no short and vegetated active/transitional rock glaciers at low elevations) or the lack of springs and the inaccessibility of some rock glaciers.

Measurements of spring-water temperature were carried out using a WTW Cond3310 (WTW GmbH, Weilheim, Germany) and a Testo 110 (Testo AG, Lenzkirch, Germany). These instruments both have 0.1 °C resolution, but the WTW has higher accuracy (±0.1 °C) compared to the Testo (±0.2 °C), which was used for backup and validation. Water temperature measurements were carried out by shading the spring from direct sunlight and avoiding probe contact with sediments, rocks and vegetation. The calibration of the two instruments was checked at the beginning and end of the annual campaigns using an ice bath. In addition, we assessed runoff using a quick visual estimation (always the same operator), similar to Strobl et al. (2020), who considered the average width, mean depth and velocity of the flow downslope of the spring. This approach was used to rule out springs with very low runoff ($< 0.1\,\mathrm{L\,s^{-1}}$).

3.3 Data analysis

Before proceeding with statistical analyses, we preliminarily filtered field data to exclude problematic or redundant measurements. First, we discarded measurements that were clearly affected by very low runoff ($< 0.1\,\mathrm{L\,s^{-1}}$) responsible for large temperature fluctuations during the day (Seppi, 2006). We then selected one measurement site for each rock glacier and for groups of springs less than 10 m from each other. Spring selection was carried out by favouring springs with the highest runoff, repeated readings in the 4 years, the closest locations of the rock glacier fronts and the lowest inter-annual temperature variability.

After this selection, 131 springs were retained. We characterize the springs using different variables (Table 3), i.e. the topographic characteristics of the catchments draining to the springs, the activity state, the topographic, geomorphological and vegetation characteristics of rock glaciers and the topographic, geomorphological, geological, vegetation and permafrost characteristics of the area immediately upslope of the springs. The latter is defined by the intersection of the catchment perimeter with a circular buffer zone with a ra-

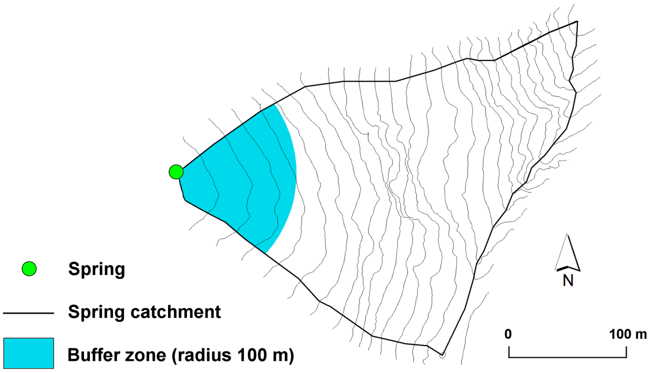

Figure 2. Delimitation of the spring upslope area, defined by the intersection of a circular buffer zone with a radius of 100 m over the catchment perimeter. The methodology was introduced and tested in Carturan et al. (2016).

dius of 100 m (Fig. 2; Carturan et al., 2016). Details of these variables, the methodology and the data sources (e.g. DEMs, orthophotos, geological maps and the literature) employed to derive them are listed and described in Table 3.

We investigated the possible relationship of each variable with the spring-water temperature by means of scatterplots, boxplots, analysis of variance (or Kruskal–Wallis one-way analysis of variance on ranks when variances were not homogeneous), Dunn's multi-comparison test, a Student's *t* test and regression analysis. We defined spring-water temperature as the median of all available temperature measurements in the four years, so that we smoothed the inter-annual variability of the water temperature. However, we also had to account for the different number of measurements available for each spring (from one up to four) and in particular for the possible low representativeness of springs measured only once. In this case, there is a possibility of having measured an extreme value far from the typical conditions of those springs. To evaluate the impact of extreme values, we computed the absolute difference between each single-year spring-water measurement and the median of all available measurements at the same spring. The mean of these absolute differences was 0.12 °C, the median was 0.05 °C, the minimum and maximum were 0 and 0.7 °C, respectively, and 89 % of the values were below 0.3 °C. These results indicate a low impact of extreme temperatures and the suitability of using the median of all available measurements (regardless of their number) in statistical analyses. For springs with temperature measured only once, we retained the single value if runoff was $> 0.1\,\mathrm{L\,s^{-1}}$.

3.4 Geophysical investigations

Electrical resistivity tomography (ERT) surveys were performed on 13–14 July 2022 on two neighbouring rock glaciers, classified as relict in the inventory of Seppi et al. (2012), to constrain spring-water temperature results at the local scale. These rock glaciers were selected considering their different characteristics (spring-water temperature, vegetation cover and elevation) and easy access. In addition, they have a uniform lithology, which minimizes the uncertainty in the interpretation of gradients in electrical resistivity. The Preghena Rock Glacier has a mean elevation of 2196 m a.s.l.; it is mostly free of vegetation (although shrubs and trees are present) and its spring-water temperature ranged between 1.6 and 1.8 °C throughout the late summer during the measuring period. The Bordolona Rock Glacier has a mean elevation of 1967 m a.s.l.; it is completely covered by vegetation and its spring-water temperature ranged between 3.5 and 3.7 °C in the late summer during the measuring period. Both rock glaciers are NE-oriented (Fig. 3).

Geophysical surveys were carried out with a Syscal Pro georesistivimeter (Iris Instruments) using arrays of 72 (Line 1: Preghena; Line 3: Bordolona) or 48 (Line 2: Preghena) electrodes, with 3 m electrode spacing (Fig. 3). Total lengths of 346 and 216 m were investigated at the Preghena and Bordolona rock glaciers. A dipole–dipole scheme was used, with two different skips of zero and four electrodes. This configuration ensured relatively high resolution at the surface and enough penetration depth at the same time. Measurements were carried out with a stack of three to six, imposing an acceptable error threshold of 5 %. To estimate a more reliable experimental error for the acquired datasets (Binley, 2015), direct and reciprocal measurements were acquired by exchanging injecting and potential dipoles for each quadrupole. To partially overcome the high contact resistances between the electrodes and boulders or debris (Hauck and Kneisell, 2008), the electrodes were inserted between the boulders using sponges soaked with saltwater (Pavoni et al., 2023). Nevertheless, at the blocky surface of the Preghena Rock Glacier the contact resistances remained steadily above $10^5\ \Omega$m, due to the dry environmental conditions. The organic soil at the Bordolona Rock Glacier guaranteed low contact resistances ($< 10^4\ \Omega$m).

The inversion process of the acquired datasets was performed with the Python-based software ResIPy (Blanchy et al., 2020) based on Occam's inversion method (Binley and Kemna, 2005). In each dataset, quadrupoles with a stacking error of higher than 5 % were removed, and the expected data error was defined using the reciprocal check (Day-Lewis et al., 2008; Pavoni et al., 2023), giving values of 20 % and 5 % for the Preghena and Bordolona rock glaciers.

3.5 Calculation of ice storage in the rock glaciers and glaciers

In order to estimate and compare the ice content of rock glaciers and glaciers in the Val di Sole, we applied an approach similar to the one used by Bolch and Marchenko (2009) in the northern Tien Shan. For the glaciers, we estimated residual volumes in 2022, starting from the 2003 ice thickness estimates provided for each glacier in the study

Table 3. Quantitative and qualitative variables used for characterizing spring areas and for statistical analyses.

