Answers to Referee #2

Below, the reviewer's comments appear in blue and our responses in **black bold**. References in the manuscript appear in *italics*. Changes made to the manuscript (revised version) are <u>underlined</u>. Line numbers refer to the original preprint.

The authors present a geomorphological rock glacier inventory of the Peruvian Andes (i.e., PRoGI) compiled through the manual mapping on Bing (and Google Earth) optical imagery. My comments are mainly concerned with the manuscript. I didn't have time to look at the actual shapefile. In my view, the paper is suitable for publication in ESSD after substantial revisions.

I suggest improving the logical flow of the introduction/results/discussion and provide stronger (basic and applied) motivations for compiling the inventory in the way it is presented/discussed in this paper. Considering that RG degree of activity in PRoGI relies on the visual assessment/interpretation of landforms, I suggest reducing substantially the length of the analysis (and accompanying text of the Results and the Discussion) concerned with the classification of rock glaciers into active, transitional, and relict. My suggestion is motivated by the high degree of uncertainty that is typically associated with the morphologically based classification of rock glacier activity. Please see my detailed comment to section 5.2.1. Overall, I believe the paper would benefit from substantial trimming. A more concise paper structure would allow the main original points of the inventory to stand out more apparently.

Please consider all of my comments on the constructive side. Thank you for your effort on this work.

Thank you very much for your positive assessment of our research and for your valuable comments on how to improve this manuscript.

General comments - manuscript:

1. TITLE: On the "high-resolution" character of the inventory I share the evaluation made by referee #1. Nowadays, the use of Bing and GE imagery (comprised between 1 and 5 m resolution) represents the norm. A high-resolution inventory, in my view, should employ sub-metric RGB imagery, and possibly LiDAR-derived DTMs for increasing three-dimensional perspective and filtering out vegetation cover over vegetated RGs. For example, this is the case of a geomorphological inventory recently compiled across South Tyrol (Italy) by Scotti et al. (2024), who utilized 0.2-to-0.5 m gridded orthophoto mosaics and a 2.5 m LiDAR DTM. Incidentally, this inventory tallies a number of rock glaciers (n = 2798) comparable to PRoGI, and may serve as a useful term of comparison in Table 8.

   The difference between an inventory compiled on GE imagery and one compiled on higher-resolution orthophoto mosaics coupled with LiDAR-derived DTMs was assessed by Brardinoni et al. (2019). Accordingly, it was found that "the number of mapped rock glaciers on GE imagery exhibited higher inter-operator heterogeneity (up to a factor of 3), and that using LiDAR and higher resolution orthophotos lowers this heterogeneity down to a factor of 2, while producing an increase in the number of mapped landforms, which become systematically smaller".

To summarize, I believe that image resolution matters and the resolution of Bing and GE imagery would not warrant a consistent "high resolution" inventorying output across a large study area such as the Peruvian Andes.

Thanks for the comment. We recognize that the term "high-resolution" can be subjective and that Bing/Google Earth images (1-5 m) are standard for the development of regional inventories. We have removed "high-resolution" from the title and manuscript, focusing on the main contributions of PRoGI as the first comprehensive inventory covering the entire Peruvian Andes and providing detailed topoclimatic attributes using standardized mapping protocols. The proposed new title is: "A comprehensive rock glacier inventory for the Peruvian Andes (PRoGI): dataset, characterization, and topoclimatic attributes.**"**

However, we have retained the term to describe images from Google Earth and Bing Maps, as other studies recognize that these satellite images belong to the high-resolution category for remote sensing data (Abdullah and Romshoo, 2024; Bhat et al., 2025).

Abdullah, T., & Romshoo, S. A. (2024). A Comprehensive Inventory, Characterization, and Analysis of Rock Glaciers in the Jhelum Basin, Kashmir Himalaya, Using High-Resolution Google Earth Data. Water, 16(16), 2327.

Bhat, I. A., Rashid, I., Ramsankaran, R. A. A. J., Banerjee, A., & Vijay, S. (2025). Inventorying rock glaciers in the Western Himalaya, India, and assessing their hydrological significance. Geomorphology, 471, 109514.

