nature portfolio

Peer Review File

100 years of monitoring in the Swiss National Park reveals overall decreasing rock glacier velocities

Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality

3rd Oct 23

Dear Mr Muñoz-Torrero Manchado,

Please allow me to appologise for the delay in sending a decision on your manuscript titled "A unique record of rock glacier kinematics and glacier interactions from the Swiss National Park spanning more than 100 years". It has now been seen by 3 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

In particular, please ensure that the revised manuscript meets the following editorial thresholds:

* Present a robust analysis of the spatiotemporal evolution of rock glaciers in the Swiss Alps, softening your statements and conclusions where necessary given the limitations of your study area.

* Conduct an assessment of the validity and accuracy of the older measurements in your time series and incorporate any associated uncertainties into your conclusions.

* Clearly differentiate results, interpretations and conclusions throughout the manuscript.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:
[link redacted]

** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Joe Aslin

Senior Editor,
Communications Earth & Environment
https://www.nature.com/commsenv/
Twitter: @CommsEarth

EDITORIAL POLICIES AND FORMATTING

We ask that you ensure your manuscript complies with our editorial policies. Please ensure that the following formatting requirements are met, and any checklist relevant to your research is completed and uploaded as a Related Manuscript file type with the revised article.

Editorial Policy: Policy requirements (Download the link to your computer as a PDF.)

Furthermore, please align your manuscript with our format requirements, which are summarized on the following checklist:
Communications Earth & Environment formatting checklist

and also in our style and formatting guide Communications Earth & Environment formatting guide .

*** DATA: Communications Earth & Environment endorses the principles of the Enabling FAIR data project (http://www.copdess.org/enabling-fair-data-project/). We ask authors to make the data that support their conclusions available in permanent, publically accessible data repositories. (Please contact the editor if you are unable to make your data available).

All Communications Earth & Environment manuscripts must include a section titled "Data Availability" at the end of the Methods section or main text (if no Methods). More information on this policy, is available at http://www.nature.com/authors/policies/data/data-availability-statements-data-citations.pdf.

In particular, the Data availability statement should include:
- Unique identifiers (such as DOIs and hyperlinks for datasets in public repositories)
- Accession codes where appropriate
- If applicable, a statement regarding data available with restrictions
- If a dataset has a Digital Object Identifier (DOI) as its unique identifier, we strongly encourage including this in the Reference list and citing the dataset in the Data Availability Statement.

DATA SOURCES: All new data associated with the paper should be placed in a persistent repository where they can be freely and enduringly accessed. We recommend submitting the data to discipline-specific, community-recognized repositories, where possible and a list of recommended repositories is provided at http://www.nature.com/sdata/policies/repositories.

If a community resource is unavailable, data can be submitted to generalist repositories such as figshare or Dryad Digital Repository. Please provide a unique identifier for the data (for example a DOI or a permanent URL) in the data availability statement, if possible. If the repository does not provide identifiers, we encourage authors to supply the search terms that will return the data. For data that have been obtained from publically available sources, please provide a URL and the specific data product name in the data availability statement. Data with a DOI should be further cited in the methods reference section.

Please refer to our data policies at http://www.nature.com/authors/policies/availability.html.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

I dont like this paper much, there are several logical gaps here and I am not sure what is 'unique' about it. Just using this word does not make it so. Abstract does not say anything about what datasets are used, over what period, what the methods are or what the results are. The abstract does not say much about this study at all. Introduction should spell out rock glacier, not RG. You need to say something about Chaix's methods, how do you know that they measured things accurately? How do their data compare to modern results? What other long kinematic records exist from other areas? This context is missing. Inference p3 para2 regarding rock glacier dating is incorrect. Likewise the inference regarding rock glacier mapping in your study area p3 para3 is also incorrect. P3 para4, you mean spatial or temporal gaps, or both? The rest of this para is very long and should be removed, you are merely describing what you do here. Specific aims are missing, please add. Fig 1 scale missing in (a), not clear where panel (b) comes from. "dense point cloud" is not clear - i can see about half a dozen dots at the top of panel (a), is that it? Methods and datasets need to be described, there is nothing here. The results section does not present RESULTS in any way, it merely conflates description and interpretation, no results are mentioned at all. I do not find this acceptable. Individual site descriptions are pretty repetitive and qualitative. Discussion is very repetitive and does not make any reference whatsoever to any evidence. The bigger picture is missing, so what? Comparison with other areas? Impacts of climate change?

Reviewer #2 (Remarks to the Author):

I read the paper by Muñoz-Torrero Manchado et al with attention and interest, and I found it valuable and worthy of attention not only for rock glacier specialists but also for those involved in climate change in high mountain environments.
The paper presents an analysis of a considerable amount of data and, although the methods used do not present major novelties per se, the long period of observations of the velocity variations allows a general evaluation between permafrost creep and changes in the climatic condition.

The paper is quite logically structured, clearly written, and the illustrations are adequate in number and quality.
I would suggest clarifying better in the title, in the summary, and soon in the introduction that the paper deals with the examination of 4 rock glaciers. At first glance, one gets the impression of a much more general paper, regional in nature.
I have included some formal and substantial observations as notes in the attached PDF. There are

some points where I believe it is necessary to provide more explanations and evaluate other possibilities with respect to the hypotheses made. Here below the main ones:
- The relationship between discontinuous permafrost limit and deceleration in RGs speed should be better documented. As it is explained in the text the deceleration is linked to the lack of supersaturation in ice (if I correctly understood), however I guess that the concept of permafrost limit does not refer to supersaturation.
- I would try to clarify better how during the post-LIA period glaciers that would have been mechanically characterized by a retreat or a steady state, have generated a downward stress propagation in the pro-glacial areas up to promote an RG movement
- I would better clarify if, during the glacier degradation, the meltwater availability may have influenced the permafrost thermal profile, and how (and if) this can be used to explain the acceleration/deceleration records. Could the hydrological input from the CG be considered a factor in modeling thermally induced creep?
- Reference is made to a climatic variability characterized by an increase in air temperature and dry conditions. In the period of observation of the velocities from RGs, how did the dry conditions vary?

I hope my comments help.
Best regards
Adriano Ribolini

Reviewer #3 (Remarks to the Author):

Dear Authors and Editor of the manuscript entitled ‘A unique record of rock glacier kinematics and glacier interactions from the Swiss National Park spanning more than 100 years’

The manuscript analyzes the spatiotemporal evolution of rock rock glaciers in the Swiss Alps. The study area is especially interesting, since there are measurements from the beginning of the 20th century. These measurements have been complemented with photogrammetry measurements to have a record that covers more than 100 years. The results obtained are of great interest, given that there are no such long series on the evolution of rock glaciers. Furthermore, an influence of glacial evolution on rock glaciers is shown.

In my opinion it is a solid and well-presented work, and that could be a significant contribution to the study of rock glaciers. Although the methodology is not entirely novel, as it has already been applied in the study of rock glaciers, the long data series, the different techniques mixed and the results obtained make, in my opinion, the manuscript suitable for publication in Communications Earth & Environment.

In any case, some suggestions and comments are made which may help to improve the work:

- The main suggestion is to add in the Introduction and the Discussion sections some sentences about the interaction of glaciers and rock glaciers during the LIA, and works about this interaction. For example, in Tantermozza results, the authors indicate that 'the more chaotic surficial geometries, possibly caused by the CG overriding this portion of the RG during the LIA'. I suggest to include references to the work of Kenner (2018) that should be relevant for the topic of this manuscript, as indicate that some rock glaciers should be much older than the upper glaciers and that the rock glaciers, were disrupted by glaciers during the LIA. Some other works, as the paper of Palacios et al. (2021) could help in this Discussion.

- Likewise, I consider that the use of the term 'Contributing glaciers' is not well justified (or at least explained), since, as indicated in the previous paragraph, it is possible that rock glaciers predate glaciers and have been partially affected by ice advances during the LIA. Also, the transition from rock glaciers, debris-covered and rock glaciers has been shown in several works and could be discussed in the fifth paragraph of the Introduction (i.e. Jones et al., 2019; Sanjosé Blasco et al., 2022).

- The geomorphological schemes of Figure 2 are not clear. The lobes are poorly distinguished. The glaciers in the upper part are not drawn either. I consider that it should be improved and colour added to the figure, to present a better cartography.

Some other minor suggestions:
- In the Abstract, consider to include some more information about the results of the work, as a concluding sentence.

- In the Introduction, consider to add some more references about RG kinematics (i.e. Kellerer-Pirklbauer, A., & Kaufmann, V., 2012; Cusicanqui et al., 2021; Tanarro et al., 2019) and especially the work of Fleischer et al. (2023), that include data from almost 100 years.

- Review the References section, as some works cited in the text do not appear in the Reference list (examples Reinosch et al., 2021; Roer et al., 2008;).

- The first paragraph of the Discussion seems like an Introduction rather than a Discussion.

- In Figure 3, I suggest changing the colour for T1 or T3, since they are very similar and cannot be distinguished well (Tantermozza and Val Sassa).

- In Figure 4, I suggest that the colour scale for all 4 rock glaciers be the same, so that comparison between them becomes easier.

- In Figure 6, consider separating rock glacier and glacier areas by lines. I suggest that the scale be the same for all 4 sites.

- In Supplementary Material 2, I also suggest the same scale bar for all 4 sites.

- I think that Supplementary Material 3 is the same than Figure 6.

Some other minor suggestions or mistakes are included in the PDF.

A unique record of rock glacier kinematics and glacier interactions from the Swiss National Park spanning more than 100 years

Alberto Muñoz-Torrero Manchado [a]; Simon Allen [a,b], Alessandro Cicoira [b], Samuel Wiesmann [c], Ruedi Haller [c], Markus Stoffel [a,d,e]

AFFILIATIONS

a Climate Change Impacts and Risks in the Anthropocene (C-CIA), Institute for Environmental Sciences, University of Geneva, 66 Bvd Carl-Vogt, CH-1205 Geneva, Switzerland

b Department of Geography, University of Zurich, Switzerland

c Swiss National Park, Runatsch 124, Chastè Planta-Wildenberg, CH-7530 Zernez, Switzerland

d Department of Earth Sciences, University of Geneva, 13 rue des Maraîchers, CH-1205 Geneva, Switzerland

e Department F.-A. Forel for Environmental and Aquatic Sciences, , University of Geneva, 66 Bvd Carl-Vogt, CH-1205 Geneva, Switzerland

ABSTRACT

The rock glaciers of the Swiss National Park were the first in the world where in-situ measurements of surface displacement were undertaken, starting with the pioneering work of Chaix in 1918. This globally unique long-term record is a main reason why these rock glaciers have recently been ordained by UNESCO as one of the top 100 IUGS geological world heritage sites. With our work we have filled the gap previously existing between the measurements from the early 20th century and the most recent measurements made over the last two decades. Through the application of photogrammetric techniques, we use this unique record spanning more than a century to geomorphologically analyze the spatiotemporal evolution of rock glaciers in the region, and to disentangle the interplay with their contributing glaciers. We show that these rock glaciers are in different phases of degradation with a general trend of deceleration and loss of volume. We observe how changes in kinematics seem to be historically controlled by the hydrological contribution of their nearby glaciers, with which they have been in close contact since the end of the Little Ice Age, but which are now severely degraded.

HIGHLIGHTS

- We provide the longest time series of rock glacier velocities worldwide (1918-2022)
- Evidence exists for a deceleration of movement and total volume loss due to permafrost degradation
- Glacier ablation and significant retreat are observed at the rock-glacier root zone after the end of the Little Ice Age
- Long term rock glacier kinematics seem heavily influenced by glacier changes

Introduction

In October 2022, rock glaciers (RG) of the Engadin (Southeastern Swiss Alps) were included by UNESCO as one of the ‘First 100 International Union of Geological Sciences (IUGS) Geological Heritage Sites’ (IUGS, 2022). This recognition was based on the high relevance of these RG, which serve as a reference for permafrost research in the Alps and where displacement rates measured over a period extending for more than 100 years are the oldest available globally. RGs are described as lobed or tongue-shaped landforms formed by a mixture of ice and frozen debris that are setting-up through gravity-driven creep (Reinosch et al., 2021). They are also known to react sensitively to climate change.

> **redacted** 03/10/2023 12:37:34
> **Highlight**
> You might consider using it as the first sentence of the section

Shortly after the creation of the Swiss National Park (SNP) in 1914, Emile and André Chaix made the first *in-situ* measurements of the velocity of a RG in the world (Chaix, 1923). During their fieldwork in 1918 and subsequent years, they assessed four RG in the SNP. Even if at that time, Chaix did not associate them as equivalent forms to those first described as RG by Capps (1910) in Alaska, in later decades it was known that they were actually the same (Wharhafting and Cox 1959) and thus making these RGs the first ones to be described in the European Alps. The four RGs analyzed by Chaix (1923) were Val Sassa and Val da l'Acqua, where the most extensive measurements and analyses were realized, as well as Valletta and Tantermozza, which they simply visited and briefly described. Two decades later, André Chaix took new measurements again on the same boulders in Val Sassa and Val da l'Acqua (Chaix 1943). However, after these pioneering measurements, for decades, there have been no new velocity data registered, until the most recent annual Differential Global Navigation Satellite System (DGNSS) measurements in Val Sassa and Val da l'Acqua were initiated by the GIS group of the SNP in 2006.

> **redacted** 03/10/2023 12:37:34
> **Highlight**
> I cannot find this in the reference list

> **redacted** 03/10/2023 12:37:34
> **Highlight**
> I read Wharhafting and Cox years ago and can't remember. Did they claim that the RGs in the SNP were the same as described in their Alaska Range paper?
> I cannot find Wharhafting and Cox 1959 in the reference list

So far, the longest kinematic analysis carried out on RGs reach back to the late 1940s or mid-1950s (e.g. Cusicanqui et al., 2021; Kääb et al., 2021; Fleischer et al., 2021; Marcer et al. 2021; Hartl et al., 2023). These long-term analyses are normally based on photogrammetric measurements from historical, vertically acquired aerial images, which can complement, or not, more recent GNSS surface measurements combined with Unnamed Aerial Vehicle (UAV) imagery (Fey and Krainer, 2020; Bearzot et al., 2022), interferometric (Brencher et al., 2021; Bertone et al., 2022) and geophysical (Maurer and Hauck, 2007; Kunz et al., 2022) analysis, or data from permafrost temperature boreholes (Arenson et al., 2002; Buchli et al., 2018; Kenner et al., 2018). From these regional to local analyses, some consensus is emerging that there has been an acceleration in the movement of rock glaciers in the Alps in recent decades, in parallel with the global increase in mean air temperature (Kääb et al., 2007; Delaloye et al., 2010; Marcer et al., 2021).

> **redacted** 03/10/2023 12:37:34
> **Highlight**
> Unmanned?

Theoretically, the acceleration of a RG can be due either to internal plastic deformation or basal sliding (Arenson et al., 2002; Cicoira et al., 2020). Internal plastic deformation can be enhanced by an increase of the permafrost temperature, causing changes in the viscosity and a reduction of the mechanical strength of the ice rich layer (Roer et al., 2008; Muller et al., 2016; Cicoira et al., 2019a). Meanwhile, most of the shear deformation takes place in the shear horizon, at about 20 m depth (Cicoira et al., 2020), where *in-situ* observations and modeling studies have suggested that water supply from rainfall, snowmelt or melting of ground ice play a major role (Arenson et al., 2002, Ikeda et al., 2008, Cicoira et al., 2019b). RG movement actually is a superimposition of both phenomena, on which the relative role played from each one will depend on the specific characteristics of the RG, including its geometry, structure and material rheology. Thus, for RGs where there is a limited contribution of rainwater or snowmelt on its surface, the dominant water inputs could be more related to the

> **redacted** 03/10/2023 12:37:35
> **Highlight**
> please specify if this depth is valid for all the RG

contributions of upstream catchment water (Croce & Milana, 2002). In this case, when RGs are spatially related to the presence of adjacent glaciers melting at a rapid rate, as currently occurs in the Alps (Sommer et al., 2020), this could have a major influence on the current and future RG dynamics during dry periods.

> **redacted** 07/09/2023 07:59:51
> **Highlight**
> see also Ribolini et al. 2010, QSR, doi.org/10.1016/j.quascirev.2009.10.008

The interaction between glaciers and RGs, in terms of the origin of RG i[illegible]bject of debate since the beginning of the study of these landforms. In fact, already in his 1923 work, Chaix described the observed RGs in the SNP as landforms possibly originating from the degradation of the frontal moraines of the receding upstream glaciers. Nowadays, debate still exists regarding the origin and formation of RGs, based on two theories that were initially opposed. On the one hand, there is the permafrost model (Wahrhaftig and Cox 1959; Haeberli, 1985) whereby the internal ice has predominantly a permafrost origin. On the other hand, the ice-core theory suggests a predominantly glacial provenance (Potter, 1972; Monnier et al., 2013; Guglielmin et al., 2018). These are two simplified theoretical end members, but other studies (Berthling, 2011) propose that a synergy between both models is possible in areas where there is a glacial-periglacial coexistence (Dusik et al., 2015; Monnier [illegible]nnar, 2015, 2017; Kenn[illegible]). Yet, previous RG dating studies have typically recorded ages between 10,000 and 3,000 yrs (e.g., Böhlert et al., 2011; Amschwand et al., 2021) which supports the more widely a[illegible]rigin, which is independent of the influence of glacier ice.

> **redacted** 07/09/2023 08:06:48
> **Highlight**
> it is not clear here why the RG ages support the permafrost origin. Although the 10-3 ka interval corresponds to the Lower-Middle Holocene, where climatic condition was on average unfavorable for the formation of glaciers, there were significant cold periods which led to glacial advances, i.e. Pre-Boreal, 8 ,2ka, 4.2ka

In the ca[illegible] shows evidence of [illegible]patially associated with [illegible] that were already mapped on the first official topographic map of Switzerland at the end of the Little Ice Age (LIA) - the 1850 Dufour map (Maisch et al., 2000). However, these glaciers do no longer appear as glaciers in the Swiss Glacier Inventory (SGI) of 1973 (Müller et al., 1976), even though bare glacier ice can still be seen at Tantermozza and Valletta. Meanwhile, for Val Sassa and Val da l'Acqua, one could hypothesize that these were currently extinct glaciers because according to satellite and historical aerial images from Swisstopo (Swissimage, 2023), there was almost no visible ice for decades. However, the extraordinarily hot summer of 2022 (Copernicus, 2023) triggered openings in the debris that exposed glacial ice in both basins (Figure 1) and confirmed the current existence of debris-covered glaciers in these two valleys as well.

> **redacted** 07/09/2023 12:47:24
> **Highlight**
> I suggest referring to the figure 2 here

The recent emergence of glacier ice, still visible in these two valleys, has motivated the present work, in which we [illegible]d the two primary aim[illegible] ~~the first time,~~ the existing gap between the recent RGs surface velocity measurements and the ones made over a hundred years ago by Emile and André Chaix; and (ii) using this unique data series to study the historical evolution of the glaciers ~~remaining~~ in the contributing areas, which we will refer hereafter as Contributing Glaciers (CG) to investigate the possible interrelationships of these with the RGs. For both purposes, we use photogrammetric techniques with recent UAV imagery and hundreds of historical aerial images from different periods since 1946, w[illegible] four RGs analyzed here. These are the same RGs described by Cha[illegible] Val Sassa and Val da l'Acqua (Figure 2). Using photogrammetry, we have been able to reconstruct high-resolution orthophotos and digital surface models (DSM) for each period and each of the four RGs analyzed. Based on these outputs, we subsequently realized manual measurements of horizontal surface velocities of the RGs yielding more than 100 years of continuous surface velocities, and thereby to establish the longest RG kinematics time-series from observational measurements. In addition, we assessed volume and geometry changes, both across the RGs and

> **redacted** 07/09/2023 08:21:12
> **Highlight**
> contributing areas of RG

> **redacted** 07/09/2023 08:27:39
> **Highlight**
> I understand and appreciate it. But it is possible that it is only now clear to the reader that the article concerns 4 rock glaciers, despite the fact that the title of the article and the abstract suggest that an in-depth analysis of the RG in the SNP would have been the focus of the work.

the surfaces that were most probably covered by the CGs in the past. The extensions of CGs have been inferred from bare ice sighting and geomorphic observations based on historical imagery, together with the analysis of extremely negative elevation changes observed between successive DSMs, clearly greater in the case of CGs as compared to RGs. These analyses helped detect a common decelerating trend in the velocity and ice degradation in RGs, along with a significant CG degradation. The progressive retreat and over-deepening of the CGs are thus thought to have diminished their 'pushing' upon the RGs, through the formation of a dynamic discontinuity in the landform, which could no longer sustain the high displacement rates of RGs after the end of the post LIA.

redacted 07/09/2023 08:30:02
Highlight
to detect

redacted 07/09/2023 08:2
Highlight
necessary here?

redacted 03/10/2023 12:39:44
Highlight
I understand that this will be discussed later. However, it seems something of a mechanic (pushing). The RG displacement was before described as provoked by i) an increase of the permafrost temperature, causing changes in the viscosity and a reduction of the mechanical strength of the ice-rich layer, or ii) basal shearing favored by from rainfall, snowmelt, or melting of ground ice. Where can I put this "pushing effect"

Figure 1. Exposed ice in Val da l'Acqua rock glacier. During the extraordinarily hot summer of 2022, several ablation and subsidence cracks occurred, exposing ice in Val da l'Acqua and Val Sassa in the Swiss National Park (Grisons, Switzerland). (a) Dense point cloud of the Val da l'Acqua rock glacier obatained from a UAV survey in September 2022. At the top part, one can observe exposed ice masses shown in detail in (b).

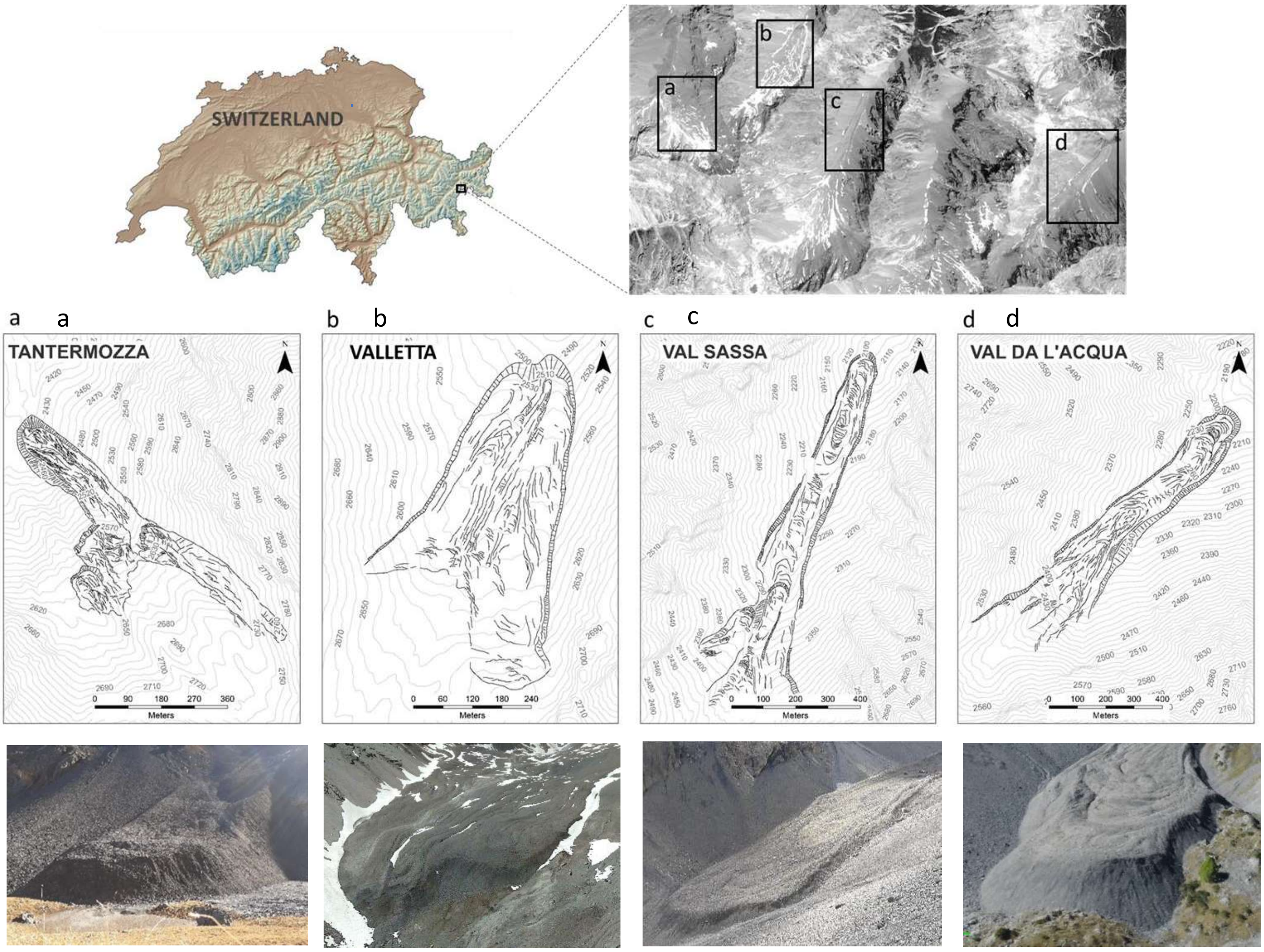


Figure 2. Study area. The four rock glaciers (RGs) and their catchment areas are located within a 5-km radius, entirely within the Swiss National Park (Grisons, Switzerland). All RG are tongue shaped type, creeping downwards in valleys with steep sidewalls of predominantly dolomitic lithology. **a) Tantermozza** has four well-differentiated lobes, 700-m long and 300-m wide, all facing NW. With an average slope of 34%, the RG extends from 2,430–2,730 m a.s.l., the upper limit of the accumulation zone of the CG reaches up to 2,900 m a.s.l., at a distance of 1300 m from the RG front. **b) Valletta** has a single tongue facing N, it is 700 m long and 350 m at its widest area, with an average slope of 22%, at elevations between 2,490 and 2,660 m a.s.l. The upper limit of the accumulation zone of the CG is at 2,880 m a.s.l., 1500 m away from the RG front. **c) Val Sassa** is a very elongated RG facing N, with a well-differentiated main lobe in the lower zone and different minor lobes in the upper zone, it is 1180 m long and 150–200 m wide. With an average slope of 23.5%, it is found between 2,110 and 2,380 m a.s.l whereas the upper limit of the CG is at 2,800 m a.s.l., at some 2,400 m from the RG front. **d) Val da l'Acqua** has a single tongue, 1170 m long by 140-220m wide, facing NE. With an average slope of 24%, it is located between 2,430 and 2,730 m a.s.l. whereas the upper limit of the accumulation zone of the CG is found at 2,890 m a.s.l., some 2,300 m from the RG front.

Results

The four RGs show a decelerating trend in mean and maximum surface velocities since 1918 (Val Sassa and Val da l'Acqua) and 1946 (for Tantermozza and Valletta) (Figs. 3–4; Supplementary Material SM1). Whereas some acceleration can be found in Val Sassa and Tantermozza in the 1950s, such an increase in displacement rates occurs in Val da l'Acqua in the 1960s. This temporary increase in velocities was followed by a continuous slowdown in movement rates from the 1960s and 1970s, with a common minimum at all sites between 1985/88

redacted 07/09/2023 08:55:48
Highlight
I would cite also here the Siegfried maps of 1900

redacted 07/09/2023 08:51:36
Highlight
unclear to me. It seems that this compensation consists of a transfer of mass from the upper to the lower parts.

and 1991. After a slight acceleration in the 1990s, a steady slowdown has been observed since the turn of the 21st century, reaching record low displacement rates in recent years. This general deceleration occurs in parallel to a significant volume loss at Val Sassa and Valletta (Figs. 5 and 6, Table 1; SM 2 and 3). Whereas elevation changes are also observed at Tantermozza and Val da l'Acqua, volume loss in the upper reaches is compensated by accumulations at the RG fronts, resulting in overall volumes today that are comparable to those of 1956. By contrast, we observe a significant continuous volume loss in all the CG since 1956, both. These CG show a reduction in area and retreat of the glacial fronts from positions similar to those occupied at the end of the LIA in 1850 (Fig. 7 and SM4), which supposedly remained in direct contact with the active areas of the RGs.

In the following, we describe the evolution of each RG in terms of surface velocities (Figs. 3–4), volume changes Figs 5–6, Table 1) as well as historical CG extensions (Fig. 7, as well as SM1–5).