Spatial scale	Variable type	Variable	Classes/abbreviation	Meaning
Catchment	Quantitative	Minimum elevation (m a.s.l.)[a]	–	Spring elevation
		Maximum elevation (m a.s.l.)[a]	–	
		Mean elevation (m a.s.l.)[a]	–	Half-sum of minimum and maximum elevations
		Planimetric length (m)[a]	–	
	Qualitative	Mean aspect[a]	NW–NE	From 315 to 45°
			NE–SE, SW–NW	From 45 to 135° and from 225 to 315°
			SE–SW	From 135 to 225°
Spring upslope area	Qualitative	Geomorphology[b,g]	ver	Slope deposit (scree slope or debris cone)
			glac	Glacial deposit
			rg	Rock glacier
			pr	Protalus rampart
			rp	Bedrock
			df	Debris flow deposit
			ls	Solifluction lobe
		Lithology[b]	TTP	Sillimanite paragneiss (Tonale Unit)
			TUG	Granate and cyanite paragneiss (Ultimo Unit)
			TUO	Orthogneiss (Ultimo Unit)
			OME	Chlorite and sericite mica schists (Peio Unit)
			OMI	Granate and staurolite mica schists (Peio Unit)
			OOG	Orthogneiss (Peio Unit)
			TPN	Metapegmatites (Tonale Unit)
			TTM	Marbles (Tonale Unit)
		Vegetation cover[c]	1	0 %–10 % covered by vegetation
			2	10 %–50 % covered by vegetation
			3	50 %–90 % covered by vegetation
			4	90 %–100 % covered by vegetation
		Permafrost evidence[a,c,h]	weqt	Winter equilibrium temperature measured by temperature data loggers
			Geophys	Geophysical investigations (this work)
			Snow	Perennial snowfields
			Movement	Surface displacement visible in multi-temporal DEMs
			None	No evidence available
		APIM[d]	Blue	Permafrost under nearly all conditions
			Purple	Permafrost mostly under cold conditions
			Yellow	Permafrost only under very favourable conditions
			White	No permafrost
		Open-work deposit[e,g]	Open work	Present
			No open work	Absent (includes boulder deposits with fine infill and/or widespread vegetation cover)
Rock glacier	Quantitative	Front slope (degrees)[a]	–	
	Qualitative	Activity[f,g]	Active/transitional	Active/transitional rock glacier
			Relict	Relict rock glacier
		Length[a]	Short	Short rock glacier length class (as defined in Sect. 3)
			Mid	Mean rock glacier length class (as defined in Sect. 3)
			Long	Long rock glacier length class (as defined in Sect. 3)
		Elevation[a]	Low	Low rock glacier elevation class (as defined in Sect. 3)
			Mid	Mean rock glacier elevation class (as defined in Sect. 3)
			High	High rock glacier elevation class (as defined in Sect. 3)
		Vegetation cover[c]	Vegetation	Vegetated rock glacier (as defined in Sect. 3 and Table 1)
			No vegetation	Non-vegetated rock glacier (as defined in Sect. 3 and Table 1)
		Front characteristics[g]	I	No vegetation, evidence of recent instability, outcrop of fine material, little or no surface weathering, weathering degree lower than the surface of the rock glacier
			II	Very little or no vegetation (< 20 %), very little or no fine material, weathering and lichen cover comparable to the surface of the rock glacier
			III	Scarce or discontinuous and cold-adapted vegetation (≤ 50 %), abundant debris, weathering similar to the surface of the rock glacier and cold air draining from voids in blocks
			IV	Completely vegetated, little outcropping debris, without voids and cold-air drainage
		Subdued topography[a,g]	*y*	The lateral and frontal ridges are clearly evident and the central part of the rock glacier is depressed with respect to them (concave contour lines).
			n	The lateral ridges are only absent or evident in the upper part of the rock glacier. From halfway down, the morphology is convex or almost flat.

[a] Derived from the 2006 and 2014 lidar DEMs of the Province of Trento (https://siat.provincia.tn.it/stem/, last access: 30 November 2024). [b] Derived from the 1 : 10 000 geological map of the Province of Trento (https://patn.maps.arcgis.com/apps/webappviewer/index.html?id=8e6cda8cc23844c9a6d3484f9bbd20f0, last access: 30 November 2024). [c] Derived from the 2014 orthophoto of the Province of Trento (https://siat.provincia.tn.it/stem/, last access: 30 November 2024). [d] Derived from the Boeckli et al. (2012) Alpine Permafrost Index Map. [e] Derived from the hill-shaded 2014 lidar DEM of the Province of Trento (https://siat.provincia.tn.it/stem/, last access: 30 November 2024). [f] Derived from the Seppi et al. (2012) rock glacier inventory. [g] Derived from field observations. [h] Ground surface temperature data reported in Carturan et al. (2016) and references therein.

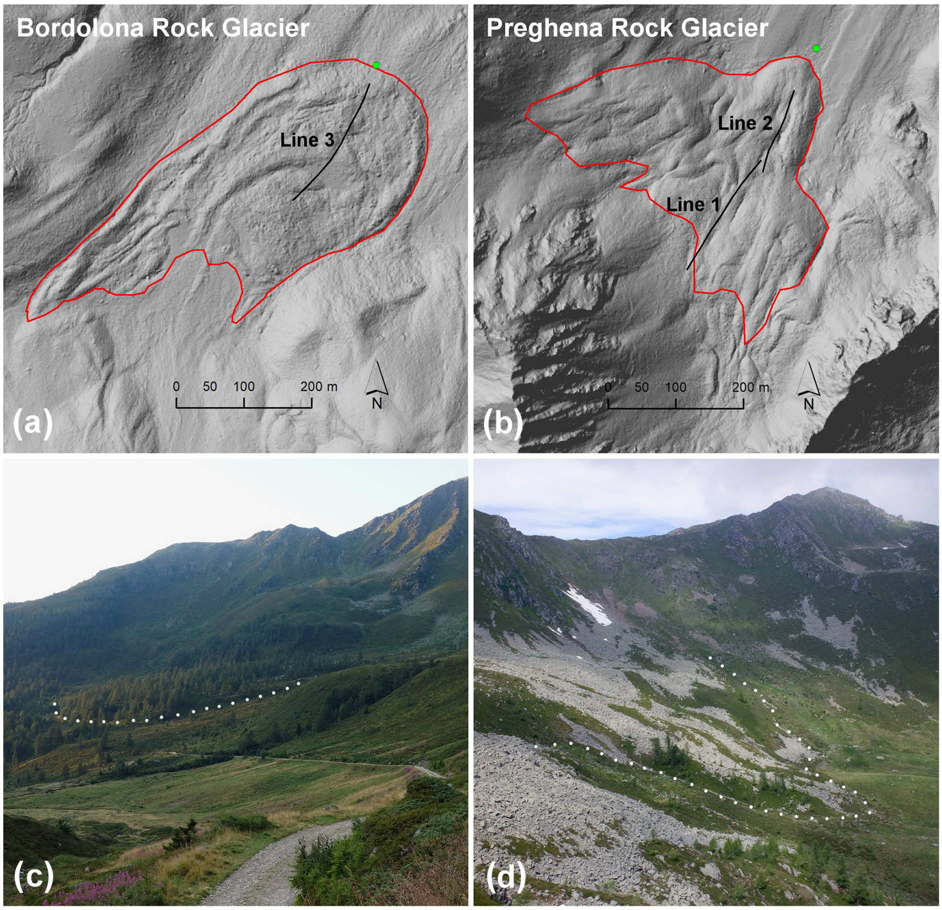

Figure 3. Locations of ERT lines (black solid lines) performed on the **(a)** Bordolona and **(b)** Preghena rock glaciers in July 2022. The green dots in panels **(a)** and **(b)** indicate the sampled springs. The white dots in panels **(c)** and **(d)** indicate the lower edges of the Bordolona and Preghena rock glaciers.

area by Farinotti et al. (2019). We first calculated the bedrock topography by subtracting the ice thickness from the glacier surface DEM (Farinotti et al., 2019). Then, we calculated the 2022 glacier thickness by subtracting the bedrock topography from a glacier surface DEM surveyed in September 2022 by the Province of Trento. We finally obtained the glacier volumes by multiplying the average thickness by the glacier area and converted the ice volume into the water volume equivalent using a mean ice density of 900 kg m^{-3}.