2. STUDY AREA: The authors adopt a climatic classification of the Peruvian Andes proposed by Bonshoms et al. (2020), which in turn is based on previous climatic characterization of glaciers across the entire South America (Sagredo and Lowell, 2012).
   Sagredo, E.A. and Lowell, T.V. (2012) Climatology of Andean glaciers: a framework to understand glacier response to climate change. Global and Planetary Change., 86-87, 101–109.
   In the results, and especially in the discussion, it will be important to remind the reader that the four broad regions were defined solely based on climate, and therefore they do not consider interactions with the relevant terrain altitudinal distribution (i.e., how much area is available in each region for RG development

above (current and former) critical isothermal altitudinal thresholds) and the dominant lithologies (i.e., propensity for rock walls to disintegrate in blocky debris, hence promote thermal ventilation and permafrost persistence). Having considered climatic regions only may explain the lack of explanatory power and the intra-regional heterogeneity observed in terms of RG spatial distribution. In this context, the subdivision of South Tyrol in physiographic zones (i.e., combining broad climatic, hypsometric, and lithologic characteristics) offered an obvious advantage, in explaining the relevant spatial variability in rock glacier density (Scotti et al., 2024).

A description (even a brief one would suffice) of the geological setting, including a list of the dominant lithologies in each of the four climatic regions is missing. Please consider adding one.

We thank the reviewer for this valuable suggestion. We have expanded the Study Area section to include geological context based on our analysis of lithological distribution across the four climatic regions. Specifically, we have added:

1. **Quantitative geological description: Added a detailed breakdown of dominant lithologies in each climatic subregion, including the main geological formations:**

   "…<u>From a geological point of view, the four subregions have distinct lithological characteristics that influence the potential for rock glacier formation. The SDOT subregion is dominated by Miocene-Neogene volcanic-sedimentary sequences (Nm-vs), which produce abundant block debris for rock glacier development. The NWOT subregion is mainly characterized by Neoproterozoic schists and gneisses (NP-esq,gn), which break down into competent debris. The NDOT contains important Paleogene-Neogene volcanic and sedimentary formations (PN-vs), while the SWOT mainly sits on Ordovician metasedimentary rocks (O-ms)."</u>
2. **Hypsometric context: The results include an analysis of the altitudinal distribution of rock glaciers that may be comparable to critical permafrost thresholds.**
3. **Explicit clarification: we have clearly indicated that the regional classification is based solely on climate:**

   "<u>It is important to emphasize that this regional framework is based solely on climatic criteria and does not incorporate other factors</u>**"**

3. METHODOLOGY: In the present inventory the authors partly follow the RGIK guidelines, partly do not. Consequently, the inventory would not be directly comparable with other RGIK-based counterparts compiled elsewhere around the globe. I am not suggesting that the inventory should adopt the entire RGIK identification, location, characterization, and delineation protocol; however, it is

important that the authors: (i) adhere to the mandatory parts of the RGIK guidelines; and (ii) clearly summarize which components of the RGIK methodological workflow are adopted, which not, and whether a different nomenclature is applied for some of the attributes.

For example, RGIK considers as mandatory component the compilation of a shapefile of primary markers. That is, a shapefile made of point elements reporting lat, long and unique identifier for each rock glacier unit (RGU) and system (RGS). Following this logic, each rock glacier is hierarchically classified into units and systems. Similarly, the RGIK morphological-based activity classification does entail classifying rock glaciers units into active, active uncertain, transitional, transitional uncertain, relict, and relict uncertain. The present inventory encompasses solely active, transitional, and relict landforms. This is a potentially critical approach, considering the inherent uncertainty associated with the classification of transitional rock glaciers i.e., note the high degree of discrepancy between international experts in the activity classification of inactive/transitional landforms (Brardinoni et al, 2019). Indeed, the test presented by Brardinoni et al involved not only RG outline delineation (see section 4.6 of the present manuscript), but also the activity classification.

We thank the reviewer for this important observation regarding RGIK guideline implementation. We have substantially revised the Methodology section to explicitly address compliance:

1. **Implementation of primary markers: We have created and attached a complementary geopackage file of primary markers (in the PANGAEA repository) with hierarchical RGU/RGS classification, thus complying with this mandatory RGIK requirement.**
2. **Explicit statement of compliance: A brief summary of the RGIK guidelines that have been adopted in full, in part, or modified has been added, along with a justification for each decision.**

   "<u>..., with specific adaptations for the scale and context of our national inventory. :</u>

   <u>(1) In accordance with the mandatory requirements of RGIK, we compiled two vectors (in *. gpkg format), the first containing the primary markers for each rock glacier unit or system and the second, the extended footprint of the polygonal delineation for each rock glacier including its associated attributes.</u>

   <u>(2) In the activity classification approach, while RGIK recommends six activity classes (including "uncertain" categories), we employed a simplified three-class system (active, transitional, and relict) due to the extensive spatial coverage required for a practically implemented system.</u>

(3) The scheme for the inventory attributes has been partially adopted from the RGIK guidelines, as they have been complemented with topoclimatic variables for hydrological and climatic applications.”