Tantermozza

Tantermozza exhibits heterogeneous kinematics across three different zones (Figs. 3–4): The front and the middle zone of the lobe further downstream, with well-developed transversal ridges (T1); the upper zone of this lobe with longitudinal ridges in the flow direction (T2); the two northernmost upper lobes (T3) with more chaotic surficial geometries, possibly caused by the CG overriding this portion of the RG during the LIA. Meanwhile, we have not observed horizontal displacements in the southernmost lobe. It presents a loss of elevation between 1956 and 2015 in these three zones, with a transition from convex shapes to a flattening in the front of T1 and with overdeepening and loss of volume of the central part in T2 and T3. Simultaneously, the CG presents a total volume loss of 2.15 ($\pm$ 0.082) million m^3 between 1956-2015, which corresponds to a total loss of 16.99 m of water equivalent (m w.e.) or tons per m^2.

redacted 07/09/2023 09:01:31
Highlight
Could you be more specific? please indicate from which evidence a generally positive mass balance can be deduced

At the end of the LIA, the position of the glacial front occupied a location immediately in contact with the upper part of the active RG, partly overriding T3. In 1935 and until 1956, even if some glacier retreat had occurred, significant ice bodies persisted in similar positions close to the upper lobes (T3). In an image acquired by Chaix in 1919 (SM5), as well as in the terrestrial images of 1935, we observe a marked convex transverse shape for all the active lobes of Tantermozza. During 1946-1956, maximum velocities occurred at the very front of T1, equal to 2.5 $m\ a^{-1}$, followed by 2 $m\ a^{-1}$ and around 1 $m\ a^{-1}$ in T3 and T2, respectively. The period 1956-1962 was the only occasion across all four catchments during which a certain positive balance is observed in CG volume, but also positive volume change in all active RG areas. During this time, T3 maintained its velocities from the previous period, whereas important accelerations are found in T2 with 2 $m\ a^{-1}$. Longitudinal ridges were formed at that time in T2 and are still present today. Meanwhile, T1 reached the highest historical velocities among all RG with 3.1 $m\ a^{-1}$. Between 1962 and 1973, a general deceleration and volume loss can be observed; it is most significant in the upper zone of T3. This subsidence translates into a clear observable change in the geometry of the longitudinal and transverse profiles from convex (local heave) to flat and concave (depletion) shapes in the frontal areas of the upper lobes, along with a sharp drop in velocities from 2 to 0.5 $m\ a^{-1}$, these low values persist to the present day. From 1973 to 1991, a continuous deceleration is observed in the main frontal lobe where velocities decreased from 2.5 to 1.3 $m\ a^{-1}$ in T1 and from 1.7 to 0.7 $m\ a^{-1}$ in T2. This slowdown was

redacted 07/09/2023 08:58:03
Highlight
meaning that the RG existence predates the LIA glacial advance

mostly concentrated in an area close to the RG front, where significant volume loss has occurred since 1962. This area already exhibited transversal ridges in the pictures taken by Chaix in 1919 and is easily recognizable nowadays with the naked eye, but also through the strong change in curvature along the longitudinal profile. Between 1988 and 1991, the largest volume losses occurred in T1 and T2; they went hand in hand with marked decelerations in movement velocities. Starting in 1991, strong ablation occurs from the CG: whereas velocities at T3 remained constant with 0.6 m per year, resulting in a practically invariable volume, T1 and T2 exhibit variations both in speeds and volumes. During the 1990s, both zones experienced accelerations and volume gains, with identical maximum speeds in both areas since 1997. Over the last two decades, T1 and T2 showed a similar deceleration, with displacement rates settling at about 0.8 $m\ a^{-1}$, without considerable volume change.

Valletta

Valletta presents a rather homogeneous dynamics longitudinally, with higher velocities in its eastern half. This part exhibits a continuous and homogenous flow as a single body, reflected in a characteristic morphometry of continuous longitudinal ridges and furrows, whereas transversal ridges are almost missing completely. The RG presents a total negative volume loss of 0.58 (+ - 0.081) million m^3, a general loss of elevation and flattening between 1956 and 2015, whereas its CG exhibited a loss of 1.92 (+ - 0.078) million m^3 (11.01 m.w.e).

In 1850, the position of the CG end moraine delimited quite closely the current upper limit of the active area of the RG. By 1935, the glacial front had already retreated approximately 300 m in the westernmost area and about 150 m in the eastern part according to terrestrial images. This differentiated retreat was maintained in the following two decades, with the easternmost part retreating another 200 m until 1956, whereas the eastern half remained in similar positions but with ice bodies becoming increasingly isolated from the main ice mass. Between 1946 and 1956, Valletta exhibits its highest historical velocities, with maxima of 2.5 $m\ a^{-1}$, like at Tantermozza at the same time. However, between 1956 and 1962, Valletta shows a completely opposite behavior to its neighbor with a drop of maximum velocities to ≤1.2 $m\ a^{-1}$, along with an important volume loss in the eastern part. In turn, contrary to what happened to the Tantermozza CG, the Valletta CG lost volume at an almost constant rate (~ 30,000 $m^3 a^{-1}$) ever since that period. RG velocities and volume remained constant over the next two decades, to be followed by an acceleration in velocities between 1979 and 1985. From then on, it presents variations in surface velocities that are very similar to those of Tantermozza. A clear drop in velocity is recorded between 1985 and 1991, reaching their historical lowest values (≤1 $m\ a^{-1}$), followed by a new acceleration between 1991-2000 (~2.2 $m\ a^{-1}$) and another drop in velocities to 1.2 $m\ a^{-1}$ from 2000 to 2019. This reduction in velocities was accompanied by a general volume loss across the entire RG, with a slight flattening of the surface in the longitudinal and transverse directions. Despite this flattening, the overall shape of the RG remains more convex than at the other RGs. In the contributing zones, the constant elevation loss is concentrated around the CG increasingly exhibiting the marked concave shape of the underlying bedrock.

Val Sassa

Val Sassa has has suffered the largest drop in speeds and sudden volume loss of the four RGs. Changes are not equally intense across the RG, three zones can rather be identified with specific behavior: The front of the main lobe (S1) is characterized by transversal ridges and furrows, separated from an intermediate zone (S2) with surficial signs of thinning and subsidence; this zone is followed by the lobes of the upper zone (S3). Val Sassa RG presents a total negative volume loss of 0.60 (+-0.023) million m^3 since 1956, mostly centred around S2 and S3, whereas the CG presents a total volume loss of 3.69 (+-0.166) million m^3 (11.83 m w.e).

redacted 07/09/2023 09:23:54
Highlight
unclear to me why this uncertainty: if the push moraines are clearly interpreted, what impedes detecting the RG upper limit?

On the 1850 Dufour map, the position of the CG front was barely 100 m away from the root zone of the Val Sassa RG. In the hiatus zone, stacked linear ridges can be identified in the 1935 oblique images, which we interpret as being push moraines; these ridges somewhat render the delimitation of the upper limit of the RG uncertain. Val Sassa showed the largest historical velocities with 2 $m\ a^{-1}$ in S1 durIng the first measurements of 1918-19,. A slight decrease in speeds was already documented between 1919 and 1921 (1.4 $m\ a^{-1}$). Terrestrial images acquired by Chaix in 1918, as well as oblique images from 1935 show transverse convex shapes in S1 and S3, but also first signs of depletion in S2. Velocities remained mostly unchanged in S1 and S3 until 1942. Between 1946 and 1956, we observe a deceleration, more marked in the lower (0.7 $m\ a^{-1}$ in S1 and S2) as compared to the upper (1.1 $m\ a^{-1}$ in S3) zones. Between 1956 and 1962, movement rates increased again to ≤1.6 $m\ a^{-1}$ in S1 and S3 and to 1 $m\ a^{-1}$ in S2. This acceleration is contemporaneous to the largest volume loss of the CG with 260,000 $m^3\ a^{-1}$ as well as the largest volume loss in the active area of the four RGs with 75,000 $m^3 a^{-1}$in S3. These losses also resulted in a clear general flattening of the previously convex landforms. During this same period, some aggradation occurred in zones S1 and S2. By this time, the area of the CG was clearly reduced compared to 1850, but an important body of isolated ice persisted in at locations that were still in contact with the upper part of the RG. Looking at the longitudinal profile, the upper parts of the CG already presented a general concave shape in 1956 which was even exacerbated after this great volume loss. From 1962 to 1973, Val Sassa RG velocities reduced in S1 and S3 down to 0.7 $m\ a^{-1}$ (i.e. to a third of previous values), with an even more dramatic drop in S2 where movement dropped to 0.2 $m\ a^{-1}$ (or one-fifth of previous value). From 1962 to 1991, volume losses did not continue at the same rate in the CG and some equilibrium can be observed in terms of volume at the RG. Noteworthy, this period of reduced losses is contemporary with the deposition of debris on previously exposed ice. The debris cover is more obvious in the eastern half of the CG and continued to build, thereby covering glacier ice completely by 2000.

redacted 07/09/2023 09:25:48
Highlight
during

After 1973, velocities in S1 and S3 dropped to 0.3 $m\ a^{-1}$, whereas S2 barely shows any movement above 0.1 $m\ a^{-1}$. Velocities remained generally low with just some acceleration in the 1990s, as at the other RGs. Since the turn of the 21st century, DGNSS and photogrammetric measurements show a decelerating trend with current velocities at S1 and S2 below 5 $cm\ a^{-1}$, and 7 $cm\ a^{-1}$ in S3. This deceleration coincided with an appreciable loss of volume at the CG (60,000 $m^3 a^{-1}$) and significant volume losses in all RG zones, producing, even at its front of S1, a depleted central area with respect to the margins.

Val da l'Acqua

Val da l'Acqua presents the most constant horizontal velocities of the four RGs, but suffered from a negative trend in surface velocities and important periods of volume losses too. The active areas of the rock glacier can be divided into two halves with different dynamic behavior. A lower half - close to the front (A1) and an upper half (A2). Compared to 1956, the RG now has a degraded upper part (A2) where losses total 0.22 (+- 0.064) million m^3 and an aggrading front with a volume gain of 0.13 (+ - 0.027) million m^3. The total volume loss of the CG amounts to 4.15 (+- 0.307) million m^3 (15.80 m w.e.), representing the greatest volume loss among the four catchments.

As in Val Sassa, the position of the CG end moraine was just slightly more than 100 m away from the active part of Val da l'Acqua RG in 1850. The glacial front can not be discerned on the historical photographs of 1918 and 1935, but according to our inferred area of the CG in 1956, the glacier ice had receded by c. 250 m with respect to the end of the LIA, leaving isolated ice patches behind. Horizontal velocities remained quite stable both in A1 and A2 from 1918 to 1962, with values ranging between 1.5 and 2 $m\ a^{-1}$, and only a slight slowdown during the period 1919-1921 (again as in Val Sassa). Between 1962 and 1973, a marked increment of the maximum speeds can be observed in very localized areas of A1 and A2 (up to 3 $m\ a^{-1}$) along with an important retreat and volume loss of the CG. Yet, these local changes in movements only had a minimal effect on the overall mean RG velocities. Between 1962 and 1973, a significant hiding of exposed ice can be observed, predominantly with debris, covering the easternmost area. Coverage here is less extensive compared to Val Sassa, still leaving a large area of ice exposed in the western half of the RG. It is in this western zone where the volume loss mainly occurred in subsequent decades. Glacier ablation was notable during 1988-1991, with appreciable deceleration and volume losses in A1, but even more so in A2 (60,000 $m^3 a^{-1}$) where losses were accompanied by a more evident deceleration in velocities. Again during 1991-2000, as in the other three RGs, an acceleration is discernible in both zones, but with a gradual migration of maximum speeds from lower to more elevated zones, resulting in the highest mean velocities seen in A2. As shown by DGNSS measures, A1 is in a clear downward trend in movement since 2000, and the speed has nowadays decreased to 0.5 $m\ a^{-1}$ or less, with some localized subsidence in the upper part evident in both the longitudinal and transverse profiles. Meanwhile, velocities in A2 maintained higher values of around 1.4 $m\ a^{-1}$, with considerable depletion produced during this period. On the CG, volume loss rates have been lower than during previous decades, as the debris has come to hide the ice in its entirety. Despite this, glacier area was reduced by almost half between 2000 and 2015 and the longitudinal profile has become closer and closer in recent years to the concave and more irregular shape of an underlying carved bedrock.

redacted 07/09/2023 09:35:52
Highlight
This having already been stated in the Introduction, I wonder whether it should be repeated here

Discussion

In the study presented here, we present a century of surface velocity and volume changes of four rock glaciers from the Eastern Swiss Alps. The rock glaciers – all located in the Swiss National Park – were the first in the world where systematic *in-situ* measurements of surface displacement were undertaken in 1918. By combing this pioneering work with photogrammetric interpretation and DGNSS measurements, we filled the gap previously existing between the measurements from the early 20th century and the most recent measurements made over the last two decades. This globally unique long-term record is one of the main reason why these rock glaciers have recently been ordained by UNESCO as one of the top 100 IUGS geological world heritage sites.

The general decelerations and total volume loss that have occurred at different rates over the past 100 years in the four RGs ~~of the SNP~~ show a behavior that is consistent with RGs slowly transitioning from secondary creep towards a state of degradation (Cicoira et al., 2020). This degradation is reflected in the general curvature of the longitudinal and transverse profiles, showing signs of ice depletion in all the RGs, but being more marked in Val Sassa and Tantermozza where deceleration has been most prolific. Me[illegible] aggradation convex shapes are still present at the fronts of the Val da l'Acqua and Valletta RGs, but [illegible] observed deceleration, which is more concentrated at the lower frontal areas of the main tongues, is inverse to the spatial variation of velocities observed in RGs which are in a process of destabilization, such as at the Äußeres Hochebenkar (Hartl et al., 2023). This frontal deceleration is more clearly ongoing in Val Sassa and Val da l'Acqua between an elevation range of 2,100 to 2,300 m a.s.l, which is exceptionally low compared to other active RGs in the Swiss Alps (Delaloye et al., 2010) and roughly coincides with the current lower limit of permafrost in this area (Boeckli et al., 2012). Therefore, the shifting of maximum speeds to higher elevations could be related with a [illegible] progressive upslope permafrost degradation, with localized loss of the ice-rich layer triggered by anomalously drier warm conditions and less snow cover (Yi et al., 2007; Springman et al. 2013). Projected [illegible] consequence of climate warming have been previously modeled by [illegible] and Haeberli (2009). The tendencies and longer term evolution of these RGs are unique and could serve as prime examples of how RG downwasting could.

Despite the uniqueness of the records presented here, we are well aware of several uncertainties that are inherent to interpretations related to different types of data sources with different resolutions [illegible] especially [illegible] for the volume changes and the implications that the latter may have on RG behavior. While in the CG [illegible] volume decrease would mainly be due to the ice melting, this is certainly more complex in the RGs. [illegible] and air, if sediments are supersaturated we will see a volume [illegible] which point a volume decrease will no longer be evident (Jones [illegible] permafrost degradation, the higher the ice content in the RG, the higher [illegible] with high content in coarse sediments, this change can be almost negligible. Besides, for active RGs, such effects have to be combined with elevation changes due to lateral extensions/compressions which can sum to produce considerable uncertainties to the calculation of ice melting volumes in RGs (Cusicanqui et al., 2021). Despite these uncertainties, and without any pretension in this work to associate volume loss purely to ice loss in the RG, we are confident that the historical elevation [illegible] observed, both in the longitudinal and transversal profiles of the four RGs, are of a sufficient magnitude and widespread enough, that they can be clearly associated with permafrost degradation.

A general accelerating trend, observed in many RGs over the last decades in the Alps and in some cases triggering destabilization, has been related to an increase in atmospheric temperature and warming of permafrost causing a thermally induced accelerated creep (Delaloye et al., 2010; Marcer et al., 2021). Whereas certain accelerations were observed at our sites during the 1950-1960s and 1990s, there has been a general trend for a deceleration in the 20th century, consistent with a general increase in air temperatures (Wuebbles et al., 2017; Allen et al.,

redacted 07/09/2023 09:39:24
Highlight
unclear to me what is a prolific deceleration

redacted 07/09/2023 09:37:13
Highlight
please consider to put in brackets a brief definition

redacted 07/09/2023 09:37:39
Highlight
ditto

redacted 07/09/2023 10:01:28
Highlight
however this climate condition should assumed to be the same for the whole RG

redacted 07/09/2023 09:42:38
Highlight
meaning mathematically inverse?
"shows an opposite trend"?

redacted 07/09/2023 09:58:15
Highlight
a bit unclear to me. As I understand, you correlate the deceleration with permafrost degradation, assuming that the higher the velocity the more intense is the permafrost degradation. "Therefore", maximum speeds at higher elevation means higher degradation there. In this perspective, do the lower speeds in correspondence of the fronts mean a less intense permafrost degradation there or a reduced content of ground ice?

redacted 07/09/2023 10:47
Highlight
that's fine. But it is also presumably that besides the modeled values, there are also local values of permafrost limit. Is there any additional evidence of permafrost existence in the examined RGs (in addition to the movement evidence) to be precise about permafrost limi

redacted 07/09/2023 13:08:04
Highlight
therefore, the variation of the velocities detected on the examined RGs is related to the changes in the saturation of the ice, i.e. to the degradation of the permafrost. However, how can this be related to the concept of a lower and discontinuous permafrost limit? in other words, the permafrost limit is related to the existence of the permafrost and not to the supersaturation of the ice, and therefore how can the variation of the measured speeds be related to an increase in the elevation of the permafrost limit?

redacted 07/09/2023 09:4
Highlight
meaning the elevation range where a frontal deceleratic was observed by Reynald Delaloye et al? or are you comparing the two deceleration dataset

redacted 07/09/202
Highlight
meaning the porosity volume of unsaturated debri

2018), which could suggest that in these cases, changes in RG kinematics would be governed by (an)other factor(s) prevailing over the thermally induced plastic deformation. The historical surface kinematics observed throughout the century-long timeseries should be explained by other elements, either topographic or hydrological (Kenner et al., 2018; Cicoira et al., 2019a; 2020). In our case, it is suggested that the spatial interaction with the CGs could have had implications regarding both factors. On the one hand, we see that the highest recorded velocities coincide with the post LIA period during which the CG termini were almost delimiting the upper contact of the active zones of the RGs. At this time, the stress propagation of the CGs would have been greater towards the proglacial foreland (Waller, 2013), thus promoting RG movement. On the other hand, the significant glacier degradation necessarily implies a large long-term reduction in the sources of hydrological input, thus suggesting a possible long-term dominant basal-shear type movement of these decelerating RGs, which would be predominant over thermally-induced creep, similar to that described at Ritigraben (Kenner et al., 2017). If this were the case, the observation of CG extensions and longitudinal profiles that show glaciers in a state of continuous depletion in the last decades, and with the glacier snouts increasingly further away from the active area of the RGs, would indicate a near future scenario with a complete absence of new important RG accelerations. These conditions would persist for a few more years, with the rate of melting for the nearly exhausted glaciers damped by the debris cover, as observed in Val Sassa and Val da l'Acqua. A slower but continuous flow of water from the CGs would thus maintain a slow secondary creep that would continue to gradually slow down as the permafrost is slowly degraded by warm and dry climatic conditions.

Regarding our observations of the historical spatial interrelationships between CGs and RGs, we cannot draw solid conclusions about the origin of the rooting ice of the RGs beyond the observed proximity between them at [illegible] signs of glacial overriding on the surface of the upper lobes at Tantermozza RG, indicating its presence prior to the glacial advance, but more importantly, that the morphology and main lobes of the four RGs already presented an extensive development and positions similar to the current ones in 1918. It is thus very unlikely that the RGs were formed from end glacial ice after the end of the LIA. While, conducting geophysical surveys or borehole investigations in these former contact areas could certainly help to decipher the former and current CG-RG interrelationship, such investigations will not be possible in the strictly protected environment of the Swiss National Park.

redacted 07/09/2023 12:48:59
Highlight
a bit unclear to me. During the post-LIA period glaciers would have been stable but more commonly in retreat. I would explain here how, despite the glacier mechanics characterized by a retreat or a steady state, a downward stress propagation would have occurred in the pro-glacial areas up to promote a RG movement

redacted 07/09/2023
Highlight
it's not clear to me. Why would the degradation of t[he] glacier necessarily imply a reduction of the hydrolog[ical] supply (I imagine in the RG)? Can glacier degradatio[n be] seen as a period of abundant meltwater? Or anyway the reduction of the cryosphere caused by the shift t[o a] non-glacial condition, what happened to the solid a[nd] liquid precipitations in the CR areas (non-converted ice)?

redacted 07/09/2023 12:58:15
Highlight
Is it possible that the meltwater influenced the thermal conditions of the permafrost, thus changing its thermal profile? If yes, can the hydrological input from the CG be considered a factor in modeling thermally induced creep?

redacted 07/09/2023 12:34:33
Highlight
this is a good point. Were the climatic conditions dry during the entire observation period (I mean the one for which the RG velocities were calculated)?

redacted 07/09/2023 12:35:
Highlight
unclear to me

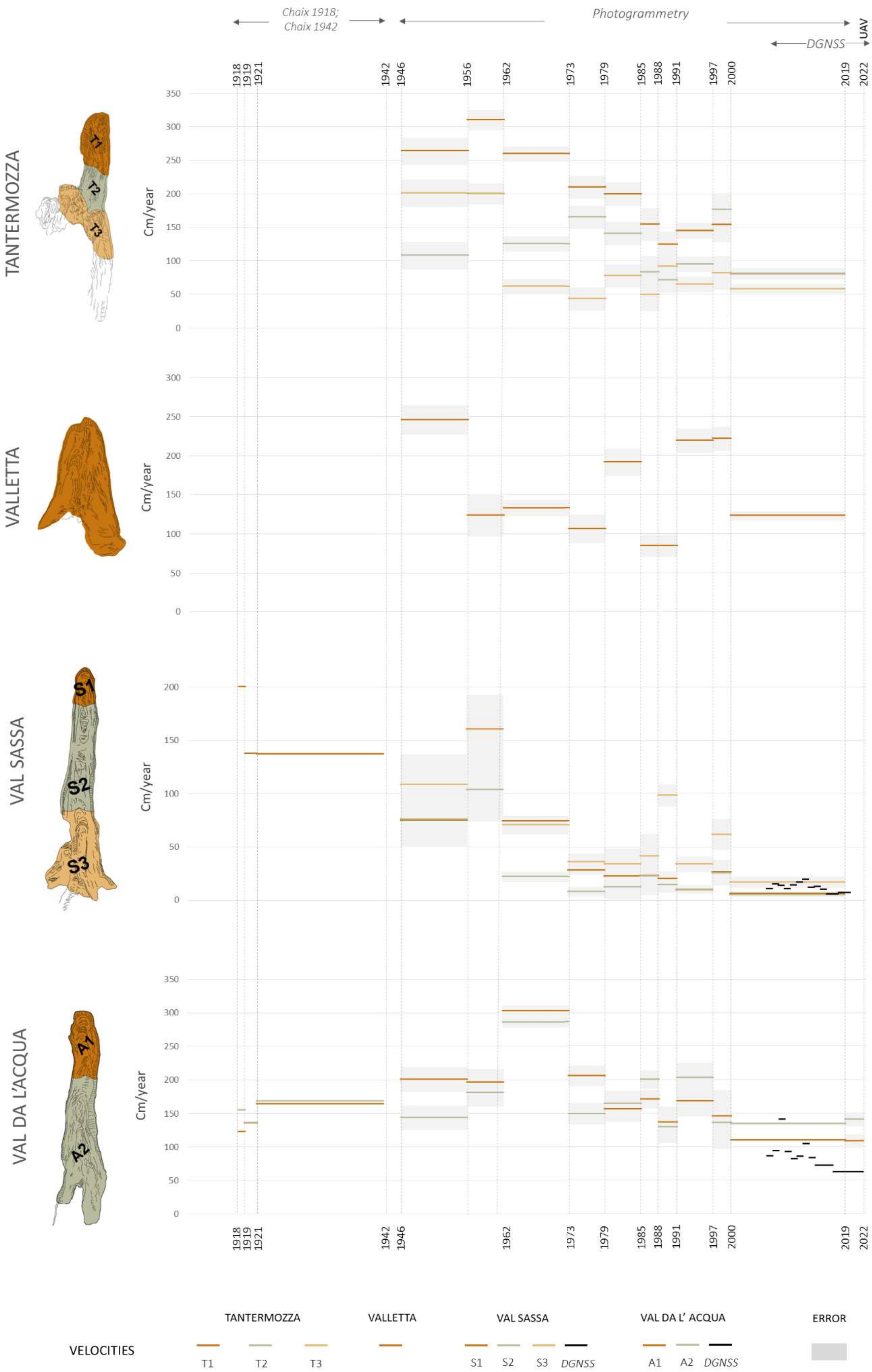


Figure 3. Horizontal maximum velocities. The four graphs summarize all the horizontal maximum velocities values for each of the analyzed zones of the rock glaciers from Chaix measures (1918-1942), orthophotos obtained from historical aerial imageries and UAV (1946-2022) and DGNSS measurement (2006-2022). The shaded areas correspond to the uncertainty in the measurements made on the orthophotos (see supplementary material 1 for raw data).

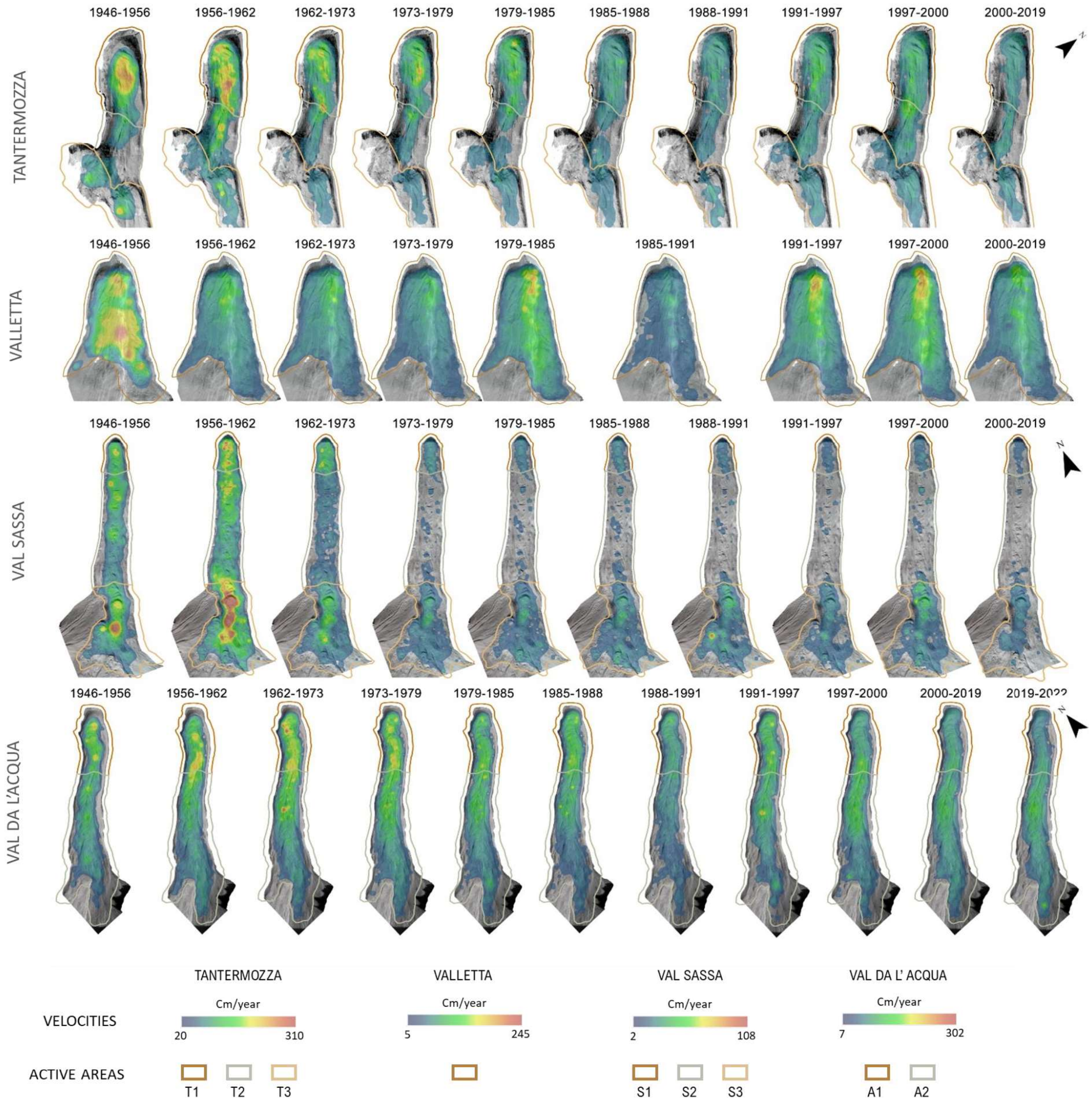


Figure 4. Interpolated velocity maps. The IDW interpolated maps show the spatial distribution of horizontal surface velocities (cm per year) measured in different periods between 1946 – 2022 within the active areas of the four rock glaciers. The active areas are separated in different zones according to different kinematics observed and shown here as different colors overlapping polygons.