For the rock glaciers, we calculated the total rock glacier volume by multiplying their area A by the average thickness provided by the Brenning (2005b) formulation:

$$T = cA^{\gamma}, \qquad (1)$$

where T is the average thickness of the rock glaciers and c and γ are constants equal to 50 and 0.2, respectively. To account for the different geometries of active/transitional and relict rock glaciers, we assumed that the volumetric ice content of active/transitional rock glaciers averages 50 % (Jones et al., 2018, and references therein) and therefore that the T_{r} for (true) relict rock glaciers is half that of active/transitional rock glaciers (i.e. they are only composed of debris and all the ice melted away). For pseudo-relict rock glaciers, we tested various hypotheses of percentage ice content, ranging between 5 % and 20 %, by calculating the average thickness T_{pr} as follows:

$$T_{\mathrm{pr}} = T_{\mathrm{r}} + T_{\mathrm{ice}}, \qquad (2)$$

where T_{ice} is the average ice thickness, calculated as a function of the volumetric percentage ice content $\%_{\mathrm{ice}}$ as

$$T_{\mathrm{ice}} = \frac{\%_{\mathrm{ice}} \cdot T_{\mathrm{r}}}{(1 - \%_{\mathrm{ice}})}. \qquad (3)$$

4 Results

4.1 Spatial variability of spring-water temperature

The water temperature of the 131 springs ranged between 0.0 and 8.5 °C, with a mean of 3.6 °C and a median of

3.4 °C (Table 4). The frequency distribution of the spring elevation (i.e. the minimum elevation of the catchments) is symmetrical and normally distributed around a sample mean of 2384 m a.s.l. The lowermost spring was sampled at 1698 m a.s.l. and the uppermost spring was sampled at 3039 m a.s.l.

The mean elevation of the spring catchments varies between 2104 and 3151 m a.s.l., whereas the maximum elevation varies between 2241 and 3352 m a.s.l. The mean and maximum elevations average 2539 and 2694 m a.s.l., respectively. Both are also symmetrical around the sample mean and are normally distributed.

The planimetric length of the spring catchments varies between 83 and 2621 m, with a mean of 610 m. The skewness and kurtosis indicate that the planimetric length is right-skewed and leptokurtic.

Spring-water temperature is significantly correlated with the mean elevation of the catchments (Fig. 4a) for all three aspect classes defined in Table 3. Linear regressions are significant ($p < 0.001$) for the south- ($R^2 = 0.30$) and east–west-facing catchments ($R^2 = 0.35$). For the north-facing catchments, there is a low significant relation ($R^2 = 0.25$, $p < 0.05$) between water temperature and elevation. In all three cases, the low R^2 suggests that other factors could affect water temperature as well. Similar results were obtained using spring elevation rather than mean catchment elevation (Fig. 5).

As expected, there is a negative relationship between water temperature and elevation (Figs. 4a and 5) but also a large overlap of water temperature among the three aspect classes. NW–NE-facing catchments have significantly colder springs compared to SE–SW-facing catchments ($p < 0.05$; Dunn's multi-comparison test applied after the Kruskal–Wallis test), whereas catchments facing NE–SE and SW–NW have water temperatures that do not differ significantly from the other two classes (Fig. 4b). NW–NE-facing catchments show a lower variability in spring-water temperature compared to the other two classes.

Figure 4c and d highlight that springs with upslope areas dominated by the presence of rock glaciers (irrespective of their activity) and bedrock outcrops are significantly colder than other springs ($p < 0.05$, Dunn's multi-comparison test applied after the Kruskal–Wallis test).

4.2 Temperature of springs downslope of rock glaciers

4.2.1 Comparison between active/transitional and relict rock glaciers

The spring-water temperature is significantly different for rock glaciers with different degrees of activity (Fig. 6a). Relict rock glaciers have a much warmer spring temperature compared to active/transitional rock glaciers (Student's t test, $p < 0.001$) and the variability of the water temperature is larger for relict rock glaciers. There is a substantial overlap between the two groups which extends between 1.2 and 3.0 °C. This range of water temperature represents 54 % of all springs downslope of rock glaciers (53 % of active/-transitional rock glaciers and 54 % of relict rock glaciers). Almost half of rock glaciers classified as relict have spring-water temperatures similar to those of rock glaciers classified as active/transitional.

The two groups of rock glaciers have significantly different minimum elevations (Fig. 6b; Student's t test, $p < 0.001$), but there is a wide elevation band between 2406 and 2630 m a.s.l., where they overlap.

4.2.2 Spring-water temperature of relict rock glaciers

The relationship between water temperature and the mean catchment elevation is rather weak for springs fed by relict rock glaciers (Fig. 7a). The linear regression is only significant ($p < 0.05$) for the catchments facing NE–SE and SW–NW, but the relation is weak ($R^2 = 0.20$). At the same elevation, catchments facing NW–NE have colder springs compared to the other two aspect classes. The spring-water temperature of the catchments facing north is similar to those of the catchments facing east, south and west located 300–400 m above.

Relict rock glacier springs with open-work deposits in their upslope areas are colder than springs without open-work deposits (Fig. 7b). For the first group, the water temperature is not related to the mean catchment elevation, whereas for the second group there is a weak but significant relationship ($p < 0.05$, $R^2 = 0.15$). Consequently, the difference in water temperature between the two groups increases towards low elevations, which suggests that open-work deposits may have a cooling effect that is particularly marked at elevations < 2500 m a.s.l.

Similar considerations can be had for rock glacier front characteristics (Fig. 7c) and for rock glacier vegetation cover (Fig. 7d). Relict rock glaciers with scarce and cold-adapted vegetation cover have colder springs compared to relict rock glaciers with abundant vegetation cover on their bodies and fronts. However, for all classes of rock glacier front characteristics and vegetation cover (Table 3), there is no significant relation between water temperature and mean catchment elevation.

Despite the large overlap between the analysed classes (Fig. 7), we found significant effects of vegetation cover (Student's t test, $p < 0.001$), open-work deposits (Student's t test, $p < 0.001$) and front characteristics (Student's t test applied to classes III and IV, $p < 0.01$) on the water temperature of springs downslope of relict rock glaciers. We did not detect any significant influence of the mean aspect of the catchment, the mean elevation of rock glaciers, their length and the presence or absence of a subdued topography on water temperature.

Table 4. Descriptive statistics for spring-water temperature measurements and quantitative variables relative to the spring catchments (as defined in Table 3).