3. **Justification of activity classification: We provide a comprehensive explanation of our simplified three-class system, acknowledging the uncertainty inherent in transitional forms but justifying our approach based on consensus mapping and the practical constraints of national-scale inventorying.**

4. RESULTS

Please consider whether all of the sub-sections are needed to convey the main message of the paper. Some may be deleted; some may be merged. I feel that some descriptive information does not lead to original insights. Currently, the results are subdivided in many sub-sections, many of which consist of a single paragraph.

This paper section (the Results) contains both results and interpretations. Please move interpretations to the Discussion e.g., lines 323-325 and lines 332-333. Just to mention a couple of examples that I have noticed in subsection 5.1.

We sincerely thank you for your thorough review and your valuable comment, which have significantly helped us to improve the manuscript's clarity and focus. We have carefully considered your feedback regarding the structure of the Results section and the mixing of results with interpretation.

We agree with the first observation and have thoroughly revised the structure of the Results section to reduce fragmentation and improve the narrative flow. Specifically, we have merged several sub-sections:

- **The original subsections** 5.3.1 "Slope distribution" and 5.3.2 "Aspect (orientation)" **have been merged into the main** 5.3 "Topographic and Climatic Attributes".
- **The subsection** 5.2.1 "Rock glacier activity" **has been integrated** into 5.2 "Rock Glacier Characteristics: Morphology and Activity", **creating a more cohesive presentation of the landforms' properties.**
- **This consolidation has reduced the total number of subsections and eliminated those comprising only a single paragraph, resulting in a more streamlined and logically structured section.**

We have meticulously reviewed the entire Results section and have removed all interpretive statements, relocating them to the Discussion section. This includes, but is not limited to, the examples you kindly pointed out:

- **Interpretations regarding the influence of climate aridity, lithology, and local geomorphological factors on rock glacier distribution (from Section 5.1) have been moved.**

- **Explanations about the significance of morphological shapes and the implications of the activity status statistics (from Section 5.2) have been transferred.**
- **Discussions on why certain slope angles or southerly aspects are preferential (from Section 5.3) have been relocated.**

5. DISCUSSION

Based on the revised structure of the Results, please consider which parts of the Discussion may be really necessary to highlight the originality and robustness of your inventory, and which others may be just chocking the reader with unnecessary details (or debatable interpretations). I believe that the overall reading of the paper would highly benefit from some Discussion simplification.

Based on the above and the need for substantial revision, I will limit my comments on the Discussion to Table 8. Considering that this manuscript is not a review paper, please consider restricting your list to inventories that can help making a more straightforward and meaningful comparison with PRoGI. For example, wouldn't be enough comparing PRoGI to other inventories in South America? Even when a worldwide comparison was deemed necessary, what is the point of comparing PRoGI with inventories that contain less (or a little more) than 100 RGs? To warrant a more reliable comparison, I would limit Table 8 to inventories that encompass thousands (or at least several hundreds) of RGs.

We sincerely thank the referee for this overarching suggestion, which has significantly improved the clarity and impact of our Discussion. We have undertaken a major simplification and restructuring:

- **We merged and condensed paragraphs to avoid repetition.**
- **We eliminated contentious interpretations and overly detailed comparisons that did not directly highlight the main findings.**

We fully agree with this logic. Following the referee's recommendation, we have substantially revised Table 8 to include only inventories that allow for meaningful and direct comparison. We have applied clear criteria, restricting the table to inventories containing several hundred rock glaciers or more, and we have prioritized major inventories from South America and other key global regions that serve as essential reference points. This makes the table more concise, reliable, and directly relevant to the scale of our study.

Specific comments:

Line 39: "Nowhere is this more evident ...". Please consider tuning this sentence down. The pace of warming is widely documented in mountain and high latitude area around the globe, and the tropical Andes are just one of them.

We thank the reviewer for this suggestion. We have modified the sentence to tone down the absolute claim, replacing "Nowhere is this more evident than in the tropical Andes...**" with "**This warming trend is particularly evident in the tropical Andes...**" to acknowledge that other mountain regions are also experiencing significant warming while still emphasizing the relevance of our study area.**

Line 43: unclear in what sense RGs would stand out as "geomorphological archives". Please expand and add references testifying to the geomorphic archival value of RGs.