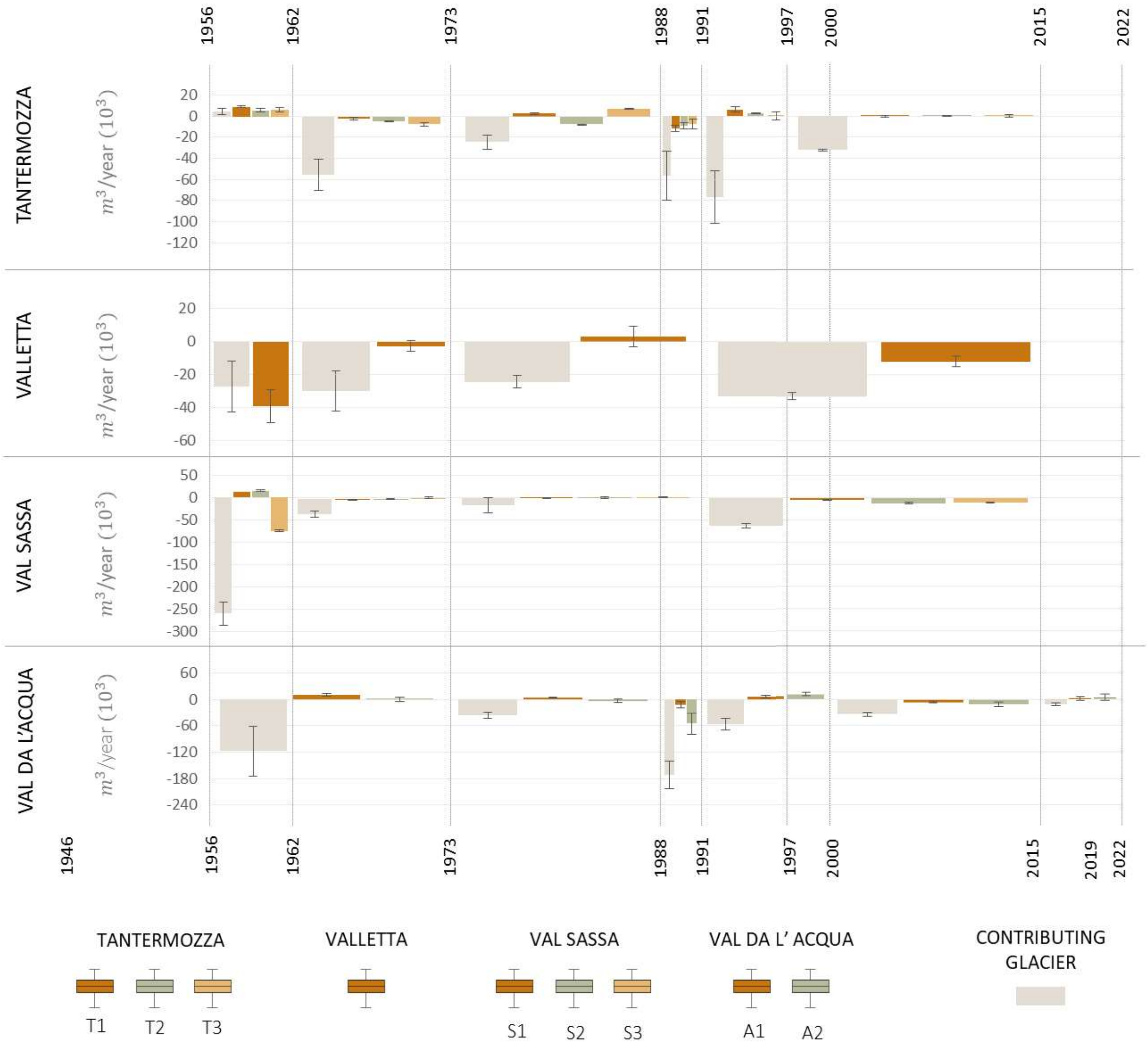


Figure 5. Volume change rate. Bar graphs show volume change rates in m^3 per $year$ at different periods from 1956 for the different active zones of the rock glaciers and Contributing Glaciers. Uncertainty is indicated by thin black lines.

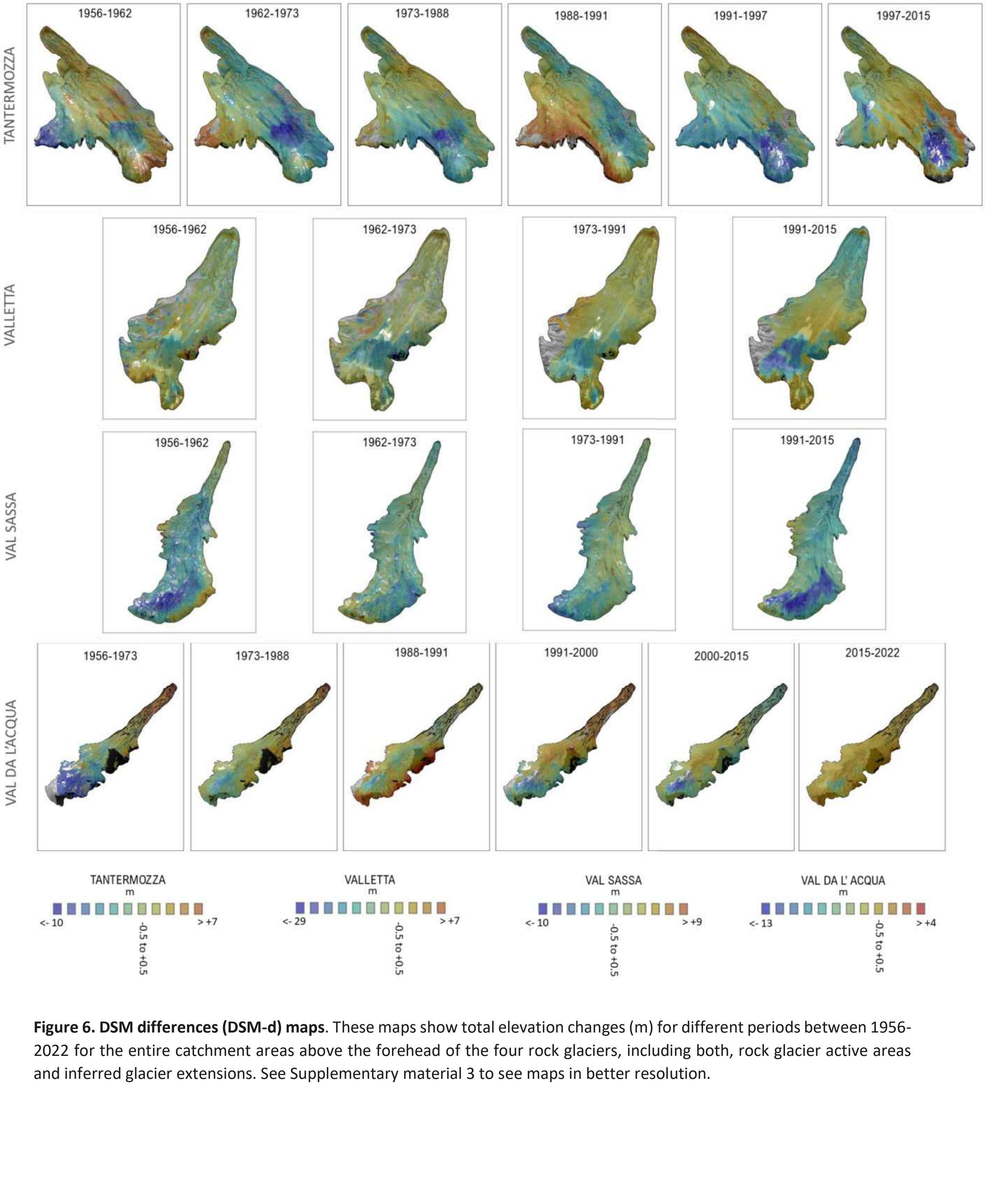


Figure 6. DSM differences (DSM-d) maps. These maps show total elevation changes (m) for different periods between 1956-2022 for the entire catchment areas above the forehead of the four rock glaciers, including both, rock glacier active areas and inferred glacier extensions. See Supplementary material 3 to see maps in better resolution.

TANTERMOZZA

	GLACIER				ACTIVE RG							
					T1+T2+T3		T1		T2		T3	
	Area (m2)	Elevation Change (m/year)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)
1956-1962	126800	0.04	27734	15701	111338	16373	47214	5773	30465	7867	33659	13152
1962-1973	132800	-0.42	-608119	161205	-83406	12848	-16178	16955	-36630	2961	-30598	18629
1973-1988	109200	-0.22	-363558	102848	19760	10039	-8035	17225	21788	3561	6007	9331
1988-1991	83600	-0.67	-168455	70189	-101168	9705	-44309	7933	-34780	7830	-22080	13352
1991-1997	84400	-0.91	-460956	150372	39047	14360	50256	16897	9385	3990	-20594	22193
1997-2015	60800	-0.53	-581153	17313	8177	12494	835	15077	17663	4986	-10321	17420
TOTAL			**-2154508**	81942	**-6251**		**29784**		**7891**		**-43926**	

VALLETTA

	GLACIER				ACTIVE RG	
	Area (m2)	Elevation Change (m/year)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)
1956-1962	174400	-0.09	-162407	92771	-201285	60008
1962-1973	158000	-0.21	-530480	134702	-27404	37173
1973-1991	139200	-0.12	-439401	66797	59998	113901
1991-2015	102400	-0.17	-789424	57132	-413236	79666
TOTAL			**-1921712**	78167	**-581927**	

VAL SASSA

	GLACIER				ACTIVE RG							
					S1+S2+S3		S1		S2		S3	
	Area (m2)	Elevation Change (m/year)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)
1956-1962	312000	-0.83	-1557160	153897	-157364	10540	40139	5095	50167	13170	-247670	13357
1962-1973	229200	-0.15	-383965	82007	-14598	19116	-24935	12201	-5518	18420	15854	26726
1973-1991	196400	-0.08	-267649	311206	95218	22894	17388	11681	23169	31901	54661	25101
1991-2015	191200	-0.32	-1484372	100942	-525147	29398	-74743	18623	-237869	54587	-212536	14984
TOTAL			**-3693146**	166945	**-601891**		**-42151**		**-170050**		**-389691**	

VAL DA L' ACQUA

	GLACIER				ACTIVE RG					
					A1+A2		A1		A2	
	Area (m2)	Elevation Change (m/year)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)
1956-1973	262800	-0.45	-2006638	952390	138595	57155	130086	39392	8510	74918
1973-1988	194400	-0.18	-536980	103552	12133	35505	61775	10702	-49642	60308
1988-1991	152400	-1.12	-512348	94929	-249098	46715	-46385	21370	-202713	72061
1991-2000	120800	-0.47	-512348	119968	234900	33942	90801	26561	144100	41323
2000-2015	108000	-0.31	-506495	66615	-439819	53761	-168916	30465	-270903	77057
2015-2022	43600	-0.25	-76751	22721	215482	36538	66942	28123	148540	44953
TOTAL			**-4151559**	307071	**-87807**		**134303**		**-222109**	

Table 1. Total volume change. Total volume changes calculated from DSM of Difference (DSM-d maps) in the different zones of the active area of the rock glaciers and in the inferred areas of the Contributing Glaciers, at different periods from 1956. Additionally, it shows area and elevation change at the inferred Contributing Glacier area for the same periods.

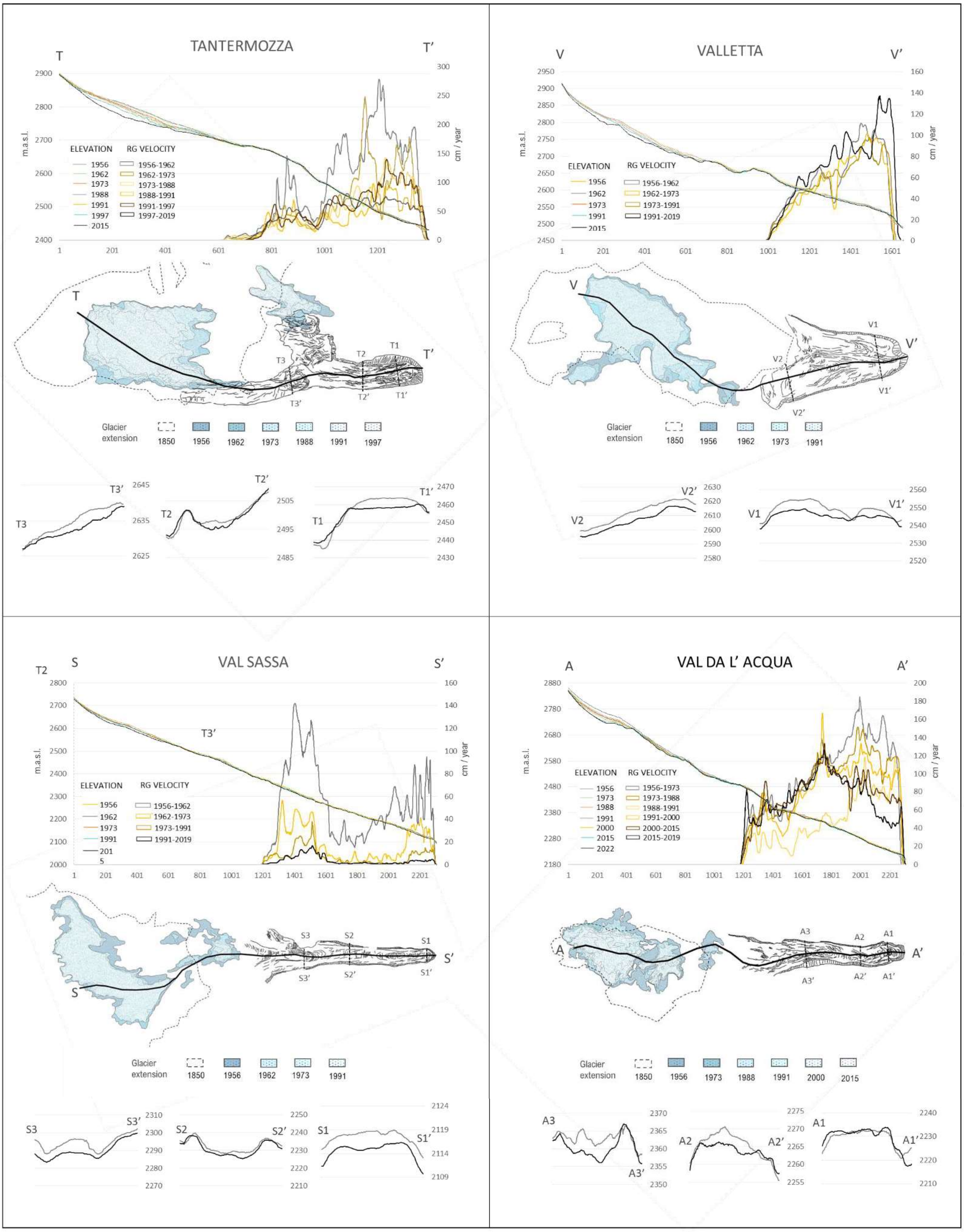


Figure 7. Velocity and Elevation longitudinal-transverse profiles. Historical evolution of elevation changes (from photogrammetry DSMs) and measured horizontal surface velocities in the rock glaciers (RGs) for corresponding periods. Longitudinal and transverse profiles covering the Contributing Glacier areas and the active rock glaciers are indicated by black lines at the bottom maps of each rock glacier. Boundary area of 1850 corresponds here to the Siegfried maps of 1900,

which better represent in these catchments the Contributing Glacier extensions of the Dufour map of 1850 (See supplementary material 4).

Methods

Antecedent works

Émile and André Chaix undertook the first in-situ measurements between 1918-1919 and 1919-1921 for Val Sassa and Val da l'Acqua RGs (Chaix, 1923). During their different field campaigns, they acquire relative displacement measurements carried out on boulders that were along transversal profiles, located both near the front of the RG as well as in the upper areas. Two decades later, in 1942, André Chaix revisited the sites and took new measurements on the same boulders (Chaix, 1943). Unfortunately to date, efforts to locate these boulders again have not been successful, and therefore, it has not been possible to continue tracking movements using the same elements. The next known measurements were made by Heinrich Jäckli in Val da l'Acqua (Jäckli, 1978). In this work he summarized past measurements for Val da l'Acqua forehead (1921-1942-1968) and acquired new velocities between 1968-1979. These measurements were conducted using different boulders than the ones measured by Chaix, but again, in the current study we have not been able to find their exact location. Even so, they serve as a reference to compare against our photogrammetric measurements from the same period.

For the last 2 decades, Differential Global Navigation Satellite System (DGNSS) surface measurements have been systematically acquired (almost yearly) by the GIS group of the SNP using boulders at 8 different positions along the Val Sassa RG body (years 2006,2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2018, 2020) and 19 locations near of the front of Val da l'Acqua (years 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2017, 2022). See Supplementary material 6 for the locations of the DGNSS measurements.

Photogrammetry

With the aim of filling the gap between the older measurements from Chaix (1918-1942) and the recent ones from DGNSS (2006-2022) in Val Sassa and Val da l'Acqua, and to obtain the first measurements for Tantermozza and Valletta RGs, we created orthophotos and DSM by carrying out photogrammetry processing from historical imagery and UAV.

Historical aerial imagery (1946 to 2000)

The Swisstopo (Swissimage, 2023) catalog presents a vast spatial and temporal coverage of historical aerial imagery. We have downloaded and pre-processed each of the available scanned historical images that cover our study area (651 images) for all the available dates, comprising 1946, 1956, 1962, 1973, 1979, 1985, 1988, 1991, 1997, 2000 and 2003. For some of the years, more than one acquisition date is available. When that befalls, we have always chosen a single date, being the one with the best resolution, greatest spatial overlap between datasets, and with less snow cover and/or shadowed areas.

To obtain better detail in the shaded areas, we have individually pre-processed each of the scanned images by adjusting brightness and contrast. Besides, if necessary, we have applied sharpening filters and matched levels between datasets that would be processed together. These adjustments considerably increase the final accuracy of the photogrammetry models, facilitate the pixel matching between datasets, and reduce the point cloud noise in the brighter and shaded areas. Despite these improvements, afterwards, manual cleaning of the point clouds noise for each of the photogrammetry models has been necessary.

Ground control points (GCP), used during the photogrammetry process, were acquired in different field campaigns with a Trimble Geo7x and post processed to obtain DGNSS locations from stable boulders, located in the immediate vicinity of the active areas of each RG (Supplementary material 7). Stability of these boulders was assessed by measuring the relative distances in the historical imagery between the boulders and different close bedrock outcrops, against the relative distances in the most recent Swisstopo orthophoto from 2019 (Swissimage, 2023). Finally, just the locations with highest precision (vertical and horizontal accuracy o + -10 to + -40 cm) were selected as GCP candidates for the photogrammetry processing. For the more inaccessible upstream areas, GCP of stable outcrops were selected using XY coordinates from the 2019 Swisstopo orthophoto (10cm pixel resolution) and Z values from the 2015 SwissALTI3D DEM (0.5m) (SwissALTI3D, 2023). The horizontal and vertical accuracy of these upstream GCP is much lower (+ - 2m) than the ones of the downstream DGNSS GCP. Even so, it is a sufficient precision for our purposes, since in these upstream areas we do not realize measurements of horizontal displacements and the elevation changes are normally greater than the measured uncertainty for each period.

Photogrammetry processing has been carried out using Pix4Dmapper 4.5.6 software separately for each RG and for each different date, resulting in 40 different orthophotos and 40 DSMs (10 for each RG) with pixel resolutions between 0.2 to 0.7m. Unfortunately, it was not possible to obtain satisfactory models from 2003 due to lower levels of overlap in the imagery.

UAV in Val da l’Acqua (2022)

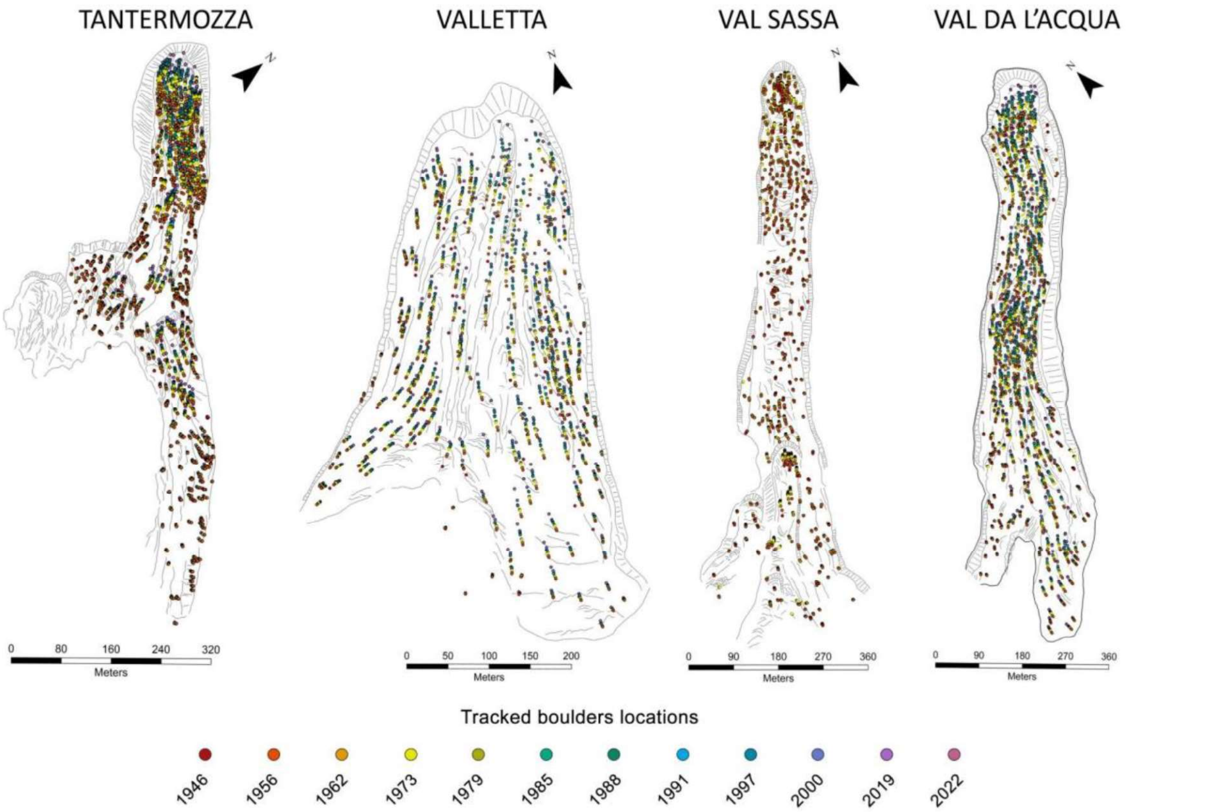
After the aperture of new cracks exposing fresh ice in the Contributing Glacier of Val da l’Acqua during 2022 summer of 2022, the GIS group of the SNP asked for a UAV survey in order to map the observed geomorphological changes. Hence, we carried out the survey covering the entire Contrubuting Glacier and RG area during September 2022, using an Ebee RTK drone. Through the same photogrammetry procedure as used for the historical imagery, we created an orthophoto and a DSM with a resolution of 10 cm per pixel. In this case, the use of GCPs was not necessary, since the RTK gave a better average horizontal and vertical accuracy of + - 2 cm for the entire area. These UAV orthophoto and DSM were used as reference for the co-registration of the rest of Val da l’Acqua photogrammetry models from the historical imagery.

Horizontal velocities assessment - Manual boulder tracking

Horizontal velocities were assessed by visual identification and tracking of boulders through consecutive images, using the orthophotos obtained from photogrammetry. As the upstream limit of the active areas are normally diffuse and may evolve over time, we tracked boulders up to the areas upstream where we do not identify any movement starting from the oldest period (1946-1956). With that, we have defined for each RG an active area limit within which we have evaluated the subsequent dynamic analyses.

The total number and density of point locations per rock glacier is dependent on the availability of boulders on the surface of each RG, trying to ensure that in each case there is a homogeneous spatial distribution, which is necessary for a subsequent interpolation of the speeds for the entirety of the RG active areas. In total, for the four RGs analyzed, we have interpreted and manually digitized 12,000 different boulder locations along the different periods (Figure 8).

Horizontal velocities for each period were calculated by computing the linear distance between XY coordinates of each tracked boulder at each date and dividing it by the number of years for the corresponding period, to obtain average surface displacements in cm per year. Finally, we created 1 m pixel resolution interpolated velocity maps for each period (Figure 4) by Inverse Distance Weight (IDW) interpolation method, using the active RG limit as a boundary area with zero velocity value.



	Maximum nr. of tracked boulders per period	Area (ha)	Density(points/ha)
TANTERMOZZA	443	10.9639	40.4053
VALLETTA	228	14.9836	15.2166
VAL SASSA	373	17.1899	21.6988
VAL DA L'ACQUA	299	18.7165	15.9752

Figure 8. Locations of tracked boulders. Positions of the 12,000 manually tracked boulders that have been used to calculate horizontal surface velocities for different periods between 1946-2022 for the four rock glaciers. The table below shows the tracked boulder densities and area (ha) of each rock glacier active area.

Elevation Change – DSM differences

Elevation changes were calculated by means of DSM differences (DSM-d) to estimate cell by cell the change between the different DSMs. Computations were performed for the entire catchment area of each RG, in order to include both active RG areas and contributing areas. Besides, DSM-d were only established for DSM datasets in which the upstream area does not show important snow cover and/or too much noise. For the most recent dataset we used the 0.5m SwissALTI3D 2015 DSM from Swisstopo. Taking these criteria into account, the periods in which DSM-d have been computed are: 1956-1962-1973-1988-1991-1997-2015 for Tantermozza; 1956-1962-1973-1991-2015 for Valletta and Val Sassa; 1956-1973-1988-1991-2000-2015-2022 for Val da l'Acqua (Figure 4 and Figure 5).

Despite the manual removal of the point cloud noise during the photogrammetry processing, final DSMs could still present wrong pixels that needed to be masked for the purpose of removing miscalculations in DSM-d. Noise masking areas were manually digitized by interpreting DSM hill-shades where these errors were easily identifiable (Supplementary material 8). Finally, total elevation differences were divided by the number of years during each corresponding period to obtain elevation changes in cm per year.

Inferred Contributing Glacier extensions

Contributing Glaciers in our study area are currently covered by debris material, hiding partially (Tantermozza and Valletta) or completely (Val Sassa and Val da l'Acqua) their boundary limits. The debris cover layer has been evolving since 1946, when the total exposed ice area was much greater than in recent decades, creating challenges for mapping the historical presence of ice bodies. Here we infer the most probable historical glacier boundaries by assuming that ice presence must be related with the areas in which the highest elevation changes occur. Accordingly, big negative values in the DSM-d would correspond to periods with considerable ablation and important positive DSM-d values with accumulation periods

In a context in which the ablation is continuous for a total period of time, the longer the period considered, the greater the negative differences in the DSM-d values and, therefore, the limits in which this process occurs will be better spatially defined. Thus, we compute DSM-d between the different DSMs and the most recent DSMs (2015 for Tantermozza, Valletta and Val Sassa and 2022 for Val da l'Acqua). From these longer-period DSM-d maps, the limits of the total negative elevation difference, which would most likely correspond with the most probable ice melting area during the entire period, are clearly recognizable (Supplementary material 4). We analyze these limits together with visual interpretation of geomorphological features in the corresponding orthophotos, to finally digitize the boundary of the most probable maximum ice extension on each date and infer it as the most probable Contributing Glacier boundaries for each historical dataset. Furthermore, we compare our inferred extents with previously published historical extents in the Swiss Glacier Inventories of 1850 (SGI1850 from Dufour map), 1900, 1935 (Siegfried maps) and 1973 (SGI1973) (Müller et al., 1976; Maisch et al., 2000).

Volume change calculations

For each time period, we have used the DSM-ds to individually determine the total volume change within active RG areas and inferred Contributing Glacier boundaries. For simplification, we have only referred to the inferred area of the Contributing Glaciers and not to the entire contributing area, since in all cases the volume change in the inferred areas of the Contributing Glacier corresponds to more than 95% of the total volume change of the contributing area. Also, in Tantermozza we have not considered the marginal westernmost inferred glacier areas as it would not drain directly over the RG active area.

To compute total volumes from DSM-d where voids are present after the masking of the DSM noise areas, we use the *Mean elevation difference by elevation bin method.* This is a broadly used approach (e.g., Kronenberg et al.,2016, Brun et al., 2017, Dussaillant et al., 2018), which has proved accurate for mass balance calculations when using unfilled DEMs or DSMs (McNabb, 2019, Huber et al. 2020). This method involves firstly computing the DSM-ds using the voided DSM and binning the resulting raster in bigger grid cells with the mean values of the aggregated pixels. The choice of the bins (or grid cells) size depends on the total elevation range for the area considered. We follow McNabb's (2019) recommendations of using a grid cell size equal to 10% of the elevation range in our analyzed area. This first step will fill the smaller voids in the DSM-ds. To fill the remaining voids, the binned raster is interpolated by a third order Local Polynomial interpolation. Finally, to obtain the volume per grid cell, the resulting mean elevation change binned raster needs to be multiplied by the area of each grid cell. The total volume for each analyzed area consists of the total sum of the bin volumes within the boundary areas. (Supplementary material 2).