$N = 131$	Median temperature (T_{Mdn})	Catchment minimum elevation (m)	Catchment maximum elevation (m)	Catchment mean elevation (m)	Catchment planimetric length (m)
Minimum	0.0	1698	2241	2104	83
Median	3.4	2367	2641	2495	539
Maximum	8.5	3039	3352	3151	2621
Range	8.5	1341	1111	1047	2538
Mean	3.6	2384	2694	2539	610
Standard error of the mean	0.2	22.6	21.9	21.0	34.9
Standard deviation	1.8	259.2	251.1	240.8	399.3
Coefficient of variation	0.500	0.109	0.093	0.095	0.655
Skewness	0.392	0.179	0.446	0.419	2.070
Kurtosis	−0.261	−0.328	−0.107	−0.391	6.095

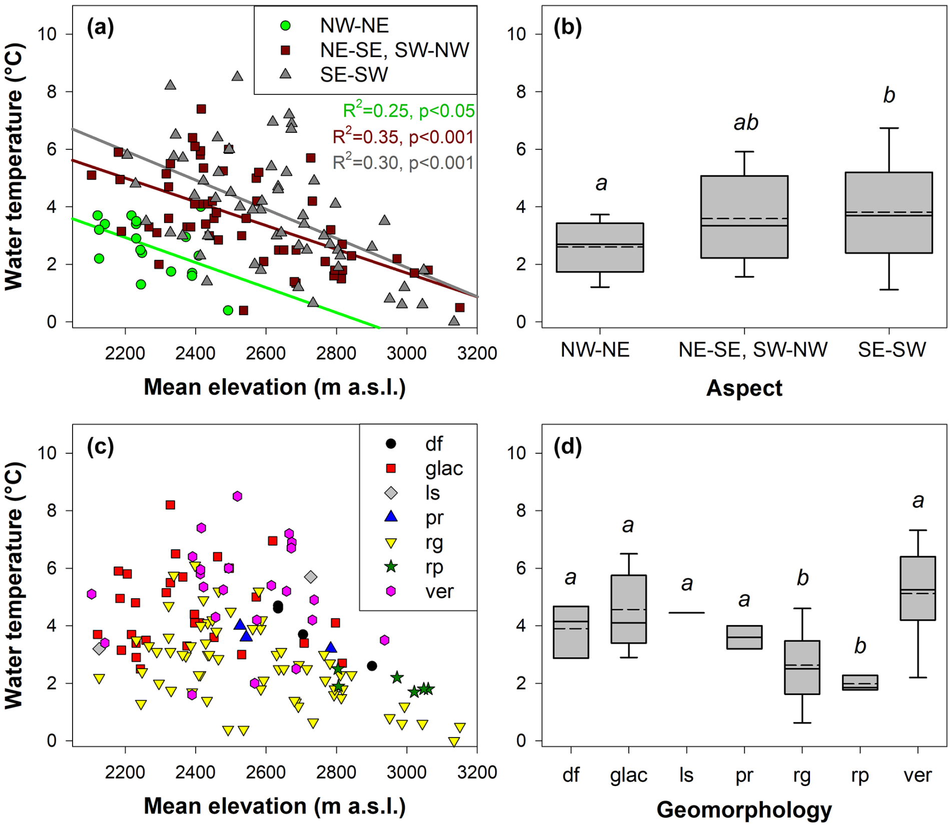

Figure 4. Relationship between spring-water temperature and **(a)** mean catchment elevation (clustered into three classes of the mean catchment aspect), **(b)** mean catchment aspect, **(c)** mean catchment elevation (clustered into seven classes of the upslope area geomorphology) and **(d)** upslope area geomorphology. The abbreviations and their meanings are given in Table 3. The boxes in panels **(b)** and **(d)** indicate the 25th and 75th percentiles, the whiskers indicate the 10th and 90th percentiles and the horizontal solid and dashed lines within the box mark the median and mean, respectively. Different letters above the boxplots indicate groups with significantly different ($p < 0.05$) water temperatures based on Dunn's multi-comparison test (applied after the Kruskal–Wallis test).

4.3 Geophysical investigations

Figure 8a and b show the inverted resistivity sections obtained for the investigation of Lines 1 and 2 acquired on the Preghena Rock Glacier. High values of resistivity ($> 8 \times 10^4$ Ωm) were found in the uppermost layer down to depths of about 7–8 m, which was associated with the dry conditions in the ERT soundings and with the air-filled voids in coarse debris and blocks typical of rock glacier environments. Below this uppermost layer, the resistivity values rapidly decrease ($< 10^4$ Ωm), indicating a plausible decrease in poros-

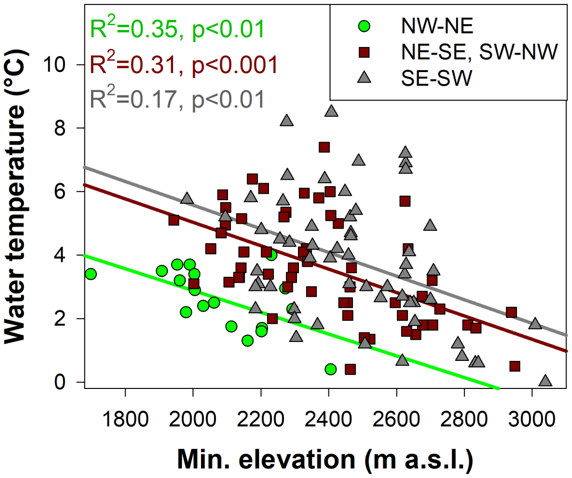

Figure 5. Relationship between spring-water temperature and minimum (spring) elevation, clustered into three classes of mean catchment aspect as in Fig. 4a.

ity and grain size in the deposit and a possible increase in water content. This low-resistivity layer develops almost continuously down to the bottom of the models. An increase in resistivity is found at the lower end of Line 1 and at the upper end of Line 2 in the area where they overlap and at a depth of about 12–13 m, reaching $1.5–2.0 \times 10^5$ Ωm. This area of increased resistivity can be interpreted as a deep frozen body, providing evidence of probable permafrost inside this rock glacier.

Figure 8c shows the inverted resistivity section obtained for investigation Line 3 acquired on the Bordolona Rock Glacier. In the shallowest layers the resistivity is between 5×10^3 and 10^4 Ωm, which is significantly lower than the shallow layer of the Preghena Rock Glacier, even if air-filled voids are common on this rock glacier as well.

Below this layer, a sharp increase in resistivity is detected along the entire investigation line, with regions frequently exceeding 2×10^4 Ωm. The highest resistivity (about 6×10^4 Ωm) is found towards the upper end of the ERT line, where a younger rock glacier lobe overlies the main body. This high-resistivity layer reaches a depth of about 15 m and can be interpreted as a frozen layer. The bottom of the high-resistivity layer, which seems discontinuous in the lower part of the ERT line and more continuous and thicker in the upper part, is highlighted by a strong decrease in resistivity below 5×10^3 Ωm. This lowermost layer is probably unfrozen and is characterized by an increase in water content and fine sediments.

4.4 Ice storage in the rock glaciers and glaciers

A total glacier ice volume of 251×10^6 m^3 and a corresponding 226×10^6 m^3 water volume equivalent were calculated for the Val di Sole in 2022. For comparison, the water volume equivalent of active/transitional rock glaciers is 42.7×10^6 m^3.

A water volume equivalent between 4.4 and 20.9×10^6 m^3, averaging 12.7×10^6 m^3, can be estimated assuming that 50 % of the total area of relict rock glaciers contains permafrost (rounded value, based on the results reported in Sect. 4.2.1) and that the average ice content ranges between 5 % and 20 % in volume.

5 Discussion

5.1 Permafrost distribution and spring-water temperature in the study area

Measurements of spring-water temperature collected in this study outside the rock glacier influence have a high spatial variability and do not show a significant relationship with elevation ($p > 0.05$). Among the springs outside the rock glacier influence, only those above 2800 m a.s.l. have a water temperature ≤ 2.2 °C, which is the upper limit reported in the literature for possible permafrost (Carturan et al., 2016).

This result lines up well with mean annual air temperature (MAAT) indications. Indeed, based on the MAAT of −0.9 °C measured between 1961 and 2010 at the Careser Diga weather station (2605 m a.s.l., in the northern part of the Val di Sole), the theoretical lower limit of discontinuous permafrost in the Val di Sole, corresponding to a MAAT of −2 °C (Haeberli, 1985), should be between 2700 and 2800 m a.s.l.

Similarly, the Alpine Permafrost Index Map (APIM; Boeckli et al., 2012) indicates a lower limit of "permafrost mostly in cold conditions" ranging between 2500 and 2900 m outside rock glaciers and coarse-block deposits, varying depending on the terrain aspect and averaging 2700 m a.s.l. Based on the mean elevation of active/transitional rock glaciers in the study area, Seppi et al. (2012) calculated a present-day lower limit of permafrost at 2720 m a.s.l.