We have expanded this concept to clarify what we mean by "geomorphological archives" and added appropriate references: "Among periglacial landforms, rock glaciers stand out as both geomorphological archives of past climate conditions, preserving information about paleo-temperatures through their internal structure and development history (Haeberli et al., 1999) and as vital water reservoirs."

Line 43-45: if adopting the RGIK (2023) technical definition of rock glaciers, please report the complete version (i.e., creep and "shearing at depth"; "optionally" ridge ad furrow topography, since these features do not always occur). Presently, the definition provided would apply just to active landforms (i.e., steep fronts).

We have updated the definition to include the complete RGIK (2023) version: "These ice-debris landforms, formed by the creep of ice-rich permafrost and shearing at depth, optionally exhibit steep fronts, lateral margins, and ridge-and-furrow surface topography (RGIK, 2023).

Line 45: Boccali et al (2019) refers to the southeastern European Alps (the Julian Alps), which are not exactly an arid region, similar to the Peruvian Andes. Consider replacing this reference with a better fit or rewriting the sentence.

We have replaced the inappropriate reference with more relevant Andean studies: "Comprising 15–70 % ice by volume (Halla et al., 2021; Haq and Baral, 2019), rock glaciers store substantial water equivalents in arid regions like the southern Peruvian Andes (Janke et al., 2017; Rangecroft et al., 2015; Schaffer et al., 2019)."

Lines 46-47: The thermal insulation (through ventilation) afforded by the surficial blocky layer is a property of rock glaciers that has been known/characterized for decades. Besides Brighenti et al (2021), please add reference to prior studies that have indeed characterized with empirical data the internal structure of rock glaciers e.g., Scapozza et al (2011), Geomorphology.

We have added the suggested reference and other key studies: "Their debris mantle confers thermal inertia through ventilation effects, buffering ground ice against short-term climate variability (Brighenti et al., 2021; Scapozza et al., 2011)."

Lines 46-47: "This dual role as climate sentinels and hydrological buffers makes rock glaciers indispensable for understanding long-term environmental change". Please clarify what is meant by climate sentinels. Are they considered climate sentinels across the Quaternary or at shorter contemporary time scales? In the former case, please add reference to Quaternary studies involving numerical dating of RGs (e.g., 10Be, 14C). In the latter case please add reference to Rock Glacier Velocity as an emergent variable of climate change.

We have clarified both temporal scales: "This dual role as climate sentinels—providing insights into both contemporary climate change through velocity monitoring (Kääb et al., 2021) and Quaternary climate history through dating of their formation (Palacios et al., 2020)—and hydrological buffers makes rock glaciers indispensable for understanding environmental change across multiple timescales**.**

Line 48: please cite a reference when stating the definition of permafrost.

We have added the requested reference: "Mountain permafrost, defined as ground remaining ≤0 °C for at least two consecutive years (van Everdingen, 1998), underpins these systems."

Line 54: To acknowledge alternative views on rock glacier origin/formation that are still matter of international debate (i.e., permafrost vs glacier-to-rock glacier transition), please consider adding a sentence in which you state that in this paper you do not address the question of ice origin and rock glacier formation.

We have added the suggested clarification: "It should be noted that while the origin of rock glaciers (permafrost creep vs. glacier-to-rock glacier transition) remains debated internationally, this paper focuses on their morphological characterization and distribution without addressing formation mechanisms**."**

Line 60 "the first high resolution" and Line 63 "By combining sub-meter remote sensing imagery". Given the imagery utilized (GE and Bing imagery ranging between 1 and 5 m cell size, as reported in Table 1, are not sub-metric), I don't see the point of considering the inventory a high-resolution one. This comment applies to the paper title too.

We have removed "high-resolution" from the description of PRoGI and corrected the resolution specification: "To address this, we present the Peruvian Rock Glacier Inventory (PRoGI v1.0), the first nationally comprehensive rock glacier dataset for the Peruvian Andes, compiled using the mapping standards of the International Permafrost Association's Action Group (RGIK, 2023). By combining high-resolution remote sensing imagery (0.5-5 m) with rigorous geospatial analysis, PRoGI v1.0 documents the distribution, morphology and climatic characteristics of rock glaciers across Peru.**”**

Lines 69-70: for the sake of conciseness, please consider removing these two lines. I think the introduction would stand up fine without them.

We have accepted your suggestion to remove those two lines, thank you very much.