Uncertainty assessment of photogrammetry measures

Even with the use of identical GCPs during the photogrammetric process, there may be significant local distortions in the alignment of the generated orthophotos and DSMs. This translates into an imprecision in the co-registration of the images that must be taken into account as relative uncertainties in the horizontal and vertical measurements. The uncertainty should be considered as a threshold measure or level of detection (LoD) (Vivero et al., 2022), above which we can begin to consider our displacement measurements as reliable. To quantify horizontal and vertical overall errors on each dataset comparison (Supplementary material 9), we firstly create random points in mapped un-changed bedrock areas, which are as close as possible to the RG and the inferred Contributing Glacier areas. Then, we register both vertical and horizontal differences of these random points for each image-pair and interpolate them (IDW), with the aim of avoiding spatial bias in the target areas. From this interpolated vertical and horizontal relative error maps we compute for each period the mean and standard deviation values within each rock glacier and Contributing Glacier areas. Finally, the horizontal uncertainty can be considered as the mean values ($disp\_\underline{xy}$) plus 2 times the standard deviation ($disp\sigma_{xy}$) (95% confidence level) of the displacements (Equation 1) (Fleicher et al., 2021).

$$error_{xy} = disp_{\underline{xy}}\,(epoch1 - epoch2) +\; 2\,disp\sigma_{xy}\,(epoch1 - epoch2) \quad (1)$$

Meanwhile, the vertical error can be considered as 2 times the standard deviation of the DSM-d in the stable areas ($disp\sigma_z$) (Fey and Krainer, 2020) and the volume uncertainty ($error_V$) for each Contributing Glacier or RG area results from the multiplication of the vertical error by the corresponding area (Equation 2)

$$error_V = \{2\,disp\sigma_z\,(epoch1 - epoch2)\}\,(area) \quad (2)$$

References

1. Ackert, jr., R. P. A rock glacier/debris-covered glacier system at Galena Creek, Absaroka Mountains, Wyoming. Geografiska Annaler: Series A, Physical Geography 80, 267–276 (1998).

2. Allen, M.R. et alFraming and Context. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty: Cambridge University Press, Cambridge, UK and New York, NY, USA, 49-92 (2018)

3. Arenson, L., Hoelzle, M. & Springman, S. Borehole deformation measurements and internal structure of some rock glaciers in Switzerland. Permafrost and Periglacial Processes 13, 117–135 (2002).

4. Bearzot, F. et al. Kinematics of an alpine rock glacier from multi-temporal UAV surveys and GNSS Data. Geomorphology 402, 108116 (2022).

5. Berthling, I. Beyond confusion: Rock glaciers as cryo-conditioned landforms. Geomorphology 131, 98–106 (2011).

6. Bertone, A. et al. Incorporating insar kinematics into rock glacier inventories: Insights from 11 regions worldwide. The Cryosphere 16, 2769–2792 (2022).

7. Boeckli, L., Brenning, A., Gruber, S. & Noetzli, J. Permafrost Distribution in the European alps: Calculation and evaluation of an index map and summary statistics. The Cryosphere 6, 807–820 (2012).

8. Brencher, G., Handwerger, A. L. & Munroe, J. S. Insar-based characterization of Rock Glacier Movement in the Uinta Mountains, Utah, USA. The Cryosphere 15, 4823–4844 (2021).

9. Brun, F., Berthier, E., Wagnon, P., Kääb, A. & Treichler, D. A spatially resolved estimate of High Mountain Asia Glacier Mass balances from 2000 to 2016. Nature Geoscience 10, 668–673 (2017).

10. Buchli, T. et al. Kinematic investigations on the Furggwanghorn Rock Glacier, Switzerland. Permafrost and Periglacial Processes 29, 3–20 (2018).

11. Copernicus. C3s Climate Bulletin shows Summer 2022 was Europe's warmest on record. Home Available at: https://climate.copernicus.eu/c3s-climate-bulletin-shows-summer-2022-was-europes-warmest-record. (Accessed: 7th August 2023)

12. Capps, S. R. Rock Glaciers in Alaska. The Journal of Geology 18, 359–375 (1910).

13. Chaix, A. Les coulées de blocs du Parc National suisse d'engadine (note préliminaire). Le Globe. Revue genevoise de géographie 62, 1–35 (1923).

14. Chaix, A. Les coulées de blocs du Parc National Suisse. nouvelles mesures et comparaison avec les «rock stream» de la sierra nevada de californie. Le Globe. Revue genevoise de géographie 82, 121–128 (1943).

15. Cicoira, A. et al. A general theory of Rock Glacier Creep based on in-situ and Remote Sensing Observations. Permafrost and Periglacial Processes 32, 139–153 (2020).

16. Cicoira, A., Beutel, J., Faillettaz, J. & Vieli, A. Water controls the seasonal rhythm of Rock Glacier Flow. Earth and Planetary Science Letters 528, 115844 (2019a).

17. Cicoira, A., Beutel, J., Faillettaz, J., Gärtner-Roer, I. & Vieli, A. Resolving the influence of temperature forcing through heat conduction on Rock Glacier Dynamics: A numerical modelling approach. The Cryosphere 13, 927–942 (2019b).

18. Croce, F. A. & Milana, J. P. Internal structure and behaviour of a Rock Glacier in the arid Andes of Argentina. Permafrost and Periglacial Processes 13, 289–299 (2002).

19. Cusicanqui, D. et al. Interpretation of volume and flux changes of the Laurichard Rock Glacier between 1952 and 2019, French Alps. Journal of Geophysical Research: Earth Surface 126, (2021).

20. Delaloye, R., Lambiel, C. & Gärtner-Roer, I. Overview of rock glacier kinematics research in the Swiss alps. Geographica Helvetica 65, 135–145 (2010).

21. Dusik, J.-M. et al. Influence of glacier advance on the development of the multipart Riffeltal Rock Glacier, Central Austrian Alps. Earth Surface Processes and Landforms 40, 965–980 (2015).

22. Dussaillant, I., Berthier, E. & Brun, F. Geodetic mass balance of the northern Patagonian Icefield from 2000 to 2012 using two independent methods. Frontiers in Earth Science 6, (2018).

23. Fey, C. & Krainer, K. Analyses of UAV and GNSS based flow velocity variations of the Rock Glacier Lazaun (ötztal Alps, South Tyrol, Italy). Geomorphology 365, 107261 (2020).

24. Fleischer, F. et al. Multi-decadal (1953–2017) rock glacier kinematics analysed by high-resolution topographic data in the Upper Kaunertal, Austria. The Cryosphere 15, 5345–5369 (2021).

25. Guglielmin, M., Ponti, S. & Forte, E. The origins of Antarctic Rock Glaciers: Periglacial or glacial features? Earth Surface Processes and Landforms 43, 1390–1402 (2018).

26. Haeberli, W. Creep of mountain permafrost: Internal structure and flow of Alpine Rock Glaciers. (wydawca nieznany, 1985).

27. Hartl, L. et al. Multi-sensor monitoring and data integration reveal cyclical destabilization of the äußeres Hochebenkar Rock Glacier. Earth Surface Dynamics 11, 117–147 (2023).

28. Jäckli, H. Der Blockstrom in der Val da l'Acqua im Schweizerischen Nationalpark. Jahrbuch der Schweizerischen Naturforschenden Gesellschaft. Annuaire de la Société Helvétique des Sciences Naturelles 158 (1978)

29. Jones, D. B., Harrison, S., Anderson, K. & Whalley, W. B. Rock glaciers and Mountain Hydrology: A Review. Earth-Science Reviews 193, 66–90 (2019).

30. Kääb, A. et al. Inventory and changes of Rock Glacier creep speeds in Ile Alatau and Kungöy Ala-too, Northern Tien Shan, since the 1950s. The Cryosphere 15, 927–949 (2021).

31. Kääb, A., Frauenfelder, R. & Roer, I. On the response of rockglacier creep to surface temperature increase. Global and Planetary Change 56, 172–187 (2007).

32. Kenner, R. et al. Factors controlling velocity variations at short-term, seasonal and multiyear time scales, Ritigraben Rock Glacier, western Swiss Alps. Permafrost and Periglacial Processes 28, 675–684 (2017).

33. Kenner, R. Geomorphological analysis on the interaction of alpine glaciers and rock glaciers since the Little Ice Age. Land Degradation & Development 30, 580–591 (2018).

34. Kenner, R., Pruessner, L., Beutel, J., Limpach, P. & Phillips, M. How rock glacier hydrology, deformation velocities and ground temperatures interact: Examples from the Swiss alps. Permafrost and Periglacial Processes 31, 3–14 (2019).

35. Kronenberg, M. et al. Mass-balance reconstruction for Glacier No. 354, Tien Shan, from 2003 to 2014. Annals of Glaciology 57, 92–102 (2016).

36. Kunz, J., Ullmann, T. & Kneisel, C. Internal structure and recent dynamics of a moraine complex in an Alpine Glacier Forefield revealed by Geophysical Surveying and sentinel-1 insar time series. Geomorphology 398, 108052 (2022).

37. Luetschg, M. & Haeberli, W. Permafrost evolution in the Swiss alps in a changing climate and the role of the snow cover. Norsk Geografisk Tidsskrift - Norwegian Journal of Geography 59, 78–83 (2005).

38. Maisch, M., et al.. Die Gletscher der Schweizer Alpen: Gletscherhochstand 1850, Aktuelle Vergletscherung, Gletscherschwundszenarien. Schlussbericht NFP 31. (Second edition. Zurich: vdf Hochschulverlag ETH Zurich, 373 p 2000).

39. Marcer, M. et al. Rock glaciers throughout the French Alps accelerated and destabilised since 1990 as air temperatures increased. Communications Earth & Environment 2, (2021).

40. Maurer, H. & Hauck, C. Geophysical Imaging of Alpine Rock Glaciers. Journal of Glaciology 53, 110–120 (2007).

41. Monnier, S. & Kinnard, C. Reconsidering the glacier to rock glacier transformation problem: New insights from the Central Andes of Chile. Geomorphology 238, 47–55 (2015).

42. Monnier, S. & Kinnard, C. Pluri-Decadal (1955–2014) evolution of glacier–rock glacier transitional landforms in the Central Andes of Chile (30–33°S). Earth Surface Dynamics 5, 493–509 (2017).

43. Monnier, S., Camerlynck, C., Rejiba, F., Kinnard, C. & Galibert, P. Evidencing a large body of ice in a Rock Glacier, vanoise massif, northern French Alps. Geografiska Annaler: Series A, Physical Geography 95, 109–123 (2013).

44. Müller, F., Caflisch, R., Müller, G. . Firn und Eis der Schweizer Alpen: Gletscherinventar (Vol. 57-57a, Publ. / Geographisches Institut, Eidgenössische Technische Hochschule). (Zürich: ETH, Geographisches Institut 1976).

45. Potter, N. Ice-cored Rock Glacier, Galena Creek, Northern Absaroka Mountains, Wyoming. Geological Society of America Bulletin 83, 3025 (1972).

46. Sommer, C. et al. Rapid glacier retreat and downwasting throughout the European Alps in the early 21st Century. Nature Communications 11, (2020).

47. Springman, S. M. et al. Rock Glacier degradation and instabilities in the European Alps: A characterisation and monitoring experiment in the Turtmanntal, CH. Landslide Science and Practice 5–13 (2013). doi:10.1007/978-3-642-31337-0_1

48. SwissALTI3D. Federal Office of Topography swisstopo (2023). Available at: https://www.swisstopo.admin.ch/en/geodata/height/alti3d.html. (Accessed: 7th August 2023)

49. Swissimage. Bundesamt für Landestopografie swisstopo (2023). Available at: https://www.swisstopo.admin.ch/de/geodata/images/ortho/swissimage10.html. (Accessed: 7th August 2023)

50. Vivero, S., Hendrickx, H., Frankl, A., Delaloye, R. & Lambiel, C. Kinematics and geomorphological changes of a destabilising rock glacier captured from close-range sensing techniques (Tsarmine Rock Glacier, western swiss alps). Frontiers in Earth Science 10, (2022).

51. Waller, R. I. Permafrost and periglacial features | permafrost and Glacier Interactions. Encyclopedia of Quaternary Science 507–513 (2013). doi:10.1016/b978-0-444-53643-3.00107-2

52. Wuebbles, D. J. et al. Executive summary. climate science special report: Fourth national climate assessment, volume I (2017). doi:10.7930/j0dj5ctg

53. Yi, S., Woo, M. & Arain, M. A. Impacts of peat and vegetation on permafrost degradation under climate warming. Geophysical Research Letters 34, (2007).

A unique record of rock glacier kinematics and glacier interactions from the Swiss National Park spanning more than 100 years

Alberto Muñoz-Torrero Manchado [a;] *Simon Allen* [a,b], *Alessandro Cicoira* [b], *Samuel Wiesmann* [c], *Ruedi Haller* [c], *Markus Stoffel* [a,d,e]

> redacted 03/10/202
> Nota adhesiva
> ';' or ','?

AFFILIATIONS

a Climate Change Impacts and Risks in the Anthropocene (C-CIA), Institute for Environmental Sciences, University of Geneva, 66 Bvd Carl-Vogt, CH-1205 Geneva, Switzerland

b Department of Geography, University of Zurich, Switzerland

c Swiss National Park, Runatsch 124, Chastè Planta-Wildenberg, CH-7530 Zernez, Switzerland

d Department of Earth Sciences, University of Geneva, 13 rue des Maraîchers, CH-1205 Geneva, Switzerland

e Department F.-A. Forel for Environmental and Aquatic Sciences, , University of Geneva, 66 Bvd Carl-Vogt, CH-1205 Geneva, Switzerland

> redacted 03/10/2023 12:59:46
> Nota adhesiva
> delete ','

ABSTRACT

The rock glaciers of the Swiss National Park were the first in the world where in-situ measurements of surface displacement were undertaken, starting with the pioneering work of Chaix in 1918. This globally unique long-term record is a main reason why these rock glaciers have recently been ordained by UNESCO as one of the top 100 IUGS geological world heritage sites. With our work we have filled the gap previously existing between the measurements from the early 20th century and the most recent measurements made over the last two decades. Through the application of photogrammetric techniques, we use this unique record spanning more than a century to geomorphologically analyze the spatiotemporal evolution of rock glaciers in the region, and to disentangle the interplay with their contributing glaciers. We show that these rock glaciers are in different phases of degradation with a general trend of deceleration and loss of volume. We observe how changes in kinematics seem to be historically controlled by the hydrological contribution of their nearby glaciers, with which they have been in close contact since the end of the Little Ice Age, but which are now severely degraded.

HIGHLIGHTS

- We provide the longest time series of rock glacier velocities worldwide (1918-2022)
- Evidence exists for a deceleration of movement and total volume loss due to permafrost degradation
- Glacier ablation and significant retreat are observed at the rock-glacier root zone after the end of the Little Ice Age
- Long term rock glacier kinematics seem heavily influenced by glacier changes

Introduction

In October 2022, rock glaciers (RG) of the Engadin (Southeastern Swiss Alps) were included by UNESCO as one of the 'First 100 International Union of Geological Sciences (IUGS) Geological Heritage Sites' (IUGS, 2022). This recognition was based on the high relevance of these RG, which serve as reference for permafrost research in the Alps and where displacement rates measured over a period extending for more than 100 years are the oldest available globally. RGs are described as lobed or tongue-shaped landforms formed by a mixture of ice and frozen debris that are setting-up through gravity-driven creep (Reinosch et al., 2021). They are also known to react sensitively to climate change.

> redacted 02/10/2023 09:07:18
> Nota adhesiva
> Rock glaciers respond much more slowly than glaciers to climate changes. Perhaps it would be appropriate to include some reference to this aspect.

> redacted 02/10/2023 09
> Nota adhesiva
> This work does not appear in the References section, p check this carefully.

Shortly after the creation of the Swiss National Park (SNP) in 1914, Emile and André Chaix made the first *in-situ* measurements of the velocity of a RG in the world (Chaix, 1923). During their fieldwork in 1918 and subsequent years, they assessed four RG in the SNP. Even if at that time, Chaix did not associate them as equivalent forms to those first described as RG by Capps (1910) in Alaska, in later decades it was known that they were actually the same (Wharhafting and Cox 1959) and thus making these RGs the first ones to be described in the European Alps. The four RGs analyzed by Chaix (1923) were Val Sassa and Val da l'Acqua, where the most extensive measurements and analyses were realized, as well as Valletta and Tantermozza, which they simply visited and briefly described. Two decades later, André Chaix took new measurements again on the same boulders in Val Sassa and Val da l'Acqua (Chaix 1943). However, after these pioneering measurements, for decades, there have been no new velocity data registered, until the most recent annual Differential Global Navigation Satellite System (DGNSS) measurements in Val Sassa and Val da l'Acqua were initiated by the GIS group of the SNP in 2006.

> redacted 02/10/2023
> Nota adhesiva
> The recent work of Fleischer et al. (2023) date back https://doi.org/10.1002/ppp.2178

> redacted 02/10/2023 09:08:11
> Nota adhesiva
> Chaix, 1943

So far, the longest kinematic analysis carried out on RGs reach back to the late 1940s or mid-1950s (e.g. Cusicanqui et al., 2021; Kääb et al., 2021; Fleischer et al., 2021; Marcer et al. 2021; Hartl et al., 2023). These long-term analyses are normally based on photogrammetric measurements from historical, vertically acquired aerial images, which can complement, or not, more recent GNSS surface measurements combined with Unnamed Aerial Vehicle (UAV) imagery (Fey and Krainer, 2020; Bearzot et al., 2022), interferometric (Brencher et al., 2021; Bertone et al., 2022) and geophysical (Maurer and Hauck, 2007; Kunz et al., 2022) analysis, or data from permafrost temperature boreholes (Arenson et al., 2002; Buchli et al., 2018; Kenner et al., 2018). From these regional to local analyses, some consensus is emerging that there has been an acceleration in the movement of rock glaciers in the Alps in recent decades, in parallel with the global increase in mean air temperature (Kääb et al., 2007; Delaloye et al., 2010; Marcer et al., 2021).

> redacted 03/10/2023 13:05:52
> Nota adhesiva
> Consider to add some more references. For example:
> Kellerer-Pirklbauer, A., & Kaufmann, V. (2012). ABOUT THE RELATIONSHIP BETWEEN ROCK GLACIER VELOCITY AND CLIMATE PARAMETERS IN CENTRAL AUSTRIA. Austrian Journal of Earth Sciences, 105(2).
>
> Cusicanqui, D., Rabatel, A., Vincent, C., Bodin, X., Thibert, E., & Francou, B. (2021). Interpretation of volume and flux changes of the Laurichard rock glacier between 1952 and 2019, French Alps. Journal of Geophysical Research: Earth Surface, 126(9), e2021JF006161.
>
> Tanarro, L. M., Palacios, D., Andrés, N., Fernández-Fernández, J. M., Zamorano, J. J., Sæmundsson, Þ., & Brynjólfsson, S. (2019). Unchanged surface morphology in debris-covered glaciers and rock glaciers in Tröllaskagi peninsula (northern Iceland). Science of the total environment, 648, 218-235.

Theoretically, the acceleration of a RG can be due either to internal plastic deformation or basal shearing (Arenson et al., 2002; Cicoira et al., 2020). Internal plastic deformation can be enhanced by an increase of the permafrost temperature, causing changes in the viscosity and a reduction of the mechanical strength of the ice rich layer (Roer et al., 2008; Muller et al., 2016; Cicoira et al., 2019a). Meanwhile, most of the shear deformation takes place in the shear horizon, at about 20 m depth (Cicoira et al., 2020), where *in-situ* observations and modeling studies have suggested that water supply from rainfall, snowmelt or melting of ground ice play a major role (Arenson et al., 2002; Ikeda et al., 2008; Cicoira et al., 2019b). RG movement actually is a superimposition of both phenomena, on which the relative role played from each one will depend on the specific characteristics of the RG, including its geometry, structure and material rheology. Thus, for RGs where there is a limited contribution of rainwater or snowmelt on its surface, the dominant water inputs could be more related to the

> redacted 02/10/2023 09:12:41
> Nota adhesiva
> ;

> redacted 03/10/2023 13:05:46
> Nota adhesiva
> ;

contributions of upstream catchment water (Croce & Milana, 2002). In this case, when RGs are spatially related to the presence of adjacent glaciers melting at a rapid rate, as currently occurs in the Alps (Sommer et al., 2020), this could have a major influence on the current and future RG dynamics during dry periods.

The interaction between glaciers and RGs, in terms of the origin of RG ice, has been a subject of debate since the beginning of the study of these landforms. In fact, already in his 1923 work, Chaix described the observed RGs in the SNP as landforms possibly originating from the degradation of the frontal moraines of the receding upstream glaciers. Nowadays, debate still exists regarding the origin and formation of RGs, based on two theories that were initially opposed. On the one hand, there is the permafrost model (Wahrhaftig and Cox 1959; Haeberli, 1985) whereby the internal ice has predominantly a permafrost origin. On the other hand, the ice-core theory suggests a predominantly glacial provenance (Potter, 1972; Monnier et al., 2013; Guglielmin et al., 2018). These are two simplified theoretical end members, but other studies (Berthling, 2011) propose that a synergy between both models is possible in areas where there is a glacial-periglacial coexistence (Dusik et al., 2015; Monnier and Kinnar, 2015, 2017; Kenner et al., 2019). Yet, previous RG dating studies have typically recorded ages between 10,000 and 3,000 yrs (e.g., Böhlert et al., 2011; Amschwand et al., 2021) which supports the more widely accepted hypothesis of a pure permafrost origin, which is independent of the influence of glacier ice.

In the case of the four RGs in the SNP, each of them shows evidence of being spatially associated with glaciers that were already mapped on the first official topographic map of Switzerland at the end of the Little Ice Age (LIA) - the 1850 Dufour map (Maisch et al., 2000). However, these glaciers do no longer appear as glaciers in the Swiss Glacier Inventory (SGI) of 1973 (Müller et al., 1976), even though bare glacier ice can still be seen at Tantermozza and Valletta. Meanwhile, for Val Sassa and Val da l'Acqua, one could hypothesize that these were currently extinct glaciers because according to satellite and historical aerial images from Swisstopo (Swissimage, 2023), there was almost no visible ice for decades. However, the extraordinarily hot summer of 2022 (Copernicus, 2023) triggered openings in the debris that exposed glacial ice in both basins (Figure 1) and confirmed the current existence of debris-covered glaciers in these two valleys as well.

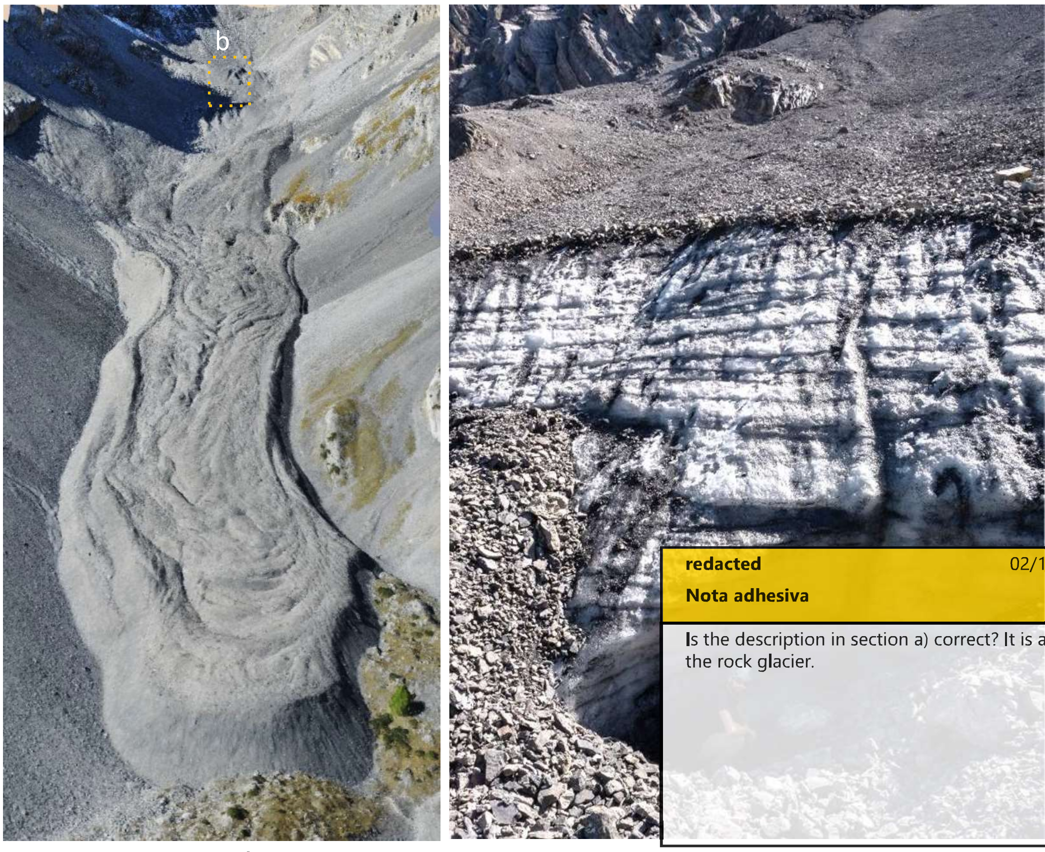
The recent emergence of glacier ice, still visible in these two valleys, has motivated the present work, in which we have had the two primary aims of (i) filling, for the first time, the existing gap between the recent RGs surface velocity measurements and the ones made over a hundred years ago by Émile and André Chaix; and (ii) using this unique data series to study the historical evolution of the glaciers remaining in the contributing areas, which we will refer hereafter as Contributing Glaciers (CG) to investigate the possible interrelationships of these with the RGs. For both purposes, we use photogrammetric techniques with recent UAV imagery and hundreds of historical aerial images from different periods since 1946, which completely cover the catchments of the four RGs analyzed here. These are the same RGs described by Chaix in 1918: Tantermozza, Valletta, Val Sassa and Val da l'Acqua (Figure 2). Using photogrammetry, we have been able to reconstruct high-resolution orthophotos and digital surface models (DSM) for each period and each of the four RGs analyzed. Based on these outputs, we subsequently realized manual measurements of horizontal surface velocities of the RGs yielding more than 100 years of continuous surface velocities, and thereby to establish the longest RG kinematics time-series from observational measurements. In addition, we assessed volume and geometry changes, both across the RGs and

redacted 02/10/2023 13:49:44
Nota adhesiva
Consider to add some sentences about the interaction of glaciers and rock glaciers during the LIA. For example, in Tantermozza results, the authors indicate that 'the more chaotic surficial geometries, possibly caused by the CG overriding this portion of the RG during the LIA'. I suggest to include references to the work of Kenner (2018) (https://doi.org/10.1002/ldr.3238) that should be relevant for the topic of this manuscript. Also related works: Palacios et al. (2021) (https://doi.org/10.1016/j.geomorph.2021.107787)

redacted 02/10/2023 09:45:24
Nota adhesiva
Also, transition between glaciers and rock glaciers has been shown in several works (i.e. https://doi.org/10.1016/j.gloplacha.2019.102999.) The work of Sanjosé Blasco et al. (2022) could be also relevant (https://doi.org/10.3390/land11050613)

redacted 02/10/2023 09:56:47
Nota adhesiva
I'm not sure the term 'Contributing glaciers' is correct. It should be noted that it is not clear whether the rock glacier formed before the glacier (and then the glacier partially advanced over the rock glacier during the LIA) or the rock glacier was generated from the retreat of that glacier (see Kenner, 2018). https://doi.org/10.1002/ldr.3238

the surfaces that were most probably covered by the CGs in the past. The extensions of CGs have been inferred from bare ice sighting and geomorphic observations based on historical imagery, together with the analysis of extremely negative elevation changes observed between successive DSMs, clearly greater in the case of CGs as compared to RGs. These analyses helped detect a common decelerating trend in the velocity and ice degradation in RGs, along with a significant CG degradation. The progressive retreat and over-deepening of the CGs are thus thought to have diminished their 'pushing' upon the RGs, through the formation of a dynamic discontinuity in the landform, which could no longer sustain the high displacement rates of RGs after the end of the post LIA.



redacted 02/10/2023 09:50:38

Nota adhesiva

Is the description in section a) correct? It is a general view o the rock glacier.

Figure 1. Exposed ice in Val da l'Acqua rock glacier. During the extraordinarily hot summer of 2022, several ablation and subsidence cracks occurred, exposing ice in Val da l'Acqua and Val Sassa in the Swiss National Park (Grisons, Switzerland). (a) Dense point cloud of the Val da l'Acqua rock glacier obatained from a UAV survey in September 2022. At the top part, one can observe exposed ice masses shown in detail in (b).