As expected, springs draining north-facing catchments are significantly colder compared to springs draining south-facing catchments. On average, there is a difference of about 3 °C between springs draining catchments at similar elevation and with opposite aspect. On average, the same spring temperature is found 500–600 m higher in south-facing catchments than in north-facing ones (Fig. 5). This result quantifies the influence of terrain exposure on the ground temperature regime and permafrost distribution in the study area, which are direct consequences of shortwave radiation inputs and related effects on snow cover and surface albedo (Boeckli et al., 2012; Wagner et al., 2019; Amschwand et al., 2024).

In our study, at all the elevations, springs draining rock glaciers are coldest, irrespective of the rock glacier activity state (Fig. 4c). This is in agreement with the findings of studies in the European Alps and in other mountain chains re-

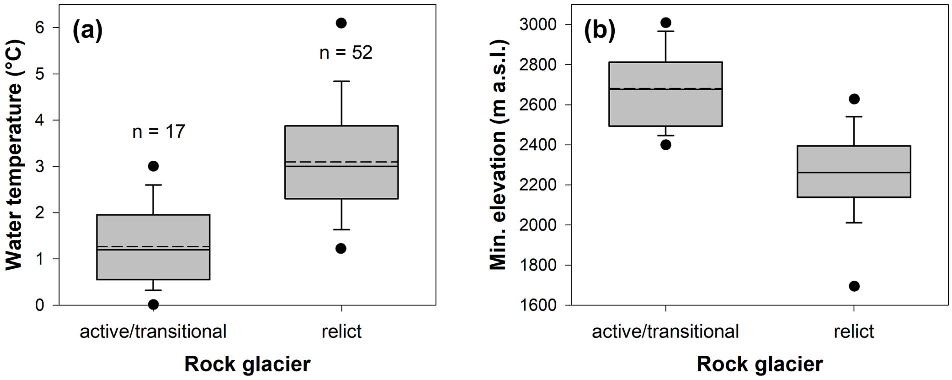

Figure 6. Spring-water temperature **(a)** and minimum elevation **(b)** of the rock glaciers sampled in the study area. The boxes indicate the 25th and 75th percentiles, the whiskers indicate the 10th and 90th percentiles and the horizontal solid and dashed lines within the box mark the median and mean, respectively. The maximum and minimum values are represented by the dots. The sample size (n) is reported in panel **(a)**).

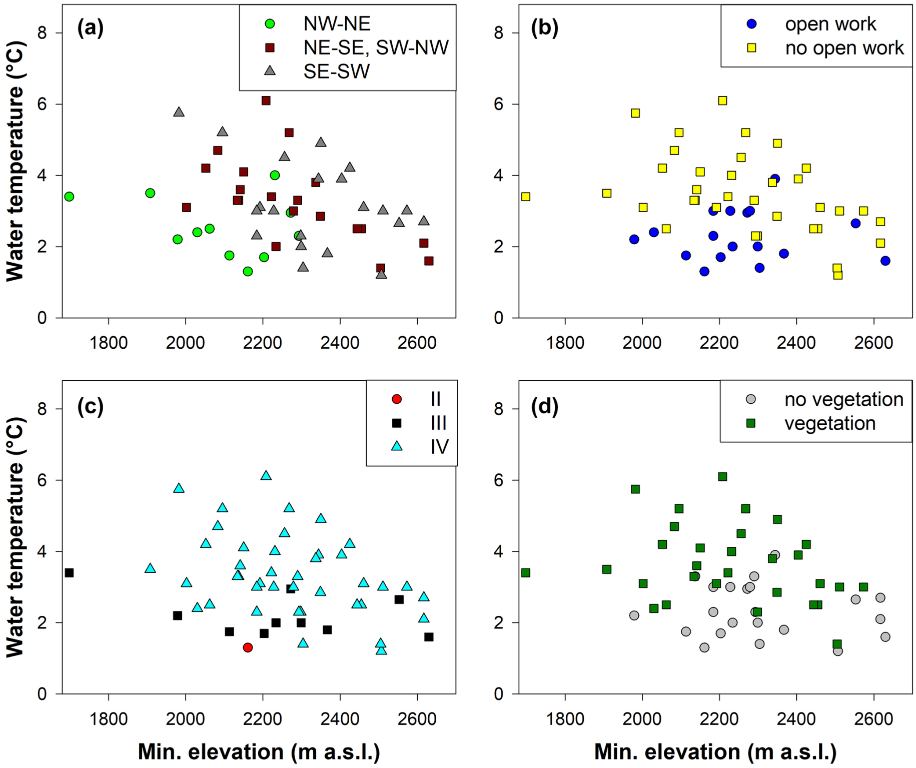

Figure 7. Relationship between the spring-water temperatures of relict rock glaciers and mean catchment elevation clustered into **(a)** three classes of mean catchment aspect, **(b)** two classes of open-work deposits in the spring upslope area, **(c)** three classes of rock glacier front characteristics and **(d)** two classes of rock glacier vegetation cover. The classes are described in Table 3.

porting rock glacier spring-water temperatures, regardless of their activity state. For example, in the Canadian Rockies, spring-water temperature from an inactive rock glacier containing small portions of permafrost reached a maximum of 2.2 °C, exercising a substantial cooling effect on the creek downstream (Harrington et al., 2018). Interestingly, cold conditions and high daily variability in spring-water temperature in summertime have been recorded in a rock glacier in Norway that shows characteristics favourable to the presence of permafrost but with minor ice bodies (Lilleøren et al., 2022). In the Austrian Alps, spring water from a relict rock glacier was monitored for 6 years, showing a mean temperature of 2.2 °C, with low seasonal variation (between 1.9 and 2.5 °C) and a decrease in the water temperature after precipitation

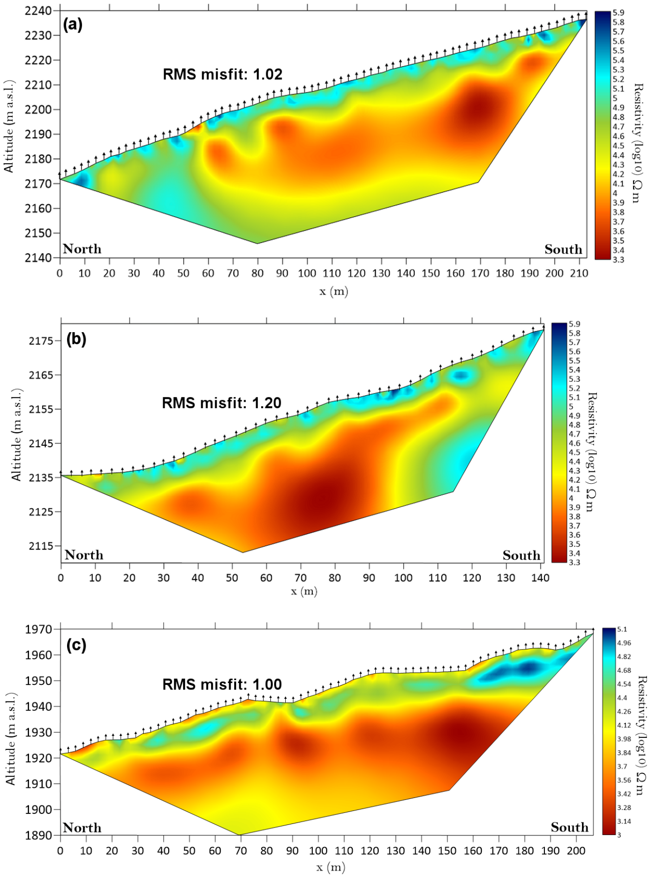

Figure 8. Inverted resistivity section of investigation Lines 1 **(a)** and 2 **(b)** on the Preghena Rock Glacier and investigation Line 3 **(c)** on the Bordolona Rock Glacier.

events attributed to the potential presence of ice lenses in the lower part of the rock glacier (Winkler et al., 2016).