Line 118: “independent check”. Please expand on the likely reliability of the modelled MAGT. Similar models are known to work relatively well in low-lying Artic regions but subject to large uncertainty in rugged mountain terrain, due to high spatial heterogeneity in sediment texture and other local variables. Most importantly, how did you proceed when a RG was labelled relict but plotted withing MAGT < 0°C? Please document your set of decision rules.

We thank the reviewer for raising this important point about the reliability of modelled MAGT data in complex mountain terrain. We have expanded this section to clarify the limitations and our usage of the Obu et al. (2019) data:

1. Added explicit limitations: We now state that the model has not been validated for Southern Hemisphere mountain regions and has known uncertainties in rugged terrain due to local-scale heterogeneity.

2. Clarified usage: We emphasize that the MAGT data were used only as a descriptive variable and supplementary indicator, not for definitive permafrost delineation.

3. Documented decision rules: We explain that discrepancies between morphological classification and modelled MAGT did not trigger reclassification, as our activity assessment was based primarily on visual morphological criteria.

4.1.2 Digitization protocol

As per prior comment, please clarify whether the RGIK protocol was adopted, or an alternative one was implemented. The three bullet points differ from what reported in the RGIK guidelines.

Lines 154-156: “In some cases, rock glaciers exhibited very extended or degraded fronts (e.g., a “tongue-shaped” that had flowed out and thinned, or a collapsed snout). In such situations, we adopted a conservative mapping approach to remain consistent with IPA guidelines for degraded features (RGIK, 2023)”. I would like to remind the authors that the RGIK conservative approach for delineating the extended outline of RGs applies to the “exaggerated” front category, and not to the “truncated” front one (cf. Figure 3 in RGIK 2023). As per prior comment, it is critical that the authors use the same RGIK terminology, if they have decided to apply the RGIK protocol. In this context, the example provided in Figure 2, alone, may result misleading to the broader audience. Together with the present example, I suggest that the authors present a more classical example (with a steep, talus-like front and better-defined lateral margins) that would form Figure 2a: an easy to map RG case. Following this logic, the present Figure 2 could become panel b (i.e., Figure 2b) representing a more complicated RG to delineate.

In addition, the mapping example shown in Figure 2 presents a number of issues:

1) the front is located immediately above a bedrock ledge, which can confound the interpretation and the delineation of the front base.

2) The eastern lateral margin and the upper boundary of the RG outline cut across morphological flow lines. What was the rationale for drawing such outline? If you believe this is a "difficult" case characterized by complex morphology in which it is not easy to assuredly draw an outline, please acknowledge so. It would be perfectly fine to document a case in which mapping is not so straight forward.

3) The western lateral margin is composed of a number of adjacent taluses and debris cones departing from the rock glacier rooftop. I do not see any clear lateral margin along the entire western side of this rock glacier. As per prior comment, if you believe this is a "difficult" case to map/outline, please declare so.

We thank the reviewer for these detailed observations about RGIK protocol implementation and Figure 2. We have substantially revised this section to address all concerns:

1. RGIK protocol clarification: We explicitly state our adoption of RGIK guidelines with specific adaptations for national-scale mapping.

"<u>When a rock glacier was identified in the imagery, we delineated it as a polygon following a consistent digitization criteria follow RGIK guidelines."</u>

2. Corrected terminology: We have replaced the generic description with precise RGIK terminology for "exaggerated" and "truncated" fronts, citing the specific RGIK figure reference.

<u>"For complex frontal and lateral margins morphology cases, we applied RGIK's conservative approach specifically for "exaggerated" fronts and lateral margins (RGIK, 2023)., where the landform boundary was drawn along collapse features or the farthest ridge, limiting extension to 50 m beyond discernible boundaries. For truncated fronts, we draw the contour maintaining an almost constant distance from the restricted contour or as a continuation of the visible extended side margins to avoid overestimation."</u>

3. Revised Figure 2: We have replaced the single problematic example with a two-panel figure showing both a "classical" easy-to-map case (Panel a) and a

complex case with mapping challenges (Panel b), clearly acknowledging the difficulties in the latter.