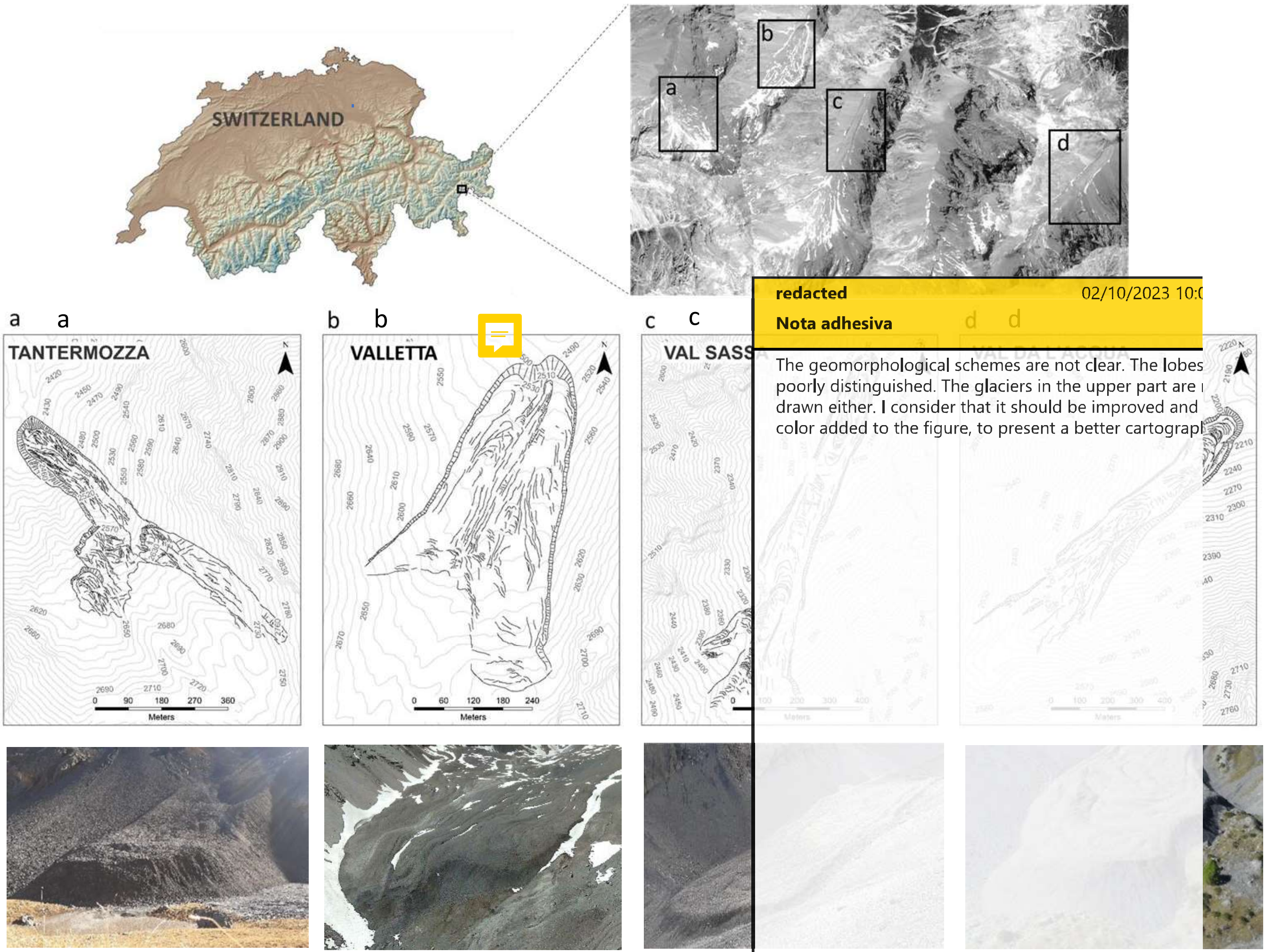


Figure 2. Study area. The four rock glaciers (RGs) and their catchment areas are located within a 5-km radius, entirely within the Swiss National Park (Grisons, Switzerland). All RG are tongue shaped type, creeping downwards in valleys with steep sidewalls of predominantly dolomitic lithology. **a) Tantermozza** has four well-differentiated lobes, 700-m long and 300-m wide, all facing NW. With an average slope of 34%, the RG extends from 2,430–2,730 m a.s.l., the upper limit of the accumulation zone of the CG reaches up to 2,900 m a.s.l., at a distance of 1300 m from the RG front. **b) Valletta** has a single tongue facing N, it is 700 m long and 350 m at its widest area, with an average slope of 22%, at elevations between 2,490 and 2,660 m a.s.l. The upper limit of the accumulation zone of the CG is at 2,880 m a.s.l., 1500 m away from the RG front. **c) Val Sassa** is a very elongated RG facing N, with a well-differentiated main lobe in the lower zone and different minor lobes in the upper zone, it is 1180 m long and 150–200 m wide. With an average slope of 23.5%, it is found between 2,110 and 2,380 m a.s.l whereas the upper limit of the CG is at 2,800 m a.s.l., at some 2,400 m from the RG front. **d) Val da l'Acqua** has a single tongue, 1170 m long by 140-220m wide, facing NE. With an average slope of 24%, it is located between 2,430 and 2,730 m a.s.l. whereas the upper limit of the accumulation zone of the CG is found at 2,890 m a.s.l., some 2,300 m from the RG front.

Results

The four RGs show a decelerating trend in mean and maximum surface velocities since 1918 (Val Sassa and Val da l’Acqua) and 1946 (for Tantermozza and Valletta) (Figs. 3–4; Supplementary Material SM1). Whereas some acceleration can be found in Val Sassa and Tantermozza in the 1950s, such an increase in displacement rates occurs in Val da l'Acqua in the 1960s. This temporary increase in velocities was followed by a continuous slowdown in movement rates from the 1960s and 1970s, with a common minimum at all sites between 1985/88 and 1991. After a slight acceleration in the 1990s, a steady slowdown has been observed since the turn of the 21st century, reaching record low displacement rates in recent years. This general deceleration occurs in parallel to a significant volume loss at Val Sassa and Valletta (Figs. 5 and 6, Table 1; SM 2 and 3). Whereas elevation changes are also observed at Tantermozza and Val da l'Acqua, volume loss in the upper reaches is compensated by accumulations at the RG fronts, resulting in overall volumes today that are comparable to those of 1956. By contrast, we observe a significant continuous volume loss in all the CG since 1956, both. These CG show a reduction in area and retreat of the glacial fronts from positions similar to those occupied at the end of the LIA in 1850 (Fig. 7 and SM4), which supposedly remained in direct contact with the active areas of the RGs.

In the following, we describe the evolution of each RG in terms of surface velocities (Figs. 3–4), volume changes Figs 5–6, Table 1) as well as historical CG extensions (Fig. 7, as well as SM1–5).

Tantermozza

Tantermozza exhibits heterogeneous kinematics across three different zones (Figs. 3–4): The front and the middle zone of the lobe further downstream, with well-developed transversal ridges (T1); the upper zone of this lobe with longitudinal ridges in the flow direction (T2); the two northernmost upper lobes (T3) with more chaotic surficial geometries, possibly caused by the CG overriding this portion of the RG during the LIA. Meanwhile, we have not observed horizontal displacements in the southernmost lobe. It presents a loss of elevation between 1956 and 2015 in these three zones, with a transition from convex shapes to a flattening in the front of T1 and with overdeepening and loss of volume of the central part in T2 and T3. Simultaneously, the CG presents a total volume loss of 2.15 ($\pm$ 0.082) million m^3 between 1956-2015, which corresponds to a total loss of 16.99 m of water equivalent (m w.e.) or tons per m^2.

At the end of the LIA, the position of the glacial front occupied a location immediately in contact with the upper part of the active RG, partly overriding T3. In 1935 and until 1956, even if some glacier retreat had occurred, significant ice bodies persisted in similar positions close to the upper lobes (T3). In an image acquired by Chaix in 1919 (SM5), as well as in the terrestrial images of 1935, we observe a marked convex transverse shape for all the active lobes of Tantermozza. During 1946-1956, maximum velocities occurred at the very front of T1, equal to 2.5 $m\ a^{-1}$, followed by 2 $m\ a^{-1}$ and around 1 $m\ a^{-1}$ in T3 and T2, respectively. The period 1956-1962 was the only occasion across all four catchments during which a certain positive balance is observed in CG volume, but also positive volume change in all active RG areas. During this time, T3 maintained its velocities from the previous period, whereas important accelerations are found in T2 with 2 $m\ a^{-1}$. Longitudinal ridges were formed at that time in T2 and are still present today. Meanwhile, T1 reached the highest historical velocities among all RG with 3.1 $m\ a^{-1}$. Between 1962 and 1973, a general deceleration and volume loss can be observed; it is most significant in the upper zone of T3. This subsidence translates into a clear observable change in the geometry of the longitudinal and transverse profiles from convex (local heave) to flat and concave (depletion) shapes in the frontal areas of the upper lobes, along with a sharp drop in velocities from 2 to 0.5 $m\ a^{-1}$, these low values persist to the present day. From 1973 to 1991, a continuous deceleration is observed in the main frontal lobe where velocities decreased from 2.5 to 1.3 $m\ a^{-1}$ in T1 and from 1.7 to 0.7 $m\ a^{-1}$ in T2. This slowdown was

redacted 02/10/2023 11:00:43
Nota adhesiva
How this positive volume change occur in the RG?

redacted 02/10/2
Nota adhesiva
',' or '.'?

mostly concentrated in an area close to the RG front, where significant volume loss has occurred since 1962. This area already exhibited transversal ridges in the pictures taken by Chaix in 1919 and is easily recognizable nowadays with the naked eye, but also through the strong change in curvature along the longitudinal profile. Between 1988 and 1991, the largest volume losses occurred in T1 and T2; they went hand in hand with marked decelerations in movement velocities. Starting in 1991, strong ablation occurs from the CG: whereas velocities at T3 remained constant with 0.6 m per year, resulting in a practically invariable volume, T1 and T2 exhibit variations both in speeds and volumes. During the 1990s, both zones experienced accelerations and volume gains, with identical maximum speeds in both areas since 1997. Over the last two decades, T1 and T2 showed a similar deceleration, with displacement rates settling at about 0.8 $m\ a^{-1}$, without considerable volume change.

Valletta

Valletta presents a rather homogeneous dynamics longitudinally, with higher velocities in its eastern half. This part exhibits a continuous and homogenous flow as a single body, reflected in a characteristic morphometry of continuous longitudinal ridges and furrows, whereas transversal ridges are almost missing completely. The RG presents a total negative volume loss of 0.58 (+ - 0.081) million m^3, a general loss of elevation and flattening between 1956 and 2015, whereas its CG exhibited a loss of 1.92 (+ - 0.078) million m^3 (11.01 m.w.e).

In 1850, the position of the CG end moraine delimited quite closely the current upper limit of the active area of the RG. By 1935, the glacial front had already retreated approximately 300 m in the westernmost area and about 150 m in the eastern part according to terrestrial images. This differentiated retreat was maintained in the following two decades, with the easternmost part retreating another 200 m until 1956, whereas the eastern half remained in similar positions but with ice bodies becoming increasingly isolated from the main ice mass. Between 1946 and 1956, Valletta exhibits its highest historical velocities, with maxima of 2.5 $m\ a^{-1}$, like at Tantermozza at the same time. However, between 1956 and 1962, Valletta shows a completely opposite behavior to its neighbor with a drop of maximum velocities to ≤1.2 $m\ a^{-1}$, along with an important volume loss in the eastern part. In turn, contrary to what happened to the Tantermozza CG, the Valletta CG lost volume at an almost constant rate (~ 30,000 $m^3 a^{-1}$) ever since that period. RG velocities and volume remained constant over the next two decades, to be followed by an acceleration in velocities between 1979 and 1985. From then on, it presents variations in surface velocities that are very similar to those of Tantermozza. A clear drop in velocity is recorded between 1985 and 1991, reaching their historical lowest values (≤1 $m\ a^{-1}$), followed by a new acceleration between 1991-2000 (~2.2 $m\ a^{-1}$) and another drop in velocities to 1.2 $m\ a^{-1}$ from 2000 to 2019. This reduction in velocities was accompanied by a general volume loss across the entire RG, with a slight flattening of the surface in the longitudinal and transverse directions. Despite this flattening, the overall shape of the RG remains more convex than at the other RGs. In the contributing zones, the constant elevation loss is concentrated around the CG increasingly exhibiting the marked concave shape of the underlying bedrock.

Val Sassa

Val Sassa has has suffered the largest drop in speeds and sudden volume loss of the four RGs. Changes are not equally intense across the RG, three zones can rather be identified with specific behavior: The front of the main lobe (S1) is characterized by transversal ridges and furrows, separated from an intermediate zone (S2) with surficial signs of thinning and subsidence; this zone is followed by the lobes of the upper zone (S3). Val Sassa RG presents a total negative volume loss of 0.60 (+-0.023) million m^3 since 1956, mostly centred around S2 and S3, whereas the CG presents a total volume loss of 3.69 (+-0.166) million m^3 (11.83 m w.e).

On the 1850 Dufour map, the position of the CG front was barely 100 m away from the root zone of the Val Sassa RG. In the hiatus zone, stacked linear ridges can be identified in the 1935 oblique images, which we interpret as being push moraines; these ridges somewhat render the delimitation of the upper limit of the RG uncertain. Val Sassa showed the largest historical velocities with 2 $m\ a^{-1}$ in S1 during the first measurements of 1918-19,. A slight decrease in speeds was already documented between 1919 and 1921 (1.4 $m\ a^{-1}$). Terrestrial images acquired by Chaix in 1918, as well as oblique images from 1935 show transverse convex shapes in S1 and S3, but also first signs of depletion in S2. Velocities remained mostly unchanged in S1 and S3 until 1942. Between 1946 and 1956, we observe a deceleration, more marked in the lower (0.7 $m\ a^{-1}$ in S1 and S2) as compared to the upper (1.1 $m\ a^{-1}$ in S3) zones. Between 1956 and 1962, movement rates increased again to ≤1.6 $m\ a^{-1}$ in S1 and S3 and to 1 $m\ a^{-1}$ in S2. This acceleration is contemporaneous to the largest volume loss of the CG with 260,000 $m^3\ a^{-1}$ as well as the largest volume loss in the active area of the four RGs with 75,000 $m^3 a^{-1}$in S3. These losses also resulted in a clear general flattening of the previously convex landforms. During this same period, some aggradation occurred in zones S1 and S2. By this time, the area of the CG was clearly reduced compared to 1850, but an important body of isolated ice persisted in at locations that were still in contact with the upper part of the RG. Looking at the longitudinal profile, the upper parts of the CG already presented a general concave shape in 1956 which was even exacerbated after this great volume loss. From 1962 to 1973, Val Sassa RG velocities reduced in S1 and S3 down to 0.7 $m\ a^{-1}$ (i.e. to a third of previous values), with an even more dramatic drop in S2 where movement dropped to 0.2 $m\ a^{-1}$ (or one-fifth of previous value). From 1962 to 1991, volume losses did not continue at the same rate in the CG and some equilibrium can be observed in terms of volume at the RG. Noteworthy, this period of reduced losses is contemporary with the deposition of debris on previously exposed ice. The debris cover is more obvious in the eastern half of the CG and continued to build, thereby covering glacier ice completely by 2000.

After 1973, velocities in S1 and S3 dropped to 0.3 $m\ a^{-1}$, whereas S2 barely shows any movement above 0.1 $m\ a^{-1}$. Velocities remained generally low with just some acceleration in the 1990s, as at the other RGs. Since the turn of the 21st century, DGNSS and photogrammetric measurements show a decelerating trend with current velocities at S1 and S2 below 5 $cm\ a^{-1}$, and 7 $cm\ a^{-1}$ in S3. This deceleration coincided with an appreciable loss of volume at the CG (60,000 $m^3 a^{-1}$) and significant volume losses in all RG zones, producing, even at its front of S1, a depleted central area with respect to the margins.

Val da l'Acqua

Val da l'Acqua presents the most constant horizontal velocities of the four RGs, but suffered from a negative trend in surface velocities and important periods of volume losses too. The active areas of the rock glacier can be divided into two halves with different dynamic behavior. A lower half - close to the front (A1) and an upper half (A2). Compared to 1956, the RG now has a degraded upper part (A2) where losses total 0.22 (+- 0.064) million $m^3$and an aggrading front with a volume gain of 0.13 (+ - 0.027) million m^3. The total volume loss of the CG amounts to 4.15 (+- 0.307) million m^3 (15.80 m w.e.), representing the greatest volume loss among the four catchments.

redacted 02/10/2023 12:3
Nota adhesiva
delete space

As in Val Sassa, the position of the CG end moraine was just slightly more than 100 m away from the active part of Val da l'Acqua RG in 1850. The glacial front can not be discerned on the historical photographs of 1918 and 1935, but according to our inferred area of the CG in 1956, the glacier ice had receded by c. 250 m with respect to the end of the LIA, leaving isolated ice patches behind. Horizontal velocities remained quite stable both in A1 and A2 from 1918 to 1962, with values ranging between 1.5 and 2 $m\ a^{-1}$, and only a slight slowdown during the period 1919-1921 (again as in Val Sassa). Between 1962 and 1973, a marked increment of the maximum speeds can be observed in very localized areas of A1 and A2 (up to 3 $m\ a^{-1}$) along with an important retreat and volume loss of the CG. Yet, these local changes in movements only had a minimal effect on the overall mean RG velocities. Between 1962 and 1973, a significant hiding of exposed ice can be observed, predominantly with debris, covering the easternmost area. Coverage here is less extensive compared to Val Sassa, still leaving a large area of ice exposed in the western half of the RG. It is in this western zone where the volume loss mainly occurred in subsequent decades. Glacier ablation was notable during 1988-1991, with appreciable deceleration and volume losses in A1, but even more so in A2 (60,000 $m^3 a^{-1}$) where losses were accompanied by a more evident deceleration in velocities. Again during 1991-2000, as in the other three RGs, an acceleration is discernible in both zones, but with a gradual migration of maximum speeds from lower to more elevated zones, resulting in the highest mean velocities seen in A2. As shown by DGNSS measures, A1 is in a clear downward trend in movement since 2000, and the speed has nowadays decreased to 0.5 $m\ a^{-1}$ or less, with some localized subsidence in the upper part evident in both the longitudinal and transverse profiles. Meanwhile, velocities in A2 maintained higher values of around 1.4 $m\ a^{-1}$, with considerable depletion produced during this period. On the CG, volume loss rates have been lower than during previous decades, as the debris has come to hide the ice in its entirety. Despite this, glacier area was reduced by almost half between 2000 and 2015 and the longitudinal profile has become closer and closer in recent years to the concave and more irregular shape of an underlying carved bedrock.

Discussion

In the study presented here, we present a century of surface velocity and volume changes of four rock glaciers from the Eastern Swiss Alps. The rock glaciers – all located in the Swiss National Park – were the first in the world where systematic *in-situ* measurements of surface displacement were undertaken in 1918. By combing this pioneering work with photogrammetric interpretation and DGNSS measurements, we filled the gap previously existing between the measurements from the early 20th century and the most recent measurements made over the last two decades. This globally unique long-term record is one of the main reason why these rock glaciers have recently been ordained by UNESCO as one of the top 100 IUGS geological world heritage sites.

redacted 02/10/2023 12:32:58
Nota adhesiva
This paragraph seems like an introduction rather than a discussion.

The general decelerations and total volume loss that have occurred at different rates over the past 100 years in the four RGs of the SNP show a behavior that is consistent with RGs slowly transitioning from secondary creep towards a state of degradation (Cicoira et al., 2020). This degradation is reflected in the general curvature of the longitudinal and transverse profiles, showing signs of ice depletion in all the RGs, but being more marked in Val Sassa and Tantermozza where deceleration has been most prolific. Meanwhile, aggradation convex shapes are still present at the fronts of the Val da l'Acqua and Valletta RGs, but with a continuous flattening trend. The observed deceleration, which is more concentrated at the lower frontal areas of the main tongues, is inverse to the spatial variation of velocities observed in RGs which are in a process of destabilization, such as at the Äußeres Hochebenkar (Hartl et al., 2023). This frontal deceleration is more clearly ongoing in Val Sassa and Val da l'Acqua between an elevation range of 2,100 to 2,300 m a.s.l, which is exceptionally low compared to other active RGs in the Swiss Alps (Delaloye et al., 2010) and roughly coincides with the current lower limit of permafrost in this area (Boeckli et al., 2012). Therefore, the shifting of maximum speeds to higher elevations could be related with a slow progressive upslope permafrost degradation, with localized loss of the ice-rich layer triggered by anomalously drier warm conditions and less snow cover (Yi et al., 2007; Springman et al. 2013). Projected increases of the lower limit of permafrost as a consequence of climate warming have been previously modeled by Luetschg and Haeberli (2005). The tendencies and longer term evolution of these RGs are unique and could serve as prime examples of how RG downwasting could.

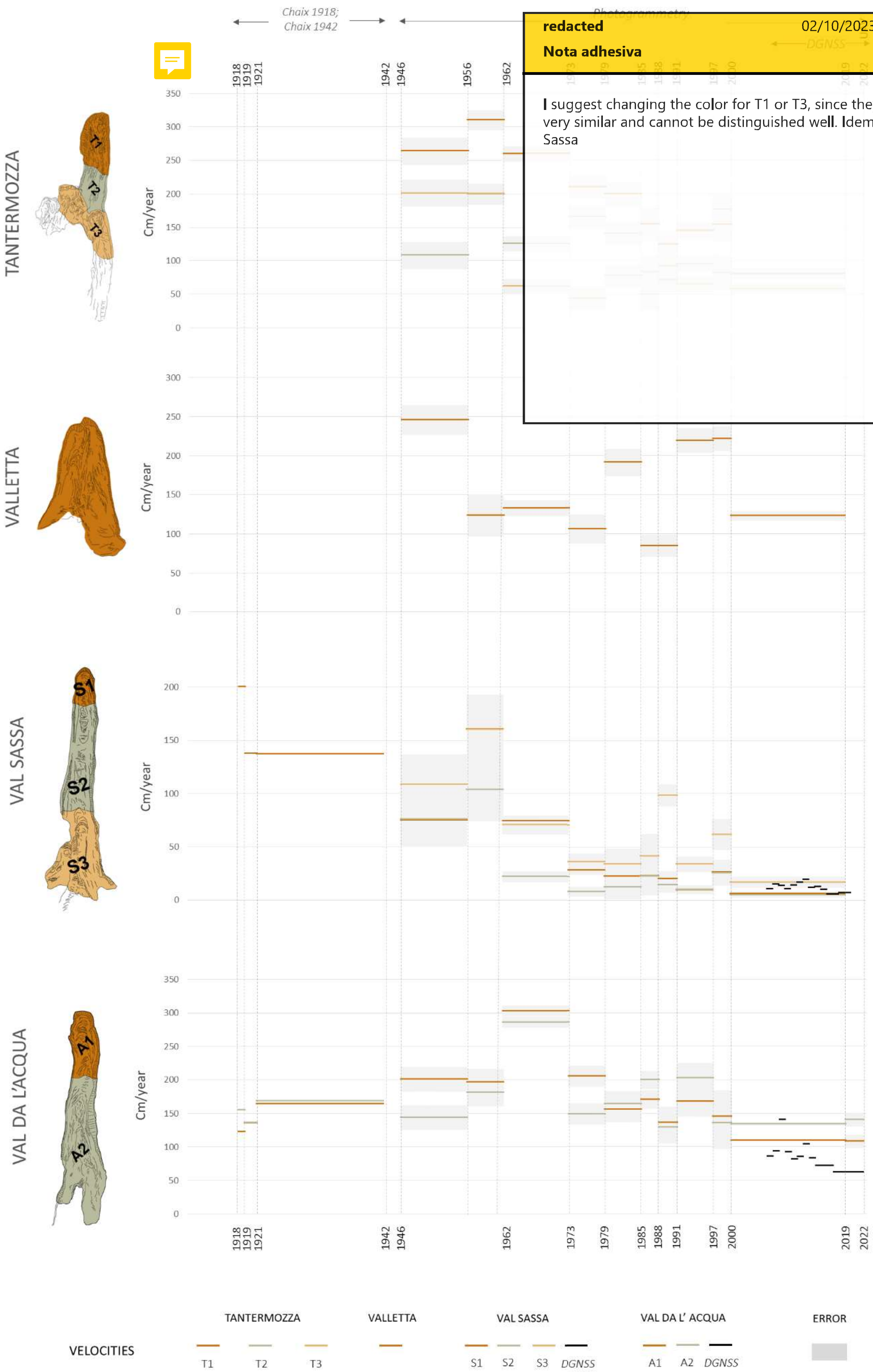
Despite the uniqueness of the records presented here, we are well aware of several uncertainties that are inherent to interpretations related to different types of data sources with different resolutions. This is especially the case for the volume changes, and the implications that the latter may have on RG behavior. While in the CG areas, the volume decrease would mainly be due to the ice melting, this is certainly more complex in the RGs. As RGs are composed of a mix of ice, sediments and air, if sediments are supersaturated we will see a volume change signal until debris porosity is reached, at which point a volume decrease will no longer be evident (Jones et al., 2019). As a result, in conditions of permafrost degradation, the higher the ice content in the RG, the higher the expected volume loss. By contrast, in RGs with high content in coarse sediments, this change can be almost negligible. Besides, for active RGs, such effects have to be combined with elevation changes due to lateral extensions/compressions which can sum to produce considerable uncertainties to the calculation of ice melting volumes in RGs (Cusicanqui et al., 2021). Despite these uncertainties, and without any pretension in this work to associate volume loss purely to ice loss in the RG, we are confident that the historical elevation changes observed, both in the longitudinal and transversal profiles of the four RGs, are of a sufficient magnitude and widespread enough, that they can be clearly associated with permafrost degradation.

A general accelerating trend, observed in many RGs over the last decades in the Alps and in some cases triggering destabilization, has been related to an increase in atmospheric temperature and warming of permafrost causing a thermally induced accelerated creep (Delaloye et al., 2010; Marcer et al., 2021). Whereas certain accelerations were observed at our sites during the 1950-1960s and 1990s, there has been a general trend for a deceleration in the 20th century, consistent with a general increase in air temperatures (Wuebbles et al., 2017; Allen et al., 2018), which could suggest that in these cases, changes in RG kinematics would be governed by (an)other factor(s) prevailing over the thermally induced plastic deformation. The historical surface kinematics observed throughout the century-long timeseries should be explained by other elements, either topographic or hydrological (Kenner et al., 2018; Cicoira et al., 2019a; 2020). In our case, it is suggested that the spatial interaction with the CGs could have had implications regarding both factors. On the one hand, we see that the highest recorded velocities coincide with the post LIA period during which the CG termini were almost delimiting the upper contact of the active zones of the RGs. At this time, the stress propagation of the CGs would have been greater towards the proglacial foreland (Waller, 2013), thus promoting RG movement. On the other hand, the significant glacier degradation necessarily implies a large long-term reduction in the sources of hydrological input, thus suggesting a possible long-term dominant basal-shear type movement of these decelerating RGs, which would be predominant over thermally-induced creep, similar to that described at Ritigraben (Kenner et al., 2017). If this were the case, the observation of CG extensions and longitudinal profiles that show glaciers in a state of continuous depletion in the last decades, and with the glacier snouts increasingly further away from the active area of the RGs, would indicate a near future scenario with a complete absence of new important RG accelerations. These conditions could persist for a few more years, with the rate of melting for the nearly exhausted glaciers damped by the debris cover, as observed in Val Sassa and Val da l'Acqua. A slower but continuous flow of water from the CGs would thus maintain a slow secondary creep that would continue to gradually slow down as the permafrost is slowly degraded by warm and dry climatic conditions.