Our results align well with those of studies reconstructing permafrost distributions by empirical modelling in the Alps and at other mountainous locations worldwide. A logistical regression model used in the Dry Andes of Argentina accounting for mean annual air temperature, terrain ruggedness and potential incoming solar radiation suggests that permafrost may occur in several types of coarse blocky deposits, including rock glaciers, even under unfavourable climatic conditions (Tapia-Baldis and Trombotto-Liaudat, 2020). A similar empirical–statistical model applied in the Austrian Alps shows that permafrost can be expected above 2500 m a.s.l. on northerly exposed slopes and above 3000 m a.s.l. on southerly exposed slopes (Schrott et al., 2012), providing an elevation difference of about 500 m between southern and northern exposures, which agrees well with our spring-water temperature results.

5.2 Rock glacier classification based on spring-water temperature

Although springs draining active/transitional rock glaciers are significantly colder than springs draining relict rock glaciers, there is a remarkable ∼ 50 % overlap in the water temperature range of the two rock glacier groups (Fig. 6a). Based on published thresholds (Haeberli, 1975; Frauenfelder et al., 1998; Scapozza, 2009; Carturan et al., 2016), 12 out of the 52 relict rock glaciers sampled in the Val di Sole (23 %) can be included in the possible permafrost category (water temperature between 1 ± 0.2 and 2 ± 0.2 °C) and none of them in the "probable permafrost" category (water temperature $< 1 \pm 0.2$ °C). However, the relatively warm water temperatures measured downstream of active/transitional rock glaciers (maximum = 3 °C, 90th percentile = 2.4 °C) and downstream of areas with permafrost evidence (maximum = 3.5 °C, 90th percentile = 2.2 °C) suggest that the upper limit of spring-water temperature for possible permafrost may be higher. Here, the 90th percentile accounts for possible misclassification of active/transitional rock glaciers and other issues affecting spring-water temperature measurements (Sect. 5.3).

Assuming a (rounded) upper limit of 2.5 °C for spring-water temperature with possible permafrost influence leads us to include 19 (38 %) relict rock glaciers in the possible permafrost category. This estimate looks more conservative than the ∼ 50 % obtained by a mere comparison of water temperature ranges of active/transitional and relict rock glaciers (Fig. 6a). These findings might suggest that permafrost in rock glaciers classified as relict is widespread in the Val di Sole and that a large fraction actually are pseudo-relict or transitional landforms containing patches of permafrost and reaching an elevation below the tree line (2000–2200 m a.s.l.). Compared to the rock glacier classification of Seppi et al. (2012), which was based on remote-sensing geomorphometric evidence combined with field observations (topographic surveys and ground surface temperature measurements for a few rock glaciers), spring-water temperature suggests the need for a reclassification as pseudo-relict of a large fraction of rock glaciers that were categorized as relict.

Examples of spring-water temperature downstream of rock glaciers in the Val di Sole are shown in Fig. 9. Cold springs draining rock glaciers classified as relict are associated with the presence of open-work deposits and scarce vegetation cover (Figs. 7 and 9). These two explanatory variables are often correlated, because vegetation tends to be scarce over coarse deposits without fine infill among blocks and vice versa. The relationship between cold spring temperature (as permafrost evidence) and these two surface characteristics was expected in our case study based on the existing literature (e.g. Guglielmin, 1997, and references therein). This relationship is only statistically significant for rock glaciers classified as relict, whereas for the active/transitional rock glaciers sampled in the study area it does not exist (Fig. A1).

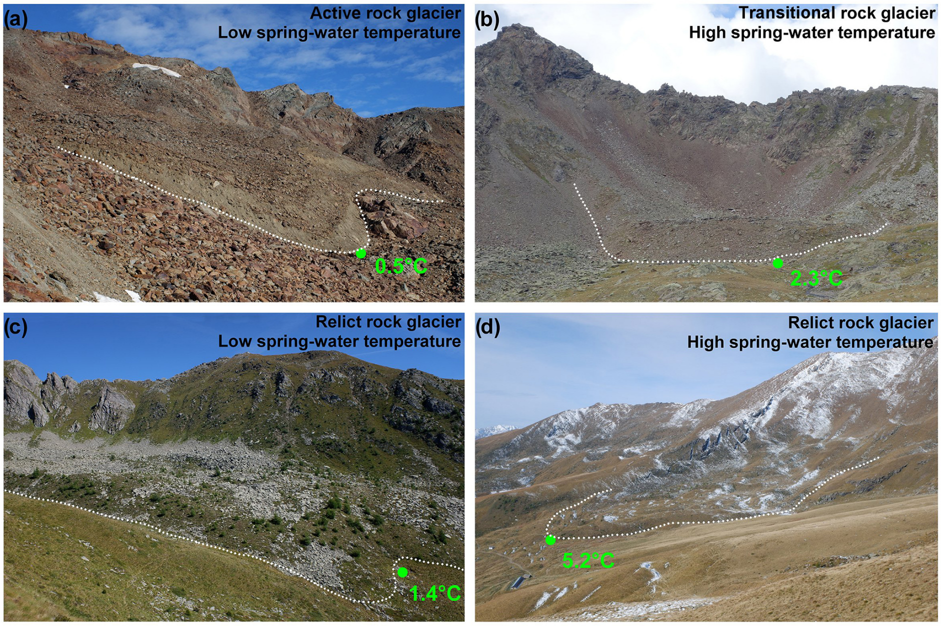

Figure 9. Examples of spring-water temperature downstream of rock glaciers in the Val di Sole: **(a)** active rock glacier with a cold spring at 2950 m a.s.l., **(b)** transitional rock glacier with a relatively warm spring at 2727 m a.s.l., **(c)** relict rock glacier with a cold spring at 2304 m a.s.l. whose surface is open-work and has scarce vegetation cover and **(d)** relict rock glacier with a warm spring at 2266 m a.s.l. whose surface is entirely covered by vegetation.

The long-term preservation of permafrost within open-work blocky deposits results from overcooling and thermal decoupling of the frozen core from the external climate (Harris and Pedersen, 1998; Morard et al., 2008; Jones et al., 2019). The low thermal conductivity in coarse open-work deposits brings lower ground temperatures compared to fine-grain material (Juliussen and Humlum, 2008; Jones et al., 2019). Soil development over surficial blocks and boulders can prevent these cooling effects (Ikeda and Matsuoka, 2002). However, if fine-grain infilling does not occur, the ground cooling effect is undisturbed. In central Europe, these processes enable the existence of permafrost far below its regional limit and reach elevations lower than 1000 m a.s.l. (Gude et al., 2003; Delaloye et al., 2003). According to Delaloye and Lambiel (2005), 1000-year-old permafrost might potentially be preserved in these types of deposits.

Open-work deposits and/or scarce vegetation cover can potentially be employed to distinguish between rock glaciers with or without permafrost, as both can be mapped based on remote-sensing imagery. However, open-work deposits and vegetation cover do not enable full distinction between "cold" and "warm" springs affected by relict rock glaciers (Fig. 7b, c and d). Individual non-open-work rock glaciers widely covered by vegetation can have spring-water temperatures as low as 1.4° and rock glaciers almost free of vegetation with blocky surfaces can have spring-water temperatures of up to 3.9 °C.