Regarding our observations of the historical spatial interrelationships between CGs and RGs, we cannot draw solid conclusions about the origin of the rooting ice of the RGs beyond the observed proximity between them at the end of the LIA in 1850. Even so, we observe signs of glacial overriding on the surface of the upper lobes at Tantermozza RG, indicating its presence prior to the glacial advance, but more importantly, that the morphology and main lobes of the four RGs already presented an extensive development and positions similar to the current ones in 1918. It is thus very unlikely that the RGs were formed from end glacial ice after the end of the LIA. While, conducting geophysical surveys or borehole investigations in these former contact areas could certainly help to decipher the former and current CG-RG interrelationship, such investigations will not be possible in the strictly protected environment of the Swiss National Park.

redacted 02/10/2023 12:37:55
Nota adhesiva

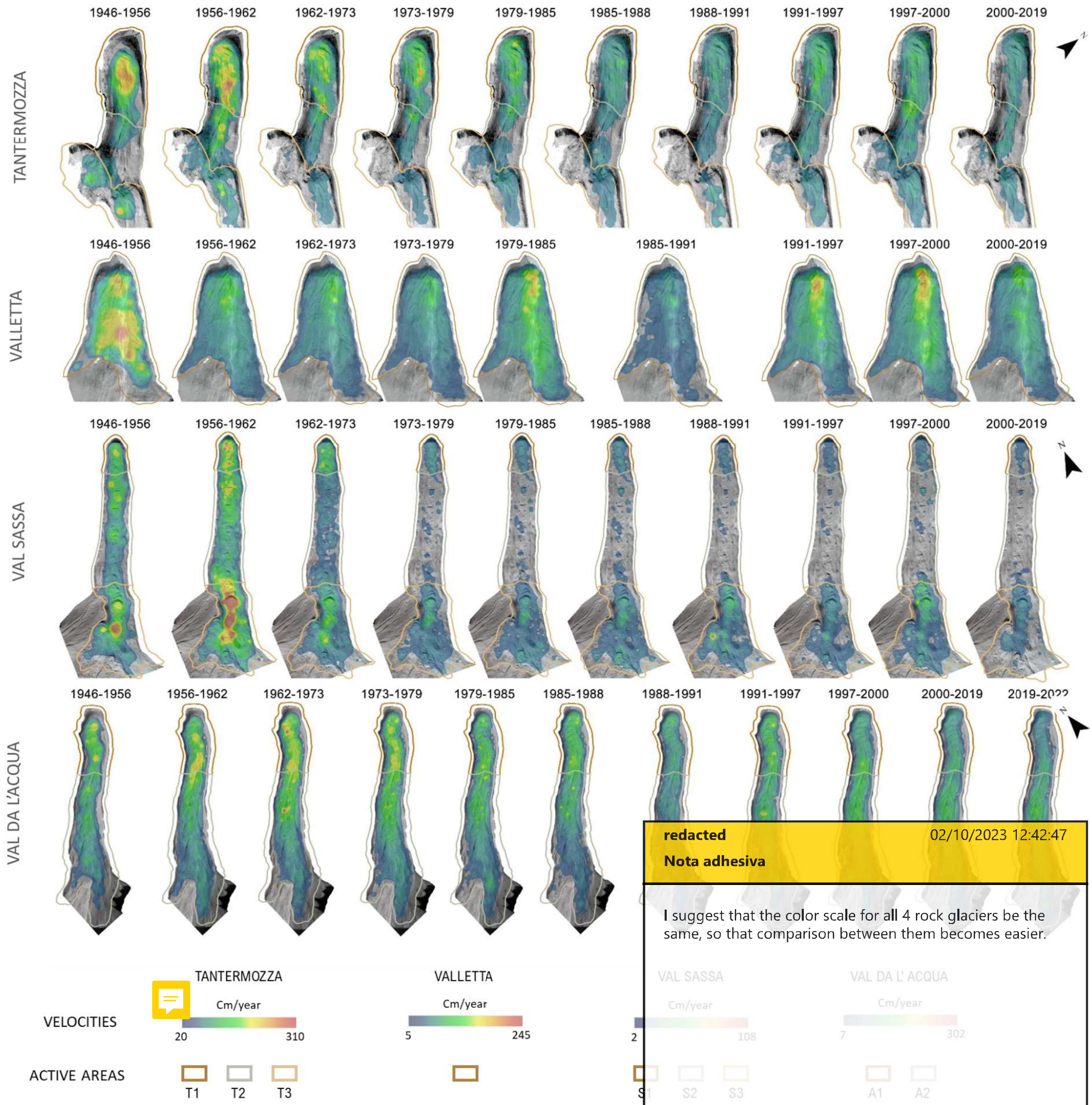
I consider that in this paragraph it would be very appropriate to include a discussion comparing the work of Kenner (2018) and others such as Palacios et al. (2021) indicating that glaciers were able to advance on rock glaciers during the LIA.



redacted 02/10/2023 12:39:48
Nota adhesiva

I suggest changing the color for T1 or T3, since they are very similar and cannot be distinguished well. Idem for Val Sassa

Figure 3. Horizontal maximum velocities. The four graphs summarize all the horizontal maximum velocities values for each of the analyzed zones of the rock glaciers from Chaix measures (1918-1942), orthophotos obtained from historical aerial imageries and UAV (1946-2022) and DGNSS measurement (2006-2022). The shaded areas correspond to the uncertainty in the measurements made on the orthophotos (see supplementary material 1 for raw data).



redacted 02/10/2023 12:42:47
Nota adhesiva

I suggest that the color scale for all 4 rock glaciers be the same, so that comparison between them becomes easier.

Figure 4. Interpolated velocity maps. The IDW interpolated maps show the spatial distribution of horizontal surface velocities (cm per year) measured in different periods between 1946 – 2022 within the active areas of the four rock glaciers. The active areas are separated in different zones according to different kinematics observed and shown here as different colors overlapping polygons.

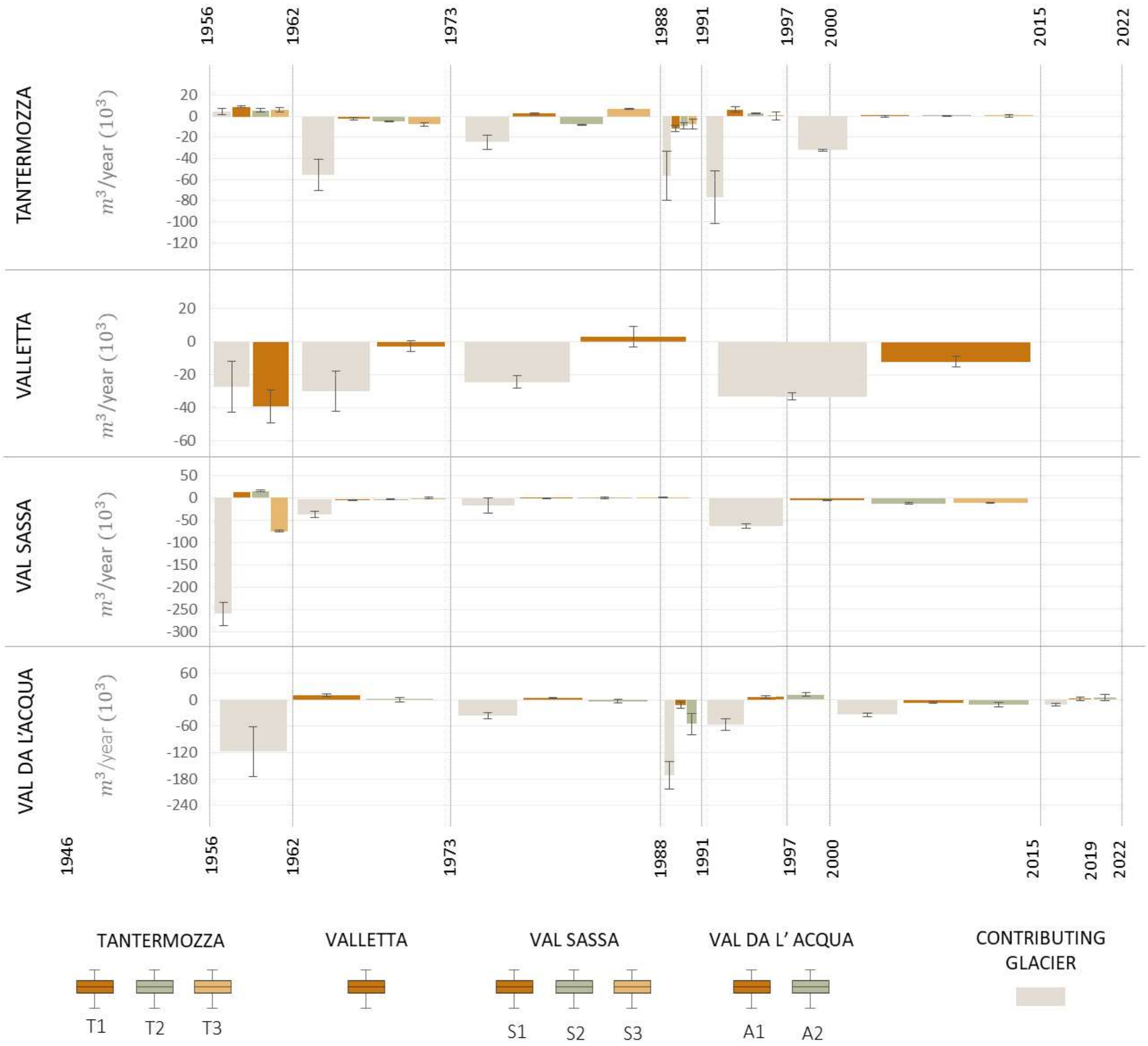
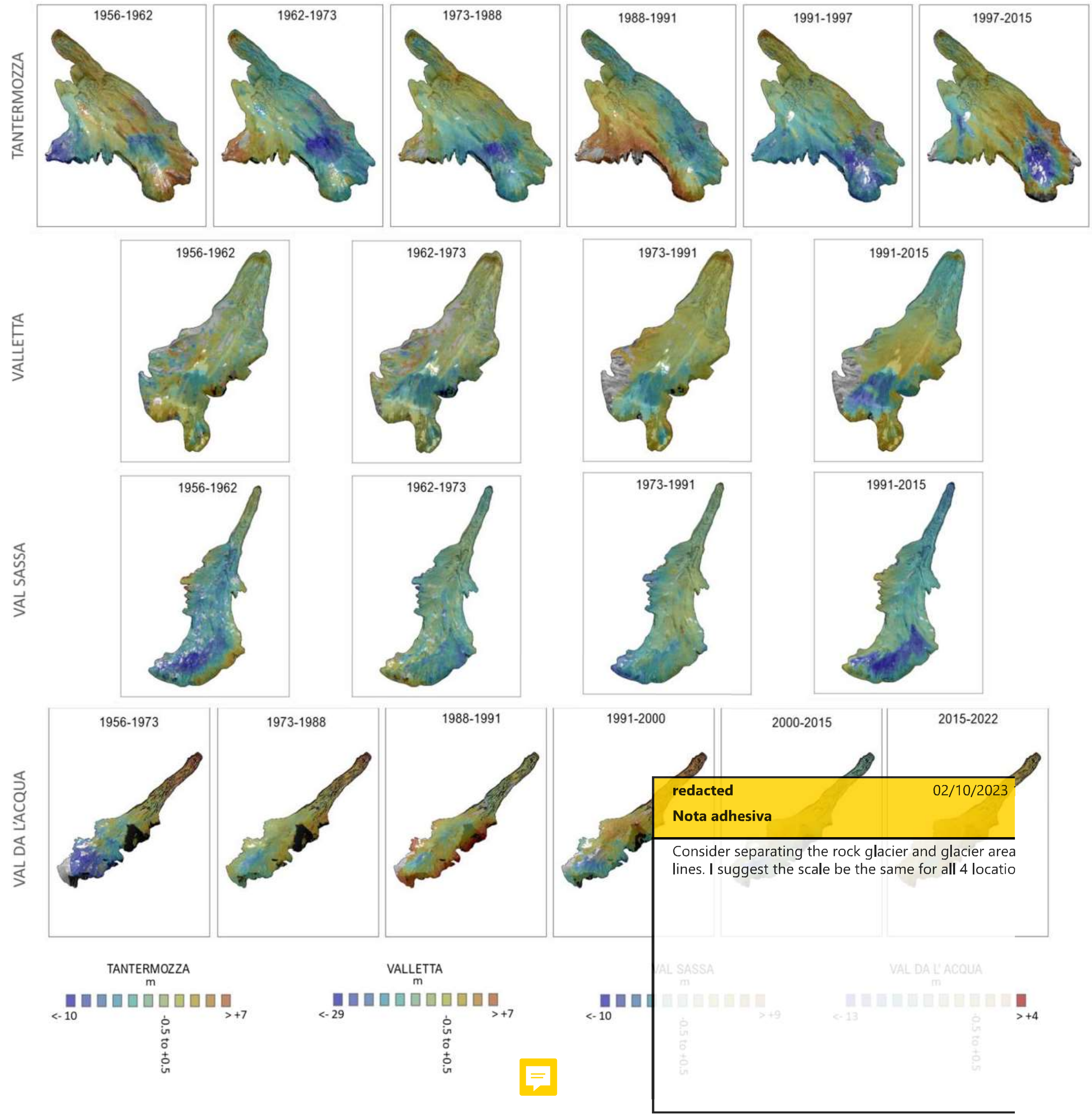


Figure 5. Volume change rate. Bar graphs show volume change rates in m^3 $per\ year$ at different periods from 1956 for the different active zones of the rock glaciers and Contributing Glaciers. Uncertainty is indicated by thin black lines.



redacted 02/10/2023
Nota adhesiva
Consider separating the rock glacier and glacier area lines. I suggest the scale be the same for all 4 locatio

Figure 6. DSM differences (DSM-d) maps. These maps show total elevation changes (m) for different periods between 1956-2022 for the entire catchment areas above the forehead of the four rock glaciers, including both, rock glacier active areas and inferred glacier extensions. See Supplementary material 3 to see maps in better resolution.

TANTERMOZZA

	GLACIER				ACTIVE RG							
					T1+T2+T3		T1		T2		T3	
	Area (m2)	Elevation Change (m/year)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)
1956-1962	126800	0.04	27734	15701	111338	16373	47214	5773	30465	7867	33659	13152
1962-1973	132800	-0.42	-608119	161205	-83406	12848	-16178	16955	-36630	2961	-30598	18629
1973-1988	109200	-0.22	-363558	102848	19760	10039	-8035	17225	21788	3561	6007	9331
1988-1991	83600	-0.67	-168455	70189	-101168	9705	-44309	7933	-34780	7830	-22080	13352
1991-1997	84400	-0.91	-460956	150372	39047	14360	50256	16897	9385	3990	-20594	22193
1997-2015	60800	-0.53	-581153	17313	8177	12494	835	15077	17663	4986	-10321	17420
TOTAL			**-2154508**	81942	**-6251**		**29784**		**7891**		**-43926**	

VALLETTA

	GLACIER				ACTIVE RG	
	Area (m2)	Elevation Change (m/year)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)
1956-1962	174400	-0.09	-162407	92771	-201285	60008
1962-1973	158000	-0.21	-530480	134702	-27404	37173
1973-1991	139200	-0.12	-439401	66797	59998	113901
1991-2015	102400	-0.17	-789424	57132	-413236	79666
TOTAL			**-1921712**	78167	**-581927**	

VAL SASSA

	GLACIER				ACTIVE RG							
					S1+S2+S3		S1		S2		S3	
	Area (m2)	Elevation Change (m/year)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)
1956-1962	312000	-0.83	-1557160	153897	-157364	10540	40139	5095	50167	13170	-247670	13357
1962-1973	229200	-0.15	-383965	82007	-14598	19116	-24935	12201	-5518	18420	15854	26726
1973-1991	196400	-0.08	-267649	311206	95218	22894	17388	11681	23169	31901	54661	25101
1991-2015	191200	-0.32	-1484372	100942	-525147	29398	-74743	18623	-237869	54587	-212536	14984
TOTAL			**-3693146**	166945	**-601891**		**-42151**		**-170050**		**-389691**	

VAL DA L' ACQUA

	GLACIER				ACTIVE RG					
					A1+A2		A1		A2	
	Area (m2)	Elevation Change (m/year)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)	Volume change (m3)	Uncertainty (m3)
1956-1973	262800	-0.45	-2006638	952390	138595	57155	130086	39392	8510	74918
1973-1988	194400	-0.18	-536980	103552	12133	35505	61775	10702	-49642	60308
1988-1991	152400	-1.12	-512348	94929	-249098	46715	-46385	21370	-202713	72061
1991-2000	120800	-0.47	-512348	119968	234900	33942	90801	26561	144100	41323
2000-2015	108000	-0.31	-506495	66615	-439819	53761	-168916	30465	-270903	77057
2015-2022	43600	-0.25	-76751	22721	215482	36538	66942	28123	148540	44953
TOTAL			**-4151559**	307071	**-87807**		**134303**		**-222109**	

Table 1. Total volume change. Total volume changes calculated from DSM of Difference (DSM-d maps) in the different zones of the active area of the rock glaciers and in the inferred areas of the Contributing Glaciers, at different periods from 1956. Additionally, it shows area and elevation change at the inferred Contributing Glacier area for the same periods.

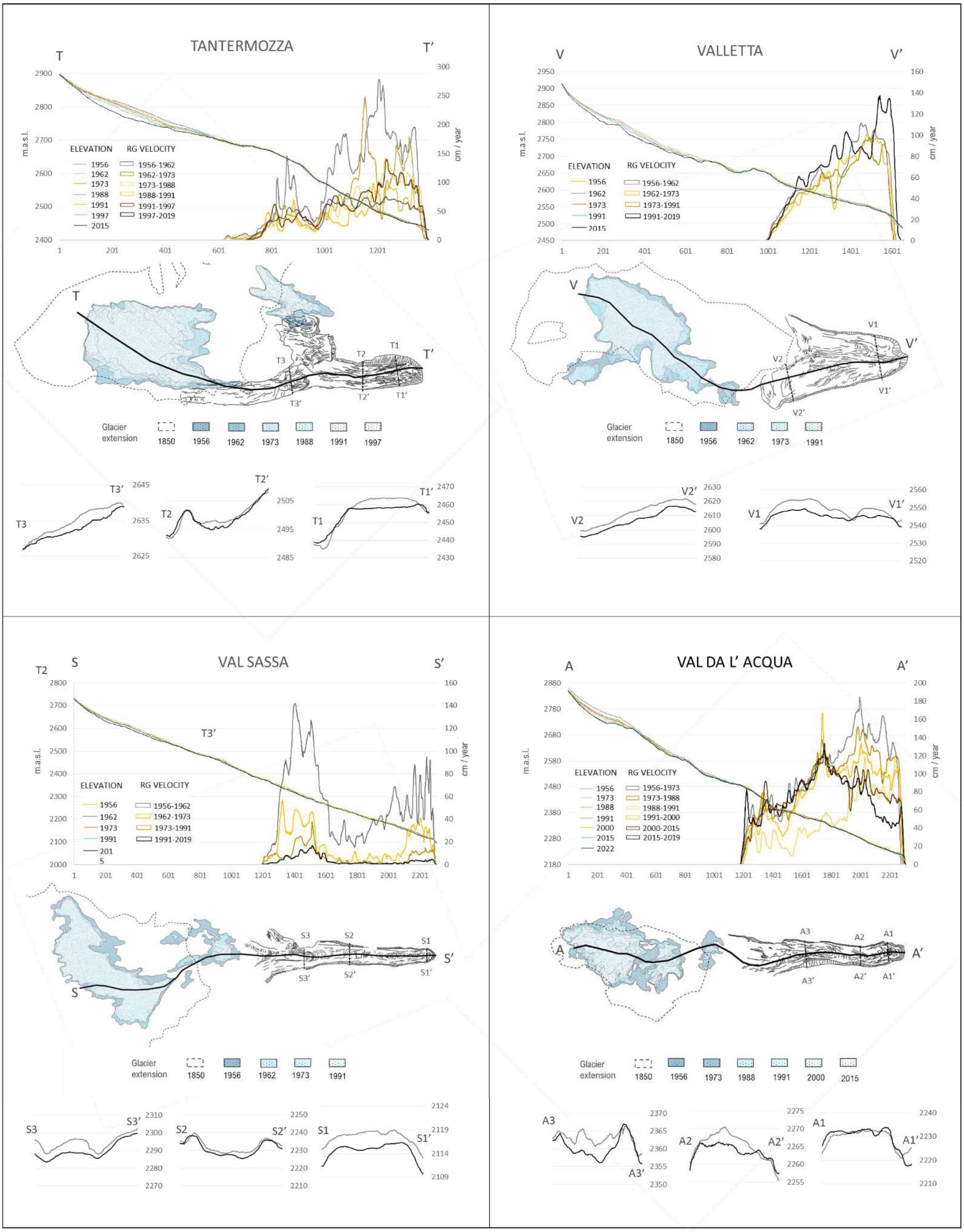


Figure 7. Velocity and Elevation longitudinal-transverse profiles. Historical evolution of elevation changes (from photogrammetry DSMs) and measured horizontal surface velocities in the rock glaciers (RGs) for corresponding periods. Longitudinal and transverse profiles covering the Contributing Glacier areas and the active rock glaciers are indicated by black lines at the bottom maps of each rock glacier. Boundary area of 1850 corresponds here to the Siegfried maps of 1900,

which better represent in these catchments the Contributing Glacier extensions of the Dufour map of 1850 (See supplementary material 4).

Methods

Antecedent works

Émile and André Chaix undertook the first in-situ measurements between 1918-1919 and 1919-1921 for Val Sassa and Val da l'Acqua RGs (Chaix, 1923). During their different field campaigns, they acquire relative displacement measurements carried out on boulders that were along transversal profiles, located both near the front of the RG as well as in the upper areas. Two decades later, in 1942, André Chaix revisited the sites and took new measurements on the same boulders (Chaix, 1943). Unfortunately to date, efforts to locate these boulders again have not been successful, and therefore, it has not been possible to continue tracking movements using the same elements. The next known measurements were made by Heinrich Jäckli in Val da l'Acqua (Jäckli, 1978). In this work he summarized past measurements for Val da l'Acqua forehead (1921-1942-1968) and acquired new velocities between 1968-1979. These measurements were conducted using different boulders than the ones measured by Chaix, but again, in the current study we have not been able to find their exact location. Even so, they serve as a reference to compare against our photogrammetric measurements from the same period.

redacted 02/10/2023 13:20:02
Nota adhesiva
delete space

For the last 2 decades, Differential Global Navigation Satellite System (DGNSS) surface measurements have been systematically acquired (almost yearly) by the GIS group of the SNP using boulders at 8 different positions along the Val Sassa RG body (years 2006,2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2018, 2020) and 19 locations near of the front of Val da l'Acqua (years 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, [illegible] 2017, 2022). See Supplementary material 6 for the locations of the DGNSS measurements.

Photogrammetry

With the aim of filling the gap between the older measurements from Chaix (1918-1942) and the recent ones from DGNSS (2006-2022) in Val Sassa and Val da l'Acqua, and to obtain the first measurements for Tantermozza and Valletta RGs, we created orthophotos and DSM by carrying out photogrammetry processing from historical imagery and UAV.

Historical aerial imagery (1946 to 2000)

The Swisstopo (Swissimage, 2023) catalog presents a vast spatial and temporal coverage of historical aerial imagery. We have downloaded and pre-processed each of the available scanned historical images that cover our study area (651 images) for all the available dates, comprising 1946, 1956, 1962, 1973, 1979, 1985, 1988, 1991, 1997, 2000 and 2003. For some of the years, more than one acquisition date is available. When that befalls, we have always chosen a single date, being the one with the best resolution, greatest spatial overlap between datasets, and with less snow cover and/or shadowed areas.

To obtain better detail in the shaded areas, we have individually pre-processed each of the scanned images by adjusting brightness and contrast. Besides, if necessary, we have applied sharpening filters and matched levels between datasets that would be processed together. These adjustments considerably increase the final accuracy of the photogrammetry models, facilitate the pixel matching between datasets, and reduce the point cloud noise in the brighter and shaded areas. Despite these improvements, afterwards, manual cleaning of the point clouds noise for each of the photogrammetry models has been necessary.

Ground control points (GCP), used during the photogrammetry process, were acquired in different field campaigns with a Trimble Geo7x and post processed to obtain DGNSS locations from stable boulders, located in the immediate vicinity of the active areas of each RG (Supplementary material 7). Stability of these boulders was assessed by measuring the relative distances in the historical imagery between the boulders and different close bedrock outcrops, against the relative distances in the most recent Swisstopo orthophoto from 2019 (Swissimage, 2023). Finally, just the locations with highest precision (vertical and horizontal accuracy o + -10 to + -40 cm) were selected as GCP candidates for the photogrammetry processing. For the more inaccessible upstream areas, GCP of stable outcrops were selected using XY coordinates from the 2019 Swisstopo orthophoto (10cm pixel resolution) and Z values from the 2015 SwissALTI3D DEM (0.5m) (SwissALTI3D, 2023). The horizontal and vertical accuracy of these upstream GCP is much lower (+ - 2m) than the ones of the downstream DGNSS GCP. Even so, it is a sufficient precision for our purposes, since in these upstream areas we do not realize measurements of horizontal displacements and the elevation changes are normally greater than the measured uncertainty for each period.

Photogrammetry processing has been carried out using Pix4Dmapper 4.5.6 software separately for each RG and for each different date, resulting in 40 different orthophotos and 40 DSMs (10 for each RG) with pixel resolutions between 0.2 to 0.7m. Unfortunately, it was not possible to obtain satisfactory models from 2003 due to lower levels of overlap in the imagery.

UAV in Val da l'Acqua (2022)

After the aperture of new cracks exposing fresh ice in the Contributing Glacier of Val da l'Acqua during 2022 summer of 2022, the GIS group of the SNP asked for a UAV survey in order to map the observed geomorphological changes. Hence, we carried out the survey covering the entire Contrubuting Glacier and RG area during September 2022, using an Ebee RTK drone. Through the same photogrammetry procedure as used for the historical imagery, we created an orthophoto and a DSM with a resolution of 10 cm per pixel. In this case, the use of GCPs was not necessary, since the RTK gave a better average horizontal and vertical accuracy of + - 2 cm for the entire area. These UAV orthophoto and DSM were used as reference for the co-registration of the rest of Val da l'Acqua photogrammetry models from the historical imagery.

redacted 02/10/2023 13:21:19 Nota adhesiva Delete space

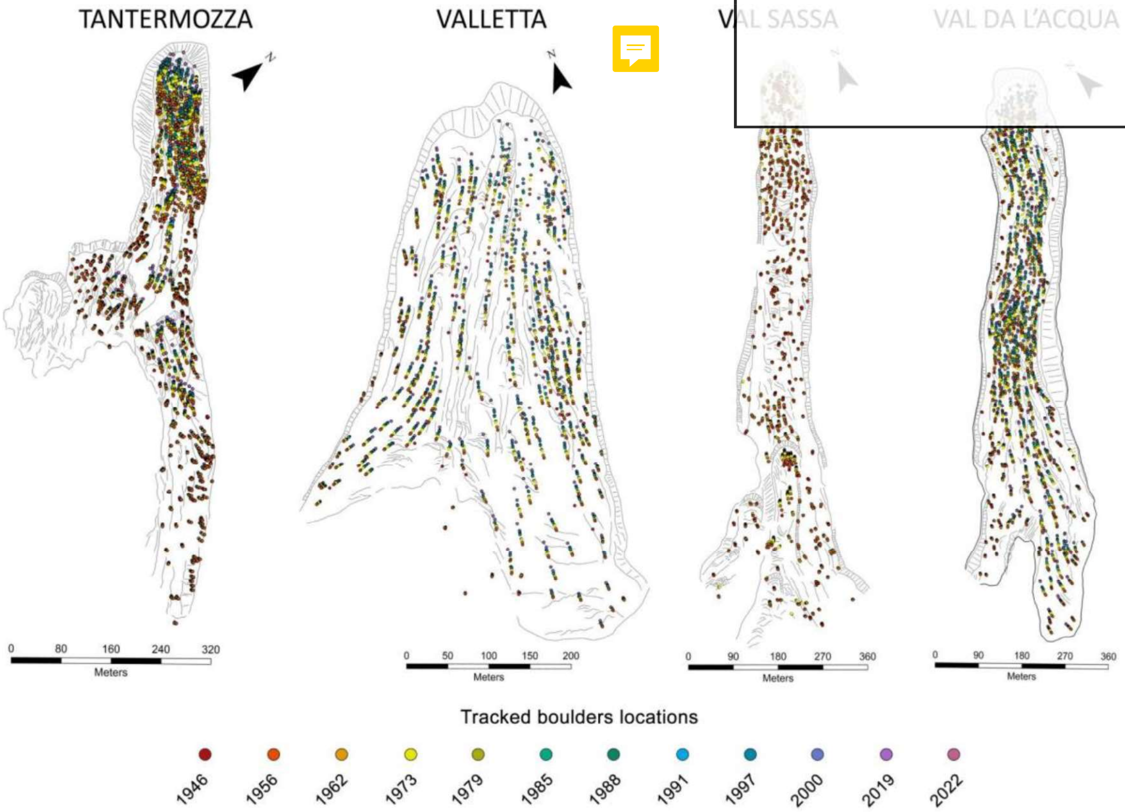
Horizontal velocities assessment - Manual boulder tracking

Horizontal velocities were assessed by visual identification and tracking of boulders through consecutive images, using the orthophotos obtained from photogrammetry. As the upstream limit of the active areas are normally diffuse and may evolve over time, we tracked boulders up to the areas upstream where we do not identify any movement starting from the oldest period (1946-1956). With that, we have defined for each RG an active area limit within which we have evaluated the subsequent dynamic analyses.

The total number and density of point locations per rock glacier is dependent on the availability of boulders on the surface of each RG, trying to ensure that in each case there is a homogeneous spatial distribution, which is necessary for a subsequent interpolation of the speeds for the entirety of the RG active areas. In total, for the four RGs analyzed, we have interpreted and manually digitized 12,000 different boulder locations along the different periods (Figure 8).