Other variables considered in this study, such as aspect, elevation, size and the presence or absence of a subdued topography in rock glaciers (Delaloye et al., 2003; Delaloye, 2004), are not related to spring-water temperature. Figure 7 suggests the existence of a group of cold springs at low elevations in north-facing catchments, even though water temperature is not significantly different from the temperatures of springs in the other two aspect classes. This result might be due to the small sample size of the NW–NE aspect class.

5.3 Limitations and uncertainties in the spring-water temperature approach

The results of this study might be affected by limitations in the experimental design, assumptions and uncertainties. First, the main assumption of this study is that spring-water temperature provides an indication of permafrost occurrence at investigated rock glaciers and spring upslope areas and can be used as a stand-alone pilot method to rapidly explore the activity states of rock glaciers in a wide area. This approach applies spring-water temperature to the catchment scale, beyond its general use as an ancillary method in other techniques such as InSAR analyses, ground surface temperature measurements and/or geophysics.

We base our assumption on previously published work and well-known temperature thresholds for permafrost probability categories (e.g. Haeberli, 1975; Frauenfelder et al., 1998; Scapozza, 2009) and on our first successful application at the catchment scale (Carturan et al., 2016). Data collected in the

Val di Sole are in line with the literature thresholds, provided that the 10 % highest spring-water temperature values are excluded (Sect. 5.2). Including these extreme values leads to about 1.5 °C higher temperature thresholds for possible permafrost compared to the literature.

The reason for this discrepancy is the uncertainty in the classification of rock glacier activity, which was based on vegetation and geomorphological characteristics and mainly assessed from remote-sensing images (Seppi et al., 2012). In the wide elevation band where active/transitional and relict rock glaciers co-exist (minimum elevation between 2406 and 2630 m), landforms with similar vegetation cover and surface geomorphology have been classified based on the authors' experience and judgement, implying a certain degree of subjectivity.

The distinction between active/transitional and relict rock glaciers is a theoretical concept, and there is a continuum between transitional and (true) relict rock glaciers (Kääb, 2013). In the absence of other evidence, this continuum hampers unambiguous distinction between transitional and relict landforms, in particular if they have similar surface characteristics. In addition, the mentioned transition is a dynamic concept, which depends on the characteristics of individual landforms, their topo-climatic setting and their response to climatic variations (Kääb, 2013).

Another source of uncertainty is related to the distance between the permafrost body and the measured springs. Water temperature is a non-conservative tracer, and if the main permafrost body is distant (e.g. more than 100 m) from the rock glacier front or if permafrost is patchy and not in contact with groundwater paths, water temperature can largely be influenced by unfrozen sediments and/or mixing with other water sources (e.g. Kellerer-Pirklbauer et al., 2017). This is the case for the Bordolona Rock Glacier (Fig. 8c), where the rather warm spring-water temperature (3.5–3.7 °C) would have led to the occurrence of permafrost being excluded in the absence of geophysical evidence.

For shorter distances, we checked the impact of spring locations downstream of rock glacier fronts at three measurement sites, where the same stream emerged briefly at the rock glacier front and a few tens of metres downstream. Measurements confirmed that there was negligible warming (from 0.0 to 0.1 °C) of the water downstream of the rock glacier front, at least as long as the water remained below the surface.

Seasonal ice that formed in the topmost ground layer during winter and spring, in areas without permafrost, might cool down spring-water temperature, leading to false positives in permafrost detection. We think that taking measurements in late summer, as proposed by the literature (e.g. Haeberli, 1975), prevents this seasonal ice from affecting spring-water temperature measurements or at least strongly minimizes its effect. The possible influence of seasonal ground ice formation should be largest after cool or short summer seasons, but this was not the case in the study period.

Depending on the measurement time, which was between 08:00 and 18:00 CET, any variation of temperature during the day might also influence the results. Hourly records of spring-water temperature collected by Seppi (2006) lead us to exclude significant variation of spring-water temperature during the day, at least for springs with runoff higher than $0.1\,\mathrm{L\,s^{-1}}$.

Several authors are cautious when discussing cold springs downslope of relict rock glaciers. For example, Winkler et al. (2016) did not exclude the presence of remaining ice lenses inside the relict Schöneben Rock Glacier (Niedere Tauern Range, Austria) as a possible explanation for the rapid cooling of the spring water after recharge events during summertime. However, the authors mention the cold thermal regime beneath coarse blocky materials as a possible explanation, which does not necessarily imply permafrost occurrence, and conclude that additional research is required for the identification of the cooling source.

We agree that additional research is required to confirm inference from spring-water temperature. With this study we add that spring-water temperature can be as high as 1.8 °C for rock glaciers where permafrost occurrence is confirmed by geophysics or ground surface temperature measurements, and it can exceed 3.5 °C where the permafrost body is far from the rock glacier front and spring, such as at the Bordolona Rock Glacier. Even if the collected data seem to suggest that the temperature thresholds might be slightly higher than those reported in the literature, further investigations are necessary to better constrain them and define their range of uncertainty. Based on the evidence discussed in this section, a warm bias might prevail over a possible cold bias in our spring-water data, leading to false negatives in permafrost detection. For this reason, the frequency of pseudo-relict rock glaciers reported in Sect. 5.2 can be considered rather conservative.

A last source of uncertainty is represented by the sampling design adopted for the Val di Sole, with its particular topographic and geological characteristics. The dominant southward aspect of the investigated rock glaciers and their spatial clustering can explain the lack of correlation between water temperature and the aspect of rock glaciers. We tried to minimize the spatial clustering of measured springs, visiting as many headwater catchments as possible and taking measurements at the largest number of springs in each catchment. However, due to logistical constraints and the inherent characteristics of the study area, a certain degree of spatial clustering was unavoidable. For this reason, the role of terrain aspect as a possible controlling factor on spring-water temperature requires additional investigation.

5.4 Geophysics

The inverted resistivity sections obtained for the Preghena Rock Glacier (Fig. 8a and b) show results compatible with the presence of permafrost patches. Even considering the high contact resistance due to the dry weather conditions preceding the survey and the location of the high-resistivity body in the areas known to be the least sensitive of the model (the bed and margins; Binley, 2015), we observe that the obtained resistivity values are typical of frozen materials (Hauck and Kneisel, 2008). The high-resistivity area is highlighted by both ERT lines in the overlapping area ($x < 70$ m in Line 1 and $x > 100$ m in Line 2; Fig. 8). The data error of 20 % applied in the inversion process was defined using the reciprocal analysis, which minimized possible inversion artifacts compared to the more commonly used stacking error (Binley, 2015). This result agrees with the low temperature of the Preghena Rock Glacier spring, which fluctuates between 1.6 and 1.8 °C throughout summer, and it suggests that this rock glacier should be classified as a pseudo-relict rock glacier.

In the Bordolona Rock Glacier (Fig. 8c), the frozen layer looks discontinuous in the lower section of the ERT line and more continuous and thicker in the upper section, where a younger lobe superposes the main body of the rock glacier. The different resistivities detected in the lower and upper sections of the ERT line could be related to a different percentage of the ice content in the frozen layers and/or a different temperature of the ice (Hilbich et al., 2008). These results suggest the probable presence of permafrost inside the Bordolona Rock Glacier, which was considered a “true” relict rock glacier due to its abundant vegetation cover, spring-water temperature above 3 °C and low mean elevation. Based on geophysical investigations, the Bordolona Rock Glacier should also be classified as a pseudo-relict rock glacier.

The acquired data were of a lower quality at the Preghena Rock Glacier due to the high contact resistance. More conclusive results should be obtained by repeating the geophysical surveys under wetter conditions, especially at the Preghena Rock Glacier, and possibly coupling ERT to seismic refraction measurements in order to obtain a reliable estimate of the percentage ice content inside these rock glaciers (Hauck et al., 2008, 2011; Wagner et al., 2019; Pavoni et al., 2023).