Horizontal velocities for each period were calculated by computing the linear distance between XY coordinates of each tracked boulder at each date and dividing it by the number of years for the corresponding period, to obtain average surface displacements in cm per year. Finally, we created 1 m pixel resolution interpolated velocity maps for each period (Figure 4) by Inverse Distance Weight (IDW) interpolation method, using the active RG limit as a boundary area with zero velocity value.

redacted 02/10/2023 13:24:09
Nota adhesiva
I suggest a high resolution for this figure, so that the blocks can be clearly identified.



	Maximum nr. of tracked boulders per period	Area (ha)	Density(points/ha)
TANTERMOZZA	443	10.9639	40.4053
VALLETTA	228	14.9836	15.2166
VAL SASSA	373	17.1899	21.6988
VAL DA L'ACQUA	299	18.7165	15.9752

Figure 8. Locations of tracked boulders. Positions of the 12,000 manually tracked boulders that have been used to calculate horizontal surface velocities for different periods between 1946-2022 for the four rock glaciers. The table below shows the tracked boulder densities and area (ha) of each rock glacier active area.

Elevation Change – DSM differences

Elevation changes were calculated by means of DSM differences (DSM-d) to estimate cell by cell the change between the different DSMs. Computations were performed for the entire catchment area of each RG, in order to include both active RG areas and contributing areas. Besides, DSM-d were only established for DSM datasets in which the upstream area does not show important snow cover and/or too much noise. For the most recent dataset we used the 0.5m SwissALTI3D 2015 DSM from Swisstopo. Taking these criteria into account, the periods in which DSM-d have been computed are: 1956-1962-1973-1988-1991-1997-2015 for Tantermozza; 1956-1962-1973-1991-2015 for Valletta and Val Sassa; 1956-1973-1988-1991-2000-2015-2022 for Val da l'Acqua (Figure 4 and Figure 5).

Despite the manual removal of the point cloud noise during the photogrammetry processing, final DSMs could still present wrong pixels that needed to be masked for the purpose of removing miscalculations in DSM-d. Noise masking areas were manually digitized by interpreting DSM hill-shades where these errors were easily identifiable (Supplementary material 8). Finally, total elevation differences were divided by the number of years during each corresponding period to obtain elevation changes in cm per year.

redacted 02/10/2023 13:26:29
Nota adhesiva
I think it is not adequately explained why they are called 'Contributing glaciers'.

Inferred Contributing Glacier extensions

Contributing Glaciers in our study area are currently covered by debris material, hiding partially (Tantermozza and Valletta) or completely (Val Sassa and Val da l'Acqua) their boundary limits. The debris cover layer has been evolving since 1946, when the total exposed ice area was much greater than in recent decades, creating challenges for mapping the historical presence of ice bodies. Here we infer the most probable historical glacier boundaries by assuming that ice presence must be related with the areas in which the highest elevation changes occur. Accordingly, big negative values in the DSM-d would correspond to periods with considerable ablation and important positive DSM-d values with accumulation periods

In a context in which the ablation is continuous for a total period of time, the longer the period considered, the greater the negative differences in the DSM-d values and, therefore, the limits in which this process occurs will be better spatially defined. Thus, we compute DSM-d between the different DSMs and the most recent DSMs (2015 for Tantermozza, Valletta and Val Sassa and 2022 for Val da l'Acqua). From these longer-period DSM-d maps, the limits of the total negative elevation difference, which would most likely correspond with the most probable ice melting area during the entire period, are clearly recognizable (Supplementary material 4). We analyze these limits together with visual interpretation of geomorphological features in the corresponding orthophotos, to finally digitize the boundary of the most probable maximum ice extension on each date and infer it as the most probable Contributing Glacier boundaries for each historical dataset. Furthermore, we compare our inferred extents with previously published historical extents in the Swiss Glacier Inventories of 1850 (SGI1850 from Dufour map), 1900, 1935 (Siegfried maps) and 1973 (SGI1973) (Müller et al., 1976; Maisch et al., 2000).

Volume change calculations

For each time period, we have used the DSM-ds to individually determine the total volume change within active RG areas and inferred Contributing Glacier boundaries. For simplification, we have only referred to the inferred area of the Contributing Glaciers and not to the entire contributing area, since in all cases the volume change in the inferred areas of the Contributing Glacier corresponds to more than 95% of the total volume change of the contributing area. Also, in Tantermozza we have not considered the marginal westernmost inferred glacier areas as it would not drain directly over the RG active area.

To compute total volumes from DSM-d where voids are present after the masking of the DSM noise areas, we use the *Mean elevation difference by elevation bin method.* This is a broadly used approach (e.g., Kronenberg et al.,2016, Brun et al., 2017, Dussaillant et al., 2018), which has proved accurate for mass balance calculations when using unfilled DEMs or DSMs (McNabb, 2019, Huber et al. 2020). This method involves firstly computing the DSM-ds using the voided DSM and binning the resulting raster in bigger grid cells with the mean values of the aggregated pixels. The choice of the bins (or grid cells) size depends on the total elevation range for the area considered. We follow McNabb's (2019) recommendations of using a grid cell size equal to 10% of the elevation range in our analyzed area. This first step will fill the smaller voids in the DSM-ds. To fill the remaining voids, the binned raster is interpolated by a third order Local Polynomial interpolation. Finally, to obtain the volume per grid cell, the resulting mean elevation change binned raster needs to be multiplied by the area of each grid cell. The total volume for each analyzed area consists of the total sum of the bin volumes within the boundary areas. (Supplementary material 2).

Uncertainty assessment of photogrammetry measures

Even with the use of identical GCPs during the photogrammetric process, there may be significant local distortions in the alignment of the generated orthophotos and DSMs. This translates into an imprecision in the co-registration of the images that must be taken into account as relative uncertainties in the horizontal and vertical measurements. The uncertainty should be considered as a threshold measure or level of detection (LoD) (Vivero et al., 2022), above which we can begin to consider our displacement measurements as reliable. To quantify horizontal and vertical overall errors on each dataset comparison (Supplementary material 9), we firstly create random points in mapped un-changed bedrock areas, which are as close as possible to the RG and the inferred Contributing Glacier areas. Then, we register both vertical and horizontal differences of these random points for each image-pair and interpolate them (IDW), with the aim of avoiding spatial bias in the target areas. From this interpolated vertical and horizontal relative error maps we compute for each period the mean and standard deviation values within each rock glacier and Contributing Glacier areas. Finally, the horizontal uncertainty can be considered as the mean values ($disp\_\underline{xy}$) plus 2 times the standard deviation ($disp\sigma_{xy}$) (95% confidence level) of the displacements (Equation 1) (Fleicher et al., 2021).

$$error_{xy} = disp_{\underline{xy}}\,(epoch1 - epoch2) + \;2\,disp\sigma_{xy}\,(epoch1 - epoch2) \quad (1)$$

Meanwhile, the vertical error can be considered as 2 times the standard deviation of the DSM-d in the stable areas ($disp\sigma_z$) (Fey and Krainer, 2020) and the volume uncertainty ($error_V$) for each Contributing Glacier or RG area results from the multiplication of the vertical error by the corresponding area (Equation 2)

$$error_V = \{2\,disp\sigma_z\,(epoch1 - epoch2)\}\,(area) \quad (2)$$

References

1. Ackert, jr., R. P. A rock glacier/debris-covered glacier system at Galena Creek, Absaroka Mountains, Wyoming. Geografiska Annaler: Series A, Physical Geography 80, 267–276 (1998).
2. Allen, M.R. et alFraming and Context. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty: Cambridge University Press, Cambridge, UK and New York, NY, USA, 49-92 (2018)
3. Arenson, L., Hoelzle, M. & Springman, S. Borehole deformation measurements and internal structure of some rock glaciers in Switzerland. Permafrost and Periglacial Processes 13, 117–135 (2002).
4. Bearzot, F. et al. Kinematics of an alpine rock glacier from multi-temporal UAV surveys and GNSS Data. Geomorphology 402, 108116 (2022).
5. Berthling, I. Beyond confusion: Rock glaciers as cryo-conditioned landforms. Geomorphology 131, 98–106 (2011).
6. Bertone, A. et al. Incorporating insar kinematics into rock glacier inventories: Insights from 11 regions worldwide. The Cryosphere 16, 2769–2792 (2022).
7. Boeckli, L., Brenning, A., Gruber, S. & Noetzli, J. Permafrost Distribution in the European alps: Calculation and evaluation of an index map and summary statistics. The Cryosphere 6, 807–820 (2012).
8. Brencher, G., Handwerger, A. L. & Munroe, J. S. Insar-based characterization of Rock Glacier Movement in the Uinta Mountains, Utah, USA. The Cryosphere 15, 4823–4844 (2021).
9. Brun, F., Berthier, E., Wagnon, P., Kääb, A. & Treichler, D. A spatially resolved estimate of High Mountain Asia Glacier Mass balances from 2000 to 2016. Nature Geoscience 10, 668–673 (2017).
10. Buchli, T. et al. Kinematic investigations on the Furggwanghorn Rock Glacier, Switzerland. Permafrost and Periglacial Processes 29, 3–20 (2018).
11. Copernicus. C3s Climate Bulletin shows Summer 2022 was Europe's warmest on record. Home Available at: https://climate.copernicus.eu/c3s-climate-bulletin-shows-summer-2022-was-europes-warmest-record. (Accessed: 7th August 2023)
12. Capps, S. R. Rock Glaciers in Alaska. The Journal of Geology 18, 359–375 (1910).
13. Chaix, A. Les coulées de blocs du Parc National suisse d'engadine (note préliminaire). Le Globe. Revue genevoise de géographie 62, 1–35 (1923).
14. Chaix, A. Les coulées de blocs du Parc National Suisse. nouvelles mesures et comparaison avec les «rock stream» de la sierra nevada de californie. Le Globe. Revue genevoise de géographie 82, 121–128 (1943).
15. Cicoira, A. et al. A general theory of Rock Glacier Creep based on in-situ and Remote Sensing Observations. Permafrost and Periglacial Processes 32, 139–153 (2020).
16. Cicoira, A., Beutel, J., Faillettaz, J. & Vieli, A. Water controls the seasonal rhythm of Rock Glacier Flow. Earth and Planetary Science Letters 528, 115844 (2019a).

17. Cicoira, A., Beutel, J., Faillettaz, J., Gärtner-Roer, I. & Vieli, A. Resolving the influence of temperature forcing through heat conduction on Rock Glacier Dynamics: A numerical modelling approach. The Cryosphere 13, 927–942 (2019b).

18. Croce, F. A. & Milana, J. P. Internal structure and behaviour of a Rock Glacier in the arid Andes of Argentina. Permafrost and Periglacial Processes 13, 289–299 (2002).

19. Cusicanqui, D. et al. Interpretation of volume and flux changes of the Laurichard Rock Glacier between 1952 and 2019, French Alps. Journal of Geophysical Research: Earth Surface 126, (2021).

20. Delaloye, R., Lambiel, C. & Gärtner-Roer, I. Overview of rock glacier kinematics research in the Swiss alps. Geographica Helvetica 65, 135–145 (2010).

21. Dusik, J.-M. et al. Influence of glacier advance on the development of the multipart Riffeltal Rock Glacier, Central Austrian Alps. Earth Surface Processes and Landforms 40, 965–980 (2015).

22. Dussaillant, I., Berthier, E. & Brun, F. Geodetic mass balance of the northern Patagonian Icefield from 2000 to 2012 using two independent methods. Frontiers in Earth Science 6, (2018).

23. Fey, C. & Krainer, K. Analyses of UAV and GNSS based flow velocity variations of the Rock Glacier Lazaun (ötztal Alps, South Tyrol, Italy). Geomorphology 365, 107261 (2020).

24. Fleischer, F. et al. Multi-decadal (1953–2017) rock glacier kinematics analysed by high-resolution topographic data in the Upper Kaunertal, Austria. The Cryosphere 15, 5345–5369 (2021).

25. Guglielmin, M., Ponti, S. & Forte, E. The origins of Antarctic Rock Glaciers: Periglacial or glacial features? Earth Surface Processes and Landforms 43, 1390–1402 (2018).

26. Haeberli, W. Creep of mountain permafrost: Internal structure and flow of Alpine Rock Glaciers. (wydawca nieznany, 1985).

27. Hartl, L. et al. Multi-sensor monitoring and data integration reveal cyclical destabilization of the äußeres Hochebenkar Rock Glacier. Earth Surface Dynamics 11, 117–147 (2023).

28. Jäckli, H. Der Blockstrom in der Val da l'Acqua im Schweizerischen Nationalpark. Jahrbuch der Schweizerischen Naturforschenden Gesellschaft. Annuaire de la Société Helvétique des Sciences Naturelles 158 (1978)

29. Jones, D. B., Harrison, S., Anderson, K. & Whalley, W. B. Rock glaciers and Mountain Hydrology: A Review. Earth-Science Reviews 193, 66–90 (2019).

30. Kääb, A. et al. Inventory and changes of Rock Glacier creep speeds in Ile Alatau and Kungöy Ala-too, Northern Tien Shan, since the 1950s. The Cryosphere 15, 927–949 (2021).

31. Kääb, A., Frauenfelder, R. & Roer, I. On the response of rockglacier creep to surface temperature increase. Global and Planetary Change 56, 172–187 (2007).

32. Kenner, R. et al. Factors controlling velocity variations at short-term, seasonal and multiyear time scales, Ritigraben Rock Glacier, western Swiss Alps. Permafrost and Periglacial Processes 28, 675–684 (2017).

33. Kenner, R. Geomorphological analysis on the interaction of alpine glaciers and rock glaciers since the Little Ice Age. Land Degradation & Development 30, 580–591 (2018).

34. Kenner, R., Pruessner, L., Beutel, J., Limpach, P. & Phillips, M. How rock glacier hydrology, deformation velocities and ground temperatures interact: Examples from the Swiss alps. Permafrost and Periglacial Processes 31, 3–14 (2019).

35. Kronenberg, M. et al. Mass-balance reconstruction for Glacier No. 354, Tien Shan, from 2003 to 2014. Annals of Glaciology 57, 92–102 (2016).

36. Kunz, J., Ullmann, T. & Kneisel, C. Internal structure and recent dynamics of a moraine complex in an Alpine Glacier Forefield revealed by Geophysical Surveying and sentinel-1 insar time series. Geomorphology 398, 108052 (2022).

37. Luetschg, M. & Haeberli, W. Permafrost evolution in the Swiss alps in a changing climate and the role of the snow cover. Norsk Geografisk Tidsskrift - Norwegian Journal of Geography 59, 78–83 (2005).

38. Maisch, M., et al.. Die Gletscher der Schweizer Alpen: Gletscherhochstand 1850, Aktuelle Vergletscherung, Gletscherschwundszenarien. Schlussbericht NFP 31. (Second edition. Zurich: vdf Hochschulverlag ETH Zurich, 373 p 2000).

39. Marcer, M. et al. Rock glaciers throughout the French Alps accelerated and destabilised since 1990 as air temperatures increased. Communications Earth & Environment 2, (2021).

40. Maurer, H. & Hauck, C. Geophysical Imaging of Alpine Rock Glaciers. Journal of Glaciology 53, 110–120 (2007).

41. Monnier, S. & Kinnard, C. Reconsidering the glacier to rock glacier transformation problem: New insights from the Central Andes of Chile. Geomorphology 238, 47–55 (2015).

42. Monnier, S. & Kinnard, C. Pluri-Decadal (1955–2014) evolution of glacier–rock glacier transitional landforms in the Central Andes of Chile (30–33°S). Earth Surface Dynamics 5, 493–509 (2017).

43. Monnier, S., Camerlynck, C., Rejiba, F., Kinnard, C. & Galibert, P. Evidencing a large body of ice in a Rock Glacier, vanoise massif, northern French Alps. Geografiska Annaler: Series A, Physical Geography 95, 109–123 (2013).

44. Müller, F., Caflisch, R., Müller, G. . Firn und Eis der Schweizer Alpen: Gletscherinventar (Vol. 57-57a, Publ. / Geographisches Institut, Eidgenössische Technische Hochschule). (Zürich: ETH, Geographisches Institut 1976).

45. Potter, N. Ice-cored Rock Glacier, Galena Creek, Northern Absaroka Mountains, Wyoming. Geological Society of America Bulletin 83, 3025 (1972).

46. Sommer, C. et al. Rapid glacier retreat and downwasting throughout the European Alps in the early 21st Century. Nature Communications 11, (2020).

47. Springman, S. M. et al. Rock Glacier degradation and instabilities in the European Alps: A characterisation and monitoring experiment in the Turtmanntal, CH. Landslide Science and Practice 5–13 (2013). doi:10.1007/978-3-642-31337-0_1

48. SwissALTI3D. Federal Office of Topography swisstopo (2023). Available at: https://www.swisstopo.admin.ch/en/geodata/height/alti3d.html. (Accessed: 7th August 2023)

49. Swissimage. Bundesamt für Landestopografie swisstopo (2023). Available at: https://www.swisstopo.admin.ch/de/geodata/images/ortho/swissimage10.html. (Accessed: 7th August 2023)

50. Vivero, S., Hendrickx, H., Frankl, A., Delaloye, R. & Lambiel, C. Kinematics and geomorphological changes of a destabilising rock glacier captured from close-range sensing techniques (Tsarmine Rock Glacier, western swiss alps). Frontiers in Earth Science 10, (2022).

51. Waller, R. I. Permafrost and periglacial features | permafrost and Glacier Interactions. Encyclopedia of Quaternary Science 507–513 (2013). doi:10.1016/b978-0-444-53643-3.00107-2

52. Wuebbles, D. J. et al. Executive summary. climate science special report: Fourth national climate assessment, volume I (2017). doi:10.7930/j0dj5ctg

53. Yi, S., Woo, M. & Arain, M. A. Impacts of peat and vegetation on permafrost degradation under climate warming. Geophysical Research Letters 34, (2007).

Tracking number: COMMSENV-23-1196A

Dear Reviewer #1,

Thanks for taking the time to read our manuscript. While only some brief general remarks were provided, below we provide a response to the points raised.

Reviewer #1 (Remarks to the Author):

I don't like this paper much, there are several logical gaps here and I am not sure what is 'unique' about it. Just using this word does not make it so. Abstract does not say anything about what datasets are used, over what period, what the methods are or what the results are. The abstract does not say much about this study at all. Introduction should spell out rock glacier, not RG. You need to say something about Chaix's methods, how do you know that they measured things accurately? How do their data compare to modern results? What other long kinematic records exist from other areas? This context is missing. Inference p3 para2 regarding rock glacier dating is incorrect. Likewise the inference regarding rock glacier mapping in your study area p3 para3 is also incorrect. P3 para4, you mean spatial or temporal gaps, or both? The rest of this para is very long and should be removed, you are merely describing what you do here. Specific aims are missing, please add. Fig 1 scale missing in (a), not clear where panel (b) comes from. "dense point cloud" is not clear - i can see about half a dozen dots at the top of panel (a), is that it? Methods and datasets need to be described, there is nothing here. The results section does not present RESULTS in any way, it merely conflates description and interpretation, no results are mentioned at all. I do not find this acceptable. Individual site descriptions are pretty repetitive and qualitative. Discussion is very repetitive and does not make any reference whatsoever to any evidence. The bigger picture is missing, so what? Comparison with other areas? Impacts of climate change?

Author's reply

While we respect your overall opinion that you "don't like this paper much" or see the value in it, we are reassured by the general comments of the other two reviewers, who both commented on the value and significant contribution of the manuscript.

The abstract has been heavily revised to provide the clear results from the study and the broader implication of these results. In the main text, we have better distinguished results, from the broader discussion/interpretation of this results, including comparison with other areas, and potential implications for further climate change. However we, note both reviewers 2 and 3 considered the manuscript well structured and well presented.

Regarding the other points raised in the general remarks, we have implemented modifications in both the introduction and the discussion sections concerning the dating of rock glaciers, guided also by the recommendations provided by Reviewer #3. Additionally, the term "research gap" in our context refers to the temporal void addressed by our study, bridging the period between the earlier rock glacier displacement measurements conducted by Chaix in 1918-1942 and the more recent data acquired through GNSS since 2006. While it is not feasible to include a scale in the oblique image of the general view presented in Fig. 1, reference scales have been incorporated in the situation figure (Fig. 2). Furthermore, we have outlined the specific objectives of our research in the concluding paragraph of the introduction. Additionally, a comprehensive account of all the methodologies employed in this study is provided at the end of the manuscript, following the structure recommended by the Communications Earth and Environment journal.

Tracking number: COMMSENV-23-1196A

Dear Reviewer #2,

Many thanks for your constructive comments and suggestions. In the following paragraphs, you will find a detailed response addressing each of your points. Additionally, the attached document includes the track-changes manuscript, highlighting all responses to your comments and corresponding modifications in the text as per your recommendations.

Reviewer #2 (Remarks to the Author):

I read the paper by Muñoz-Torrero Manchado et al with attention and interest, and I found it valuable and worthy of attention not only for rock glacier specialists but also for those involved in climate change in high mountain environments.

The paper presents an analysis of a considerable amount of data and, although the methods used do not present major novelties per se, the long period of observations of the velocity variations allows a general evaluation between permafrost creep and changes in the climatic condition.

The paper is quite logically structured, clearly written, and the illustrations are adequate in number and quality.

- I would suggest clarifying better in the title, in the summary, and soon in the introduction that the paper deals with the examination of 4 rock glaciers. At first glance, one gets the impression of a much more general paper, regional in nature.

Author's reply:

We concur with your recommendations. In response, we have incorporated the clarification in both the title and the abstract, explicitly stating that our study is confined to four rock glaciers situated in distinct valleys of the Swiss National Park. Additionally, as per your suggestion, we have mentioned earlier in the Introduction, specifically in the second paragraph, the names of these 4 rock glaciers on which we focus our study. Furthermore, we have explicitly stated this in other sections of the text to avoid any potential misinterpretation that might suggest our results are more general.

- I have included some formal and substantial observations as notes in the attached PDF. There are some points where I believe it is necessary to provide more explanations and evaluate other possibilities with respect to the hypotheses made. Here below the main ones:

- The relationship between discontinuous permafrost limit and deceleration in RGs speed should be better documented. As it is explained in the text the deceleration is linked to the lack of supersaturation in ice (if I correctly understood), however I guess that the concept of permafrost limit does not refer to supersaturation.

Author's reply:

We agree that deceleration in speeds in the lower front of the rock glaciers should not be directly related with the upward displacement of the lower permafrost limit. While we infer permafrost decelerations as consequence of lack of supersaturation, permafrost existence doesn't depend on this.

Despite this, we infer that the same process that can drive a progressive upward migration of the lower limit of the permafrost as predicted by Luetschg and Haeberli (2005) could have been driving progressive upslope ice depletion from the lower parts of the RG in the last decades. We hypothesize that the ice depletion, particularly pronounced in the lower parts of the rock glaciers in preceding decades, may have contributed to the observed current lower velocities in the lower fronts. It is noteworthy that contemporary velocities are now lower in the front lobes compared to the upper parts. This is a notable shift from historical patterns where velocities were higher at the front than in the upper areas.

According to this we have changed the text in the discussion as follow:

"... The recent more prominent deceleration at the front of the RG than in the upper parts, may be linked to a gradual upslope permafrost degradation in precedent decades, leading to the localized loss of the ice-rich layer, particularly at lower elevations. As observed in SM10, rising annual mean air temperatures (AMAT) in our study area have led to discernible negative anomalies in snow cover since the mid-1980s . This phenomenon prompts a reduction in snow cover insulation (Springman et al., 2013), which as suggested by Luetschg and Haeberli (2005) may increase annual mean ground temperatures (AMGT). When coupled with an altitudinal temperature gradient of -0.65°C/100m (Barry and Chorley, 2010), this scenario provides a plausible explanation for the observed upslope shift in velocities, with AMGT above zero gradually advancing upslope in recent decades. This effect may be compounded with a progressive dynamical disconnection of the RG's fronts from the upper rooting zones. Notably, this trend is conspicuous in Val Sassa, where an elongated nearly immobile transition zone in S2 has persisted for decades. ..."

- I would try to clarify better how during the post-LIA period glaciers that would have been mechanically characterized by a retreat or a steady state, have generated a downward stress propagation in the pro-glacial areas up to promote an RG movement

Author's reply:

We agree. Our expression in the text lacked clarity. When we were writing "At this time..:" we wanted to refer "Towards the end of the LIA" but not to the beginning of our velocity measures. Towards the end of the LIA the stress propagation would have been greater than in subsequent decades where the stress probably would have diminished. Therefore, when our velocity measures started this stress was already likely diminished in comparison to the one when glaciers still advanced.

Now is changed in the text as follow:

"... Until the end of LIA, the stress propagation of the AGs would have been greater towards the proglacial foreland, thus promoting RG movement (Delaloye et al., 2013; Waller, 2013). However, in the subsequent decades, as glaciers retreated, the diminishing stress resulted in a reduction in mechanical influence over the RGs."

- I would better clarify if, during the glacier degradation, the meltwater availability may have influenced the permafrost thermal profile, and how (and if) this can be used to explain the acceleration/deceleration records. Could the hydrological input from the CG be considered a factor in modelling thermally induced creep?

Author's reply:

We believe that thermal influence of input meltwater from adjacent glaciers should be considered when modelling thermally induced creep together with precipitation and snowmelt. This consideration is essential, as it can exert an influence by enhancing the temperature of the permafrost layers by introducing non-conductive heat transfer process (Haeberli et al., 2006). Meanwhile, as modelled by Cicoira et al. (2019) the ground-water flow that reaches the shear horizon influences its pressure regime and its mechanical state promoting basal-shear type movement. This basal-shear movement, in particular cases, could be predominant over thermal induced creep, as seen in Kenner et al., 2017.

We have implemented significant revisions in the text concerning this matter, aiming to improve the clarity of our interpretation of the results. Specifically, in the discussion section, we have incorporated an explanation highlighting that while ice melting has occurred nearly continuously from the adjacent glaciers, the intensity of this melting has varied over time. We posit that such fluctuations could have played a role in influencing the variations in creep velocities observed in the rock glacier. By systematically comparing volume changes in the adjacent glaciers and RG over corresponding periods, alongside contemporaneous accelerations and decelerations in the RGs, we have observed a potential influence of the hydrological contribution of the adjacent glaciers on rock glacier velocities. This relationship holds true when the RGs are in non-ice-depletion conditions. Specifically, we find that RGs accelerate during periods characterized by anomalously higher ice-melt rates in the glaciers, and decelerate when the ice-melt rate in the glaciers is reduced.

It's important to note that this phenomenon appears to occur primarily in periods when the RG is not undergoing significant ice-depletions. However, in periods marked by significant ice-depletion in the RGs, a simultaneous deceleration occurred, even in the presence of a high water supply from adjacent glaciers. This phenomenon was observed in Tantermozza between 1962-1973 and across all the RGs by the end of the 1980s. The exceptional rate of ice loss, both in the AGs and all RGs between 1985-1991 coincides with the abrupt winter warming and reduction in snow days in the Alps since the late 1980s reported by Sippel et al., (2020) and aligned with climatic conditions in our area (SM10). We believe that this suggests a significant short-response and high sensitivity of these RGs to external climatic forcing, but without an associated immediate thermal-induced creep by plastic deformation. Still, the permafrost degradation during this warming period, could have had a delay effect promoting the general creep acceleration observed during the 1990's, as the general acceleration observed by Marcer et al., (2021) in RGs in the Western Alps during the same time-frame. Considering this, we propose that the AG hydrological inputs likely drive a possible shorter-response dominant basal-shear type movement of these four decelerating RGs, which would be predominant over a delayed thermally-induced creep, similar to that described at Ritigraben (Kenner et al., 2017).

- Reference is made to a climatic variability characterized by an increase in air temperature and dry conditions. In the period of observation of the velocities from RGs, how did the dry conditions vary?

Author's reply:

Upon analysing the data from proximal weather stations, now included in Supplementary Material 10 (SM10), we discovered a trend towards warmer and drier conditions in the area, leading to evident negative anomalies in snow cover since the mid-1980s. Prior to this period, negative precipitation anomalies were noted between 1930 and 1950, primarily coupled with colder anomalies during that timeframe.