5.5 Ice storage in the rock glaciers and glaciers of the Val di Sole

Calculations of the ice contained in the pseudo-relict rock glaciers of the study area assumed that 50 % of the total area of relict rock glaciers contains permafrost (Sect. 4.2.1) and that the average ice content ranges between 5 % and 20 % in volume. This range is a first hypothesis based on the few geophysical data available at pseudo-relict rock glaciers (Delaloye, 2004; Colucci et al., 2019; Pavoni et al., 2023; this work). To our knowledge, the amount of ice in pseudo-relict rock glaciers has yet to be quantified.

Even if preliminary and affected by significant uncertainty, these estimates provide an order of magnitude of water stored as ice in the rock glaciers of the Val di Sole. The water equivalent ratio for rock glacier ice versus glacier ice averages 1 : 4.1 and ranges between 1 : 3.6 and 1 : 4.8, considering the minimum and maximum estimates reported above. Importantly, based on these calculations, 23 % of the total rock glacier water volume would be stored inside pseudo-relict rock glaciers. Even assuming a lower bound of the percentage ice content (5 %), pseudo-relict rock glaciers would contribute a significant 9 % of the total rock glacier water volume.

Based on the more conservative estimate reported in Sect. 5.2 for the frequency of pseudo-relict rock glaciers (38 % instead of 50 % of the total area covered by rock glaciers classified as relict), the water equivalent ratio for rock glacier ice versus glacier ice would average 1 : 4.3 and would range between 1 : 3.9 and 1 : 4.9, with 18 % of the total rock glacier water volume stored inside pseudo-relict rock glaciers. Even if a little smaller, these numbers do not change the meaning of the results significantly.

The obtained water equivalent ratio of rock glacier ice to glacier ice (between 1 : 4 and 1 : 5) is in the highest range of the values reported in the literature for mountainous regions where both glaciers and rock glaciers exist. Other studies in the European Alps (e.g. Barsch, 1977; Wagner et al., 2021) found ratios varying between 1 : 01 and 1 : 83, depending on the catchment glacierization. A much larger range was reported for the Andes of between 1 : 228 and 8.3 : 1. The largest ratios were found in arid regions of the Andes (Brenning, 2005a; Azócar and Brenning, 2010; Rangecroft et al., 2015; Janke et al., 2017). Bolch and Marchenko (2009) reported ratios between 1 : 67 and 1 : 10 for the northern Tien Shan between Kazakhstan and Kyrgyzstan.

In the Val di Sole, the ice volume of rock glaciers is already of the same order of magnitude as the ice contained in glaciers. Considering that the permafrost thaw rates are 1 or 2 orders of magnitude slower compared to the glacier ice (Hock et al., 2019; Haeberli et al., 2017) and that more than 3 % of the glacier ice volume is depleted each year in the study area (Carturan and De Blasi, 2021), the calculated ratio is expected to approach unity within 2–3 decades.

6 Concluding remarks

We have surveyed spring-water temperature in an area of 795 km^2 in the Val di Sole to understand the influence of topographic and geomorphological factors and to test whether this can be used to preliminarily differentiate between active/transitional and relict rock glaciers. Spring-water temperature measurements enabled us to characterize a large number of rock glaciers and to provide a first estimate of the frequency of pseudo-relict rock glaciers in this area. Overall, our results point to significant hydrological importance of rock glaciers classified as relict in the study area, which is expected to increase in the future due to atmospheric warming.

In general, we have found that the spatial variability of spring-water temperature is controlled by elevation, aspect and the presence of rock glaciers in the upslope area. Compared to other landforms in the upslope area, rock glaciers have colder springs, irrespective of their activity state.

The spring-water temperature of rock glaciers classified so far as relict is higher and has a larger spatial variability compared to active/transitional rock glaciers. However, there is a remarkable ∼ 50 % (38 %, excluding extremes) overlap in the spring temperature range of the two rock glacier groups. Relict rock glaciers tend to have colder springs if their surface is blocky and scarcely covered by (cold-adapted) vegetation.

The spring-water temperature data suggest that one-third of the rock glaciers classified as relict might actually be pseudo-relict, thus containing permafrost. The exact percentage cannot be derived unambiguously from spring-water temperature because (i) other evidence is required to confirm inference from water temperature, (ii) there is uncertainty in the classification of the activity state of rock glaciers, (iii) there is geophysical evidence that rock glaciers containing permafrost may have "warm" springs (up to 3.7 °C) and consequently (iv) there is uncertainty in the definition of the thresholds for differentiation among the absent, possible or probable permafrost categories. We recommend further investigations to reduce this uncertainty, e.g. performing geophysics on rock glaciers with a larger variability in surface characteristics, activity and settings and/or analysing the temporal variability of spring-water temperature.

Despite these uncertainties, our study shows that rock glacier spring-water temperature can provide a pilot approach to estimating the spatial distribution of permafrost in vast areas and an auxiliary element for the classification of rock glaciers, whose permafrost content might otherwise be underestimated. This method can be applied in other mountainous regions, with the possible exception of arid or semi-arid regions, where the presence of springs is scarce.

Geophysics applied to two rock glaciers classified as relict enabled us to detect the presence of permafrost. While the blocky Preghena Rock Glacier, whose spring temperature was < 1.8 °C throughout the summer, was expected to contain permafrost, its occurrence in the Bordolona Rock Glacier was not expected, because this is entirely covered by dense vegetation and spring temperature reached 3.7 °C in late summer.

Preliminary calculations of water resources stored as ice inside the rock glaciers of the Val di Sole reveal that they amount to ∼ 24 % of the water volume equivalent stored in glaciers, which are disappearing very quickly. Remarkably, 20 % of the total rock glacier water volume is stored inside rock glaciers classified as relict.

This study highlights the need for additional investigations and improved understanding of these periglacial landforms. In particular, the possible presence of permafrost in a large fraction of rock glaciers classified as relict poses critical questions regarding the origin, preservation, current behaviour, seasonal dynamics and future evolution of this permafrost. Thorough study of pseudo-relict rock glaciers is required to understand the evolution of active, transitional and relict landforms, which is important in view of current and projected climate change.

Appendix A

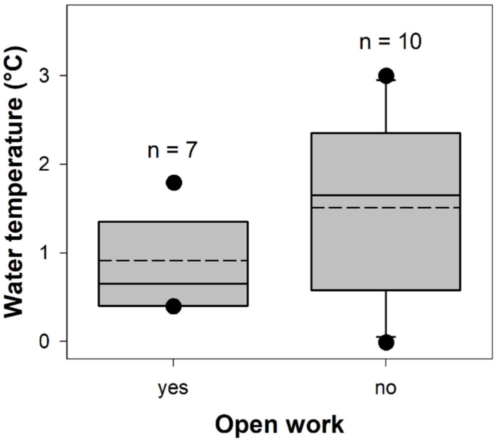

Figure A1. Spring-water temperatures for intact rock glaciers with and without open-work deposits on their surfaces. The boxes indicate the 25th and 75th percentiles, the whiskers indicate the 10th and 90th percentiles and the horizontal solid and dashed lines within the box mark the median and mean, respectively. The maximum and minimum values are represented by the dots. The sample size (n) is reported above the boxplots.

Data availability. The spring-water temperature dataset used in this work is freely available from the Research Data Unipd repository (https://doi.org/10.25430/RESEARCHDATA.CAB.UNIPD.IT.00001366; Carturan, 2024).

Author contributions. LC designed the methodological approach and carried out the sampling campaigns with the support of AA, RS, MT, TZ and GZ. MP and JB carried out the geophysical surveys in cooperation with LC, CM and MZ and interpreted the results. GZ, LC and AA performed the statistical analyses of the dataset. LC prepared the first draft of the manuscript with contributions from GZ, MP and CM. All the authors contributed to the editing of the manuscript.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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