We have included now briefly in the discussion the possible implication of these dry conditions in the recent evolution of RG velocities as follow:

"…. As observed in SM10, rising annual mean air temperatures (AMAT) in our study area have led to discernible negative anomalies in snow cover since the mid-1980s. This phenomenon prompts a reduction in snow cover insulation (Springman et al., 2013), which as suggested by Luetschg and Haeberli (2005) may increase annual mean ground temperatures (AMGT). …"

"… . Meanwhile, in periods marked by significant ice-depletion in the RGs, a simultaneous deceleration occurred, even in the presence of a high water supply from adjacent glaciers. This phenomenon was observed in Tantermozza between 1962-1973 and across all the RGs by the end of the 1980s. The exceptional rate of ice loss, both in the AGs and all RGs between 1985-1991 coincides with the abrupt winter warming and reduction in snow days in the Alps since the late 1980s reported by Sippel et al., (2020) and aligned with climatic conditions in our area (SM10). …"

"…Additionally, the reduction in the cryosphere due to the transition to non-glacial conditions might lead to an increase in precipitation not converted to ice in the glacier. Consequently, this could result in a rise of the amount of immediate water supply into the rock glaciers (RG) from precipitation in the contributing areas, potentially intensifying basal shearing during periods with high solid or liquid precipitation. This effect might have been mitigated in the last decades by the observed positive trend in warmer temperatures and dry conditions (SM10). …"

Tracking number: COMMSENV-23-1196A

Dear Reviewer #3,

Many thanks for your constructive comments and suggestions. In the following paragraphs, you will find a detailed response addressing each of your points. Additionally, the attached document includes the track-changes manuscript, highlighting all responses to your comments and corresponding modifications in the text as per your recommendations.

Reviewer #3 (Remarks to the Author):

Dear Authors and Editor of the manuscript entitled 'A unique record of rock glacier kinematics and glacier interactions from the Swiss National Park spanning more than 100 years'.

The manuscript analyzes the spatiotemporal evolution of rock glaciers in the Swiss Alps. The study area is especially interesting, since there are measurements from the beginning of the 20th century. These measurements have been complemented with photogrammetry measurements to have a record that covers more than 100 years. The results obtained are of great interest, given that there are no such long series on the evolution of rock glaciers. Furthermore, an influence of glacial evolution on rock glaciers is shown.

In my opinion it is a solid and well-presented work, and that could be a significant contribution to the study of rock glaciers. Although the methodology is not entirely novel, as it has already been applied in the study of rock glaciers, the long data series, the different techniques mixed and the results obtained make, in my opinion, the manuscript suitable for publication in Communications Earth & Environment.

In any case, some suggestions and comments are made which may help to improve the work:

- The main suggestion is to add in the Introduction and the Discussion sections some sentences about the interaction of glaciers and rock glaciers during the LIA, and works about this interaction. For example, in Tantermozza results, the authors indicate that 'the more chaotic surficial geometries, possibly caused by the CG overriding this portion of the RG during the LIA'. I suggest to include references to the work of Kenner (2018) that should be relevant for the topic of this manuscript, as indicate that some rock glaciers should be much older than the upper glaciers and that the rock glaciers, were disrupted by glaciers during the LIA. Some other works, as the paper of Palacios et al. (2021) could help in this Discussion.

Author's reply:

We agree that this historical interactions between the adjacent glaciers and rock glaciers was an interesting topic which was discussed somewhat vaguely in the text. The observed potential overriding of the glacier over the top part lobes of Tantermozza during the end of the LIA, was mentioned in the results but merely repeated in the Discussion without any comparable example. In this regard the work from Kenner et al., 2018, and in particular the interactions between the glacier of Vadret Muragl and the RG of Muragl, which are located just 5km from our study area provide good example for comparison. The potential overriding in Tantermozza together with the push moraines observed in the historical terrestrial images (1918 and 1935) of Val Sassa RG could correspond with the maximum glacier advance at the end of the LIA. Besides, the work from Palacios et al. (2021) seems very relevant in this regard, with precise dating methods that rock glaciers preceding the LIA, could have an origin related with much older glacial retreats.

Following your suggestions, we have added this topic in the Introduction and Discussion with references to Kenner et al., 2018 and Palacios et al., 2021 as follow:

In the 5th paragraph of the Introduction:

" ... Additionally, other studies displaying great complexity between these landform transitions, the use of multiple dating-methods combined with detailed morphological analysis has revealed glaciers overriding precedent RGs during the Little Ice Age (LIA) (Kenner et al., 2018), or emergence of RGs as consequence of ancient glacier retreat (Palacios et al., 2021)."

In the last paragraph of the Discussion we have added:

"...Even so, the observed signs of glacial overriding on the surface of the upper lobes at Tantermozza RG, and the small push moraines just above the top part of the RG of Val Sassa, could correspond to the maximum limit glacier advance at the end of LIA. We infer that these cases are similar to the interactions described by kenner et al. (2018) between the glacier of Vadret Muragl and the RG of Muragl, situated just 5km north-west to our study area, on which the RG was precedent to the overriding glacier."

"... Despite this, we cannot conclude that ancient glacier retreats were not involved in the origin of the debris material forming the RGs, as was demonstrate by Palacios et al. (2021) in the Héðinsdalsjökull RG in Iceland."

- Likewise, I consider that the use of the term 'Contributing glaciers' is not well justified (or at least explained), since, as indicated in the previous paragraph, it is possible that rock glaciers predate glaciers and have been partially affected by ice advances during the LIA. Also, the transition from rock glaciers, debris-covered and rock glaciers has been shown in several works and could be discussed in the fifth paragraph of the Introduction (i.e. Jones et al., 2019; Sanjosé Blasco et al., 2022).

Author's reply:

We acknowledge the potential for confusion caused by the use of the term 'Contributing Glaciers.' The term 'Contributing' may mistakenly imply that RG originates from glaciers. However, our intention was to specifically refer to glaciers upstream in the same valley to each RG, i.e., glaciers from the contributing areas.

After careful consideration, we find that the term 'Adjacent Glaciers' more accurately conveys our intended meaning. Consequently, we have replaced 'Contributing Glaciers' (CG) with 'Adjacent Glaciers' (AG) in the text.

- The geomorphological schemes of Figure 2 are not clear. The lobes are poorly distinguished. The glaciers in the upper part are not drawn either. I consider that it should be improved and colour added to the figure, to present a better cartography.

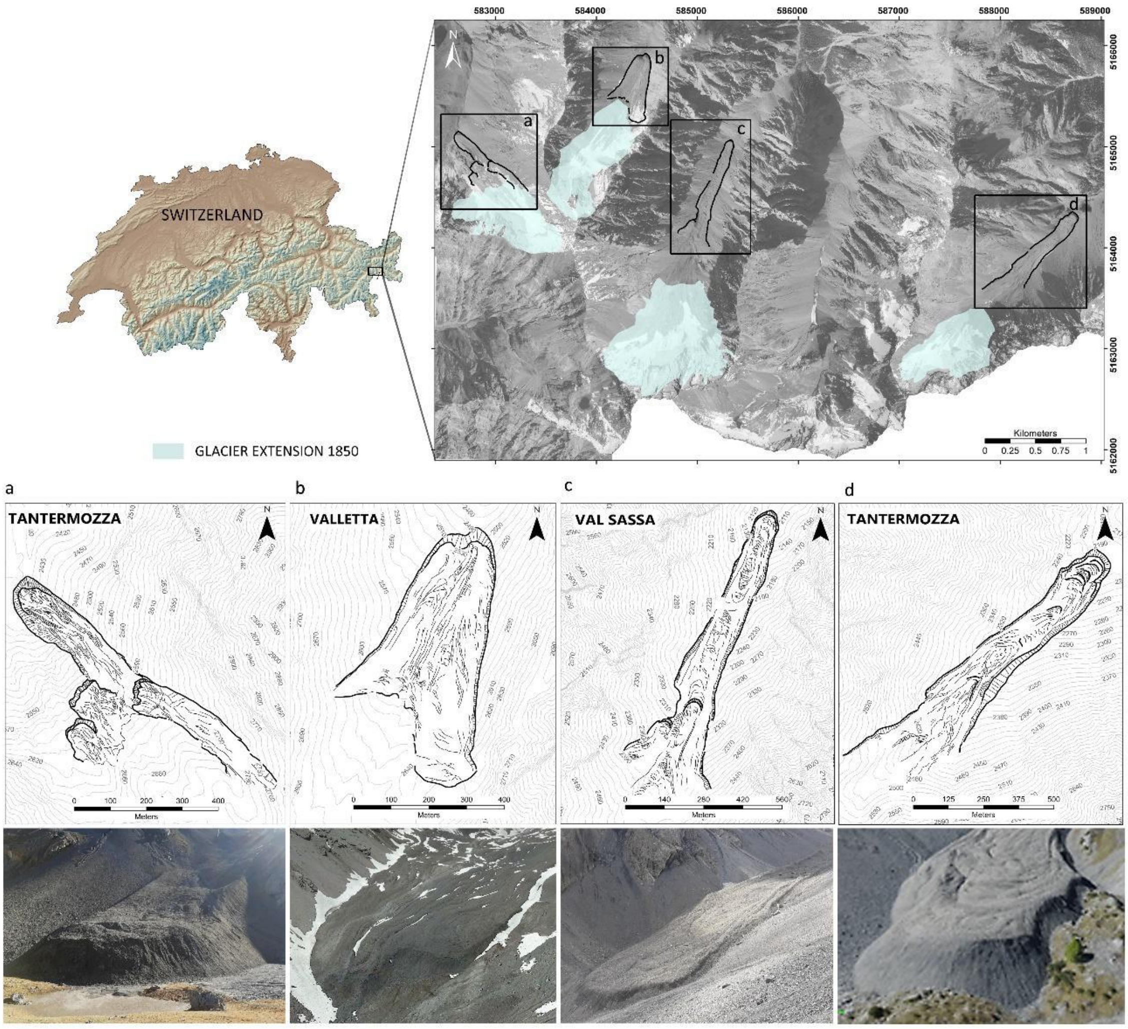
Author's reply:

We concur that the schematic geomorphology lines may be overly detailed for the current scale of visualization. More notably, the lack of differentiation in symbology presents a challenge in distinguishing the main lobes within the rock glaciers. This issue is particularly evident in Tantermozza, composed of several distinct lobes, and to a lesser extent in Val Sassa, where the upper lobe is not easily discernible.

Additionally, we acknowledge the necessity to represent adjacent glaciers in Figure 2 to provide readers with a preliminary understanding of their extensions and spatial interactions with the rock glaciers. Given that the mapped potential historical extensions of adjacent glaciers are a result of our study (and we believe therefore would not make sense to show them already in the situation figure), we opted to include glacier extensions from 1850 as per Dufour maps, as referenced in the introduction. Meanwhile mapped historical inferred glacier extensions are still shown in Figure 7.

In the general view of Figure 2, we have incorporated glacier extensions as colored polygons along with a simplified scheme outlining the rock glacier boundaries. Simultaneously, in the detailed views (a, b, c, d), we represent geomorphological scheme lines with two distinct symbologies: a thicker line to emphasize main lobes and lighter, thinner lines to denote secondary lineation. To enhance clarity, we have masked contour lines over the rock glacier extensions for a more coherent visualization. New version of Figure 2

:



Some other minor suggestions:

- In the Abstract, consider to include some more information about the results of the work, as a concluding sentence.

Author's reply:

We acknowledge that the abstract lacked a conclusive final sentence. Consequently, we have modify the conclusion of the abstract as follows::

"... Our findings reveal historical kinematic changes influenced by the hydrological contributions of adjacent glaciers, which were closely connected since the Little Ice Age but are now severely degraded. The observed hydrological control, favouring basal-shear movement over thermally-induced creep in these decelerating rock glaciers, suggests that ongoing climate-induced glacier degradation will likely result in a future scenario with limited new accelerations. Instead, a steady water flow from adjacent glaciers may sustain a gradual secondary creep, progressively slowing as permafrost degradation continues, driven by predicted warming and dry climatic conditions in the Alps."

- In the Introduction, consider to add some more references about RG kinematics (i.e. Kellerer-Pirklbauer, A., & Kaufmann, V., 2012; Cusicanqui et al., 2021; Tanarro et al., 2019) and especially the work of Fleischer et al. (2023), that include data from almost 100 years.

Author's reply:

Many thanks for your suggestions. We have added Kellerer-Pirklbauer, A., & Kaufmann, V. (2012); Tanarro et al. (2019) and Fleischer et al. (2023) to the text and reference list. Cusicanqui et al. (2021) was already added. Tanarro et al., 2019 proved valuable due to some similarities in the geomorphological context and dynamic evolution with respect to our analysed rock glaciers. Specially relevant for us is the Fleischer et al., 2023 providing the longest rock glacier analysis before our own study, with velocities analysis since 1938 and elevation changes since 2022.

All these new references are now included in the third paragraph of the Introduction as follows:

"... So far, the longest kinematic analysis carried out on RGs reach back to 1922 with the work of Fleischer et al. (2022). In their comprehensive study, they integrated an stereophotogrammetric map of 1922 with flow velocity profiles of 1938 and photogrammetric data from later decades to reconstruct the geomorphic evolution of the Innere Ölgruben rock glacier (Austria). . Other long-term analyses, dating back to the late 1940s or mid-1950s (e.g. Kellerer-pirklbauer and Kaufmann, 2012; Tanarro et al., 2019; Cusicanqui et al., 2021; Kääb et al., 2021; Fleischer et al., 2021; Marcer et al. 2021; Hartl et al., 2023) are normally based on photogrammetric measurements from historical, vertically acquired aerial images, which can complement, or not, more recent GNSS surface measurements..."

- Review the References section, as some works cited in the text do not appear in the Reference list (examples Reinosch et al., 2021; Roer et al., 2008;).

Author's reply:

Many thanks for noticing these errors.

We have systematically reviewed the citations in the text, addressing any previously missed references, and updated the Reference list accordingly.

- The first paragraph of the Discussion seems like an Introduction rather than a Discussion.

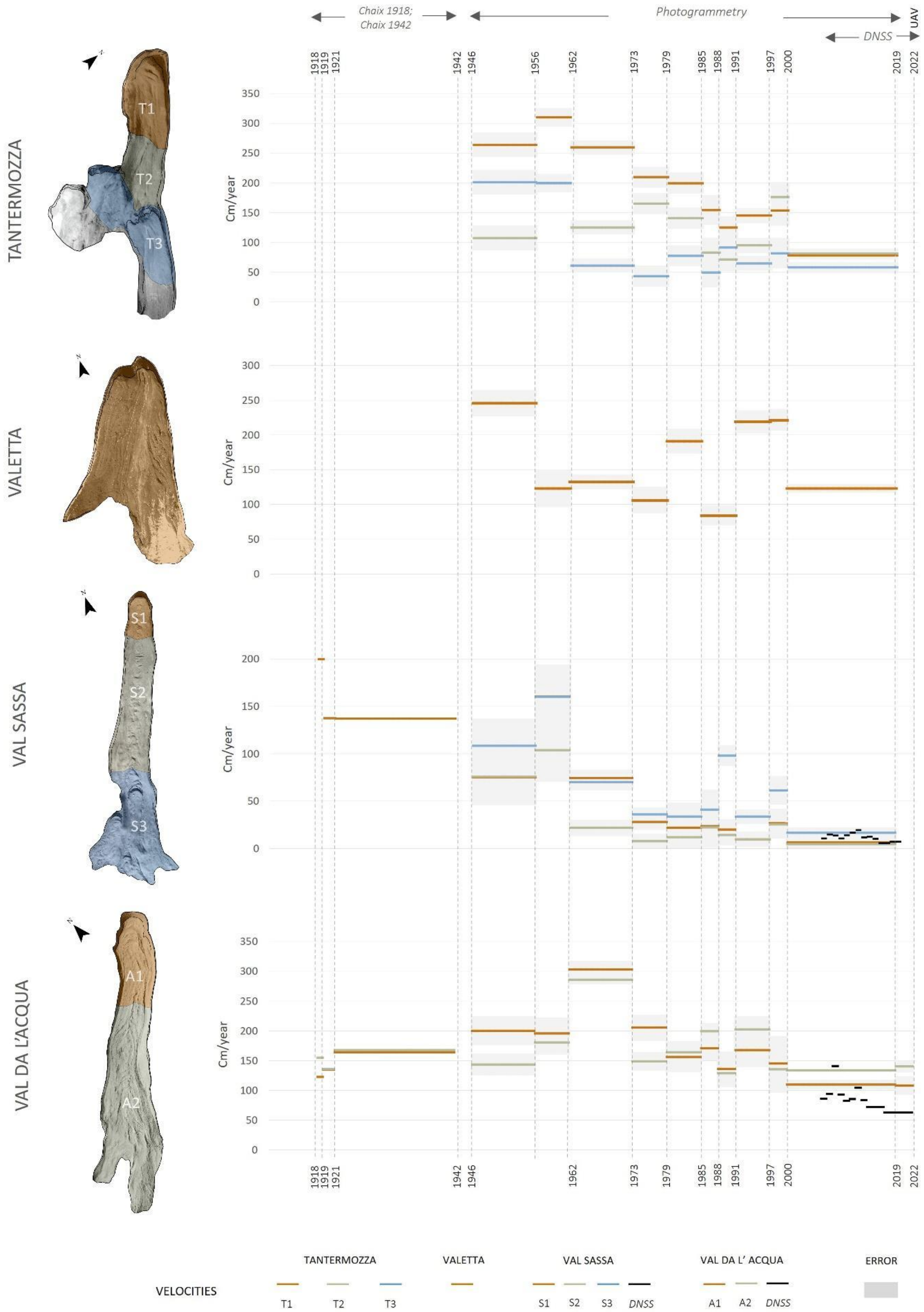
Author's reply:

We concur that, when initially drafted, it seemed necessary to include a summary as an introduction to the discussion. However, upon further review, we no longer perceive the need for its inclusion; it appears redundant. Consequently, we have removed it from the text and will proceed directly to the discussion of the results.

- In Figure 3, I suggest changing the colour for T1 or T3, since they are very similar and cannot be distinguished well (Tantermozza and Val Sassa).

Author's reply:

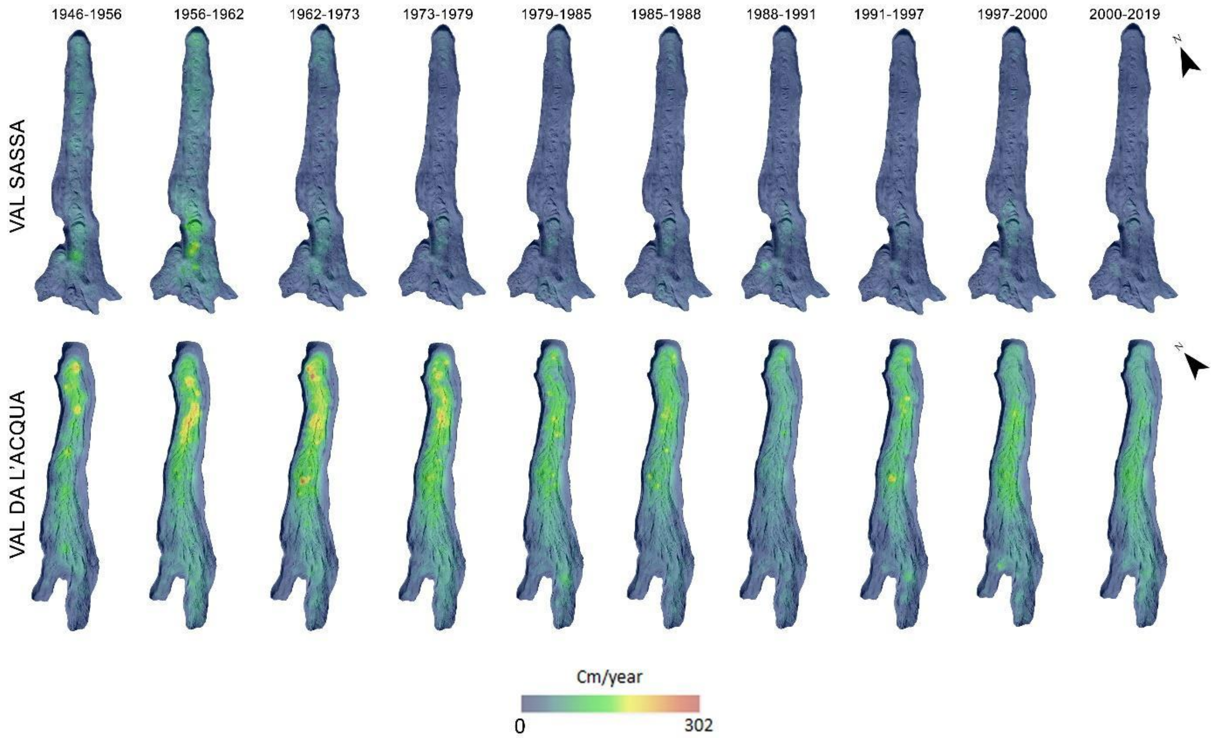
Now the colour in T3 and S3 is changed to blue. We have changed also the style of the left reference maps to not show in the background the old geomorphological schemes.



- In Figure 4, I suggest that the colour scale for all 4 rock glaciers be the same, so that comparison between them becomes easier.

Author's reply:

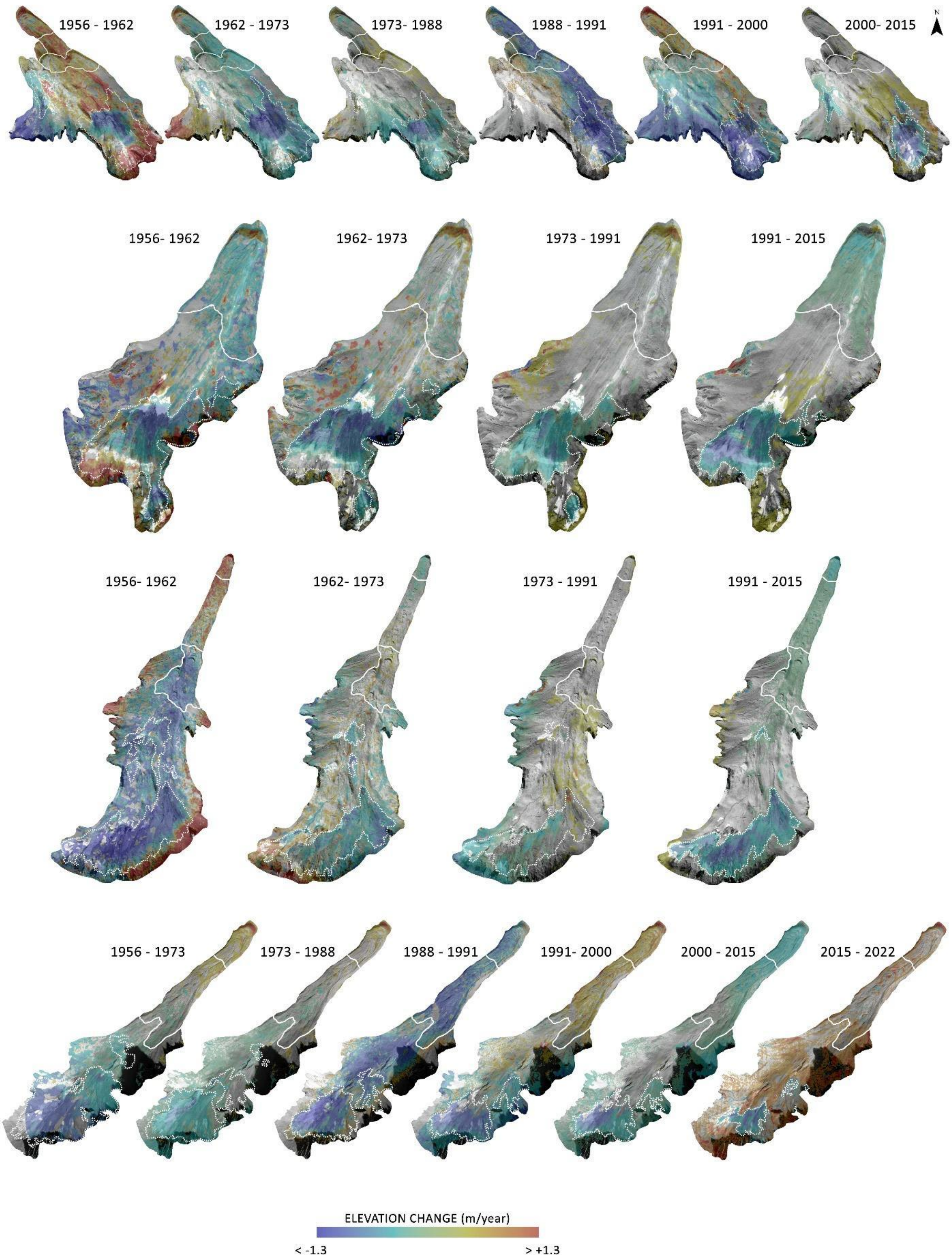
Thanks for the suggestion. We did different versions of this figure considering this. Unfortunately, when using the same scale for different rock glaciers at certain time periods, even if resulting in better comparison between the different velocities of the rock glaciers, it doesn't allow to see clearly the spatial evolution of velocities within each rock glacier. As illustrated in the example below, using the same color bar for both Val Sassa and Val da l'Acqua makes it arduous to discern spatial differences in velocities between the upper lobe and the front lobe in Val Sassa, despite these differences being quite significant. The use of colour bars with a bigger number of transitions between different colours in logarithmic colour bars, could be also an alternative, but in our opinion made the figures less clean and more complex for interpretation.



- In Figure 6, consider separating rock glacier and glacier areas by lines. I suggest that the scale be the same for all 4 sites.

Author's reply:

Following your suggestions we have modified Figure 6. Specifically, we have added both rock glaciers active areas and inferred glacier extension for each period. Additionally, the Elevation Change raster maps now share a standardized scale, allowing for meaningful comparisons between rock glaciers and different time periods. In order to enhance comparability across periods, the displayed elevation changes are now presented as meters per year for each respective timeframe, rather than the total period change.



TANTERMOZZA
1956 - 1962
1962 - 1973
1973- 1988
1988 - 1991
1991 - 2000
2000- 2015
N
VALLETTA
1956- 1962
1962- 1973
1973 - 1991
1991 - 2015
VAL SASSA
1956- 1962
1962- 1973
1973 - 1991
1991 - 2015
VAL DA L'ACQUA
1956 - 1973
1973 - 1988
1988 - 1991
1991- 2000
2000 - 2015
2015 - 2022
ELEVATION CHANGE (m/year)
< -1.3
> +1.3

- In Supplementary Material 2, I also suggest the same scale bar for all 4 sites.

Author’s reply:

Following your suggestions I have revised the figures presented in Supplementary Material 2. In the updated version, a consistent scale has been applied across all figures, facilitating direct comparisons between different sites.

- I think that Supplementary Material 3 is the same than Figure 6.

Author’s reply:

Many thank for noticing this error.

Indeed, in an earlier draft of the paper, Figure 6 differed from its final form, failing to display the entirety of the maps. Subsequently, when creating the revised Figure 6, an oversight occurred, and we neglected to remove the outdated version from Supplementary Material 3. This error has now been rectified, and the obsolete version has been removed.

Some other minor suggestions or mistakes are included in the PDF.

25th Jan 24

Dear Mr Muñoz-Torrero Manchado,

Your manuscript titled "A unique record of rock glacier kinematics and glacier interactions across four valleys in the Swiss National Park spanning more than 100 years" has now been seen by our reviewers, whose comments appear below (Reviewer #1 was unable to provide a second report). In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

EDITORIAL REQUESTS:

Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table".

*****Please take care to match our formatting and policy requirements. We will check revised manuscript and return manuscripts that do not comply. Such requests will lead to delays. *****

Please outline your response to each request in the right hand column. Please upload the completed table with your manuscript files as a Related Manuscript file.

If you have any questions or concerns about any of our requests, please do not hesitate to contact me.

SUBMISSION INFORMATION:

In order to accept your paper, we require the files listed at the end of the Editorial Requests Table; the list of required files is also available at https://www.nature.com/documents/commsj-file-checklist.pdf .

OPEN ACCESS:

Communications Earth & Environment is a fully open access journal. Articles are made freely accessible on publication under a CC BY license (Creative Commons Attribution 4.0 International License). This license allows maximum dissemination and re-use of open access materials and is preferred by many research funding bodies.

For further information about article processing charges, open access funding, and advice and support from Nature Research, please visit https://www.nature.com/commsenv/article-processing-charges

At acceptance, you will be provided with instructions for completing this CC BY license on behalf of all authors. This grants us the necessary permissions to publish your paper. Additionally, you will be asked to declare that all required third party permissions have been obtained, and to provide billing information in order to pay the article-processing charge (APC).

Please use the following link to submit the above items:
[link redacted]
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Joe Aslin

Deputy Editor,
Communications Earth & Environment
https://www.nature.com/commsenv/
Twitter: @CommsEarth

REVIEWERS' COMMENTS:

Reviewer #2 (Remarks to the Author):

Dear Authors

Thank you for taking into consideration my comments/suggestions that arose after my first review. Your replies and changes to the text fully satisfy me and, in my opinion, the paper is now much more detailed, free of parts that are not clearly explained, and more convincing.
I have no other comments,
Thank you, best wishes
Adriano Ribolini

Reviewer #3 (Remarks to the Author):

Dear authors,
I have carefully read the new version of the manuscript and, in my opinion, the work can be accepted in its current form. The responses to the comments raised in the first review are satisfactory, and I consider that with the new changes the work is more solid.