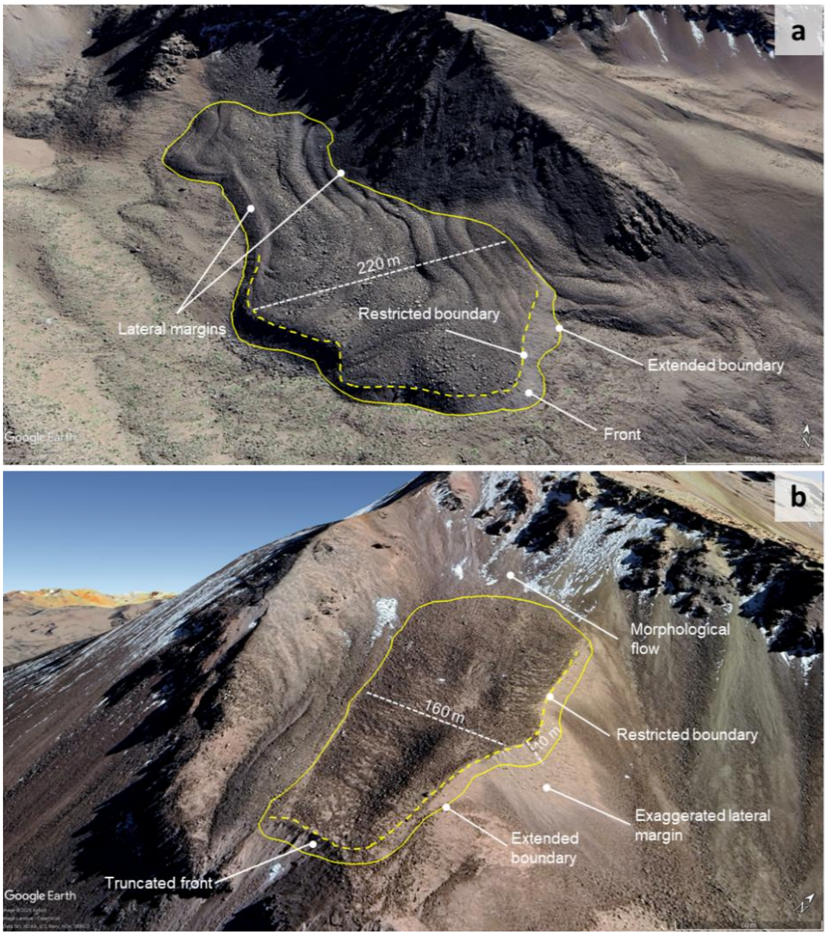


Figure 2. Rock glacier mapping examples: (a) Classical case with well-defined morphology (15°37'3.79" S, 72°23'0.32" W) showing clear frontal and lateral margins; Complex case with mapping challenges (17°04'30" S, 69°59'24" W) showing truncated frontal morphology and uncertain lateral boundaries.

4. Transparent discussion of mapping challenges: We now explicitly describe the complexities and uncertainties in delineating challenging rock glaciers like the one originally shown, explaining our conservative approach in such cases.

These modifications provide greater transparency about our methodological choices and mapping challenges.

4.1.3 Quality Control

In the RGIK protocol, the identification of RGs comes as a first step, which involves mapping primary markers and then classifying them as: rock glaciers, uncertain rock glaciers, and not rock glaciers. This means that an RGIK inventory ultimately retains some primary markers labelled as "uncertain rock glaciers".

In the case of PRoGI, please clarify how uncertain landforms were dealt with. I can imagine that a subset of landforms has remained uncertain. Were these landforms excluded or retained in the inventory? The last two sentences (lines 187-189) are not clear on this point.

Line 171: please replace the full stop with colons at the end of the sentence and before the list.

Line 172: Sun et al 2024 is most likely a repetition and should probably be deleted from the first bullet point.

We thank the reviewer for these important clarifications. We have revised this section to address all points:

1. Uncertain landforms clarification: We explicitly state that uncertain features were either resolved through consensus review or excluded from the final inventory if identification remained ambiguous.

2. Colon correction: We have replaced the full stop with colons as suggested.

3. Repetition removal: We have deleted the redundant "Sun et al., 2024" reference from the first bullet point.

4. RGIK alignment: We clarify how our certainty levels (0 and 1) correspond to RGIK's "uncertain rock glacier" category and describe our resolution process.

4.2 Geomorphological identification criteria

Based on its content, this part does not deal with the identification but with the classification of the activity status (or degree of activity). Please change the title of this sub-section accordingly.

Some of the morphological and thematic criteria utilized here hold the risk of reading too much in terms of activity, while not disposing of reliable kinematic data. For example:

1) Vegetation: I don't find particularly useful using vegetation as a possible criterion for discriminating relict from active and transitional counterparts. Borrowing criteria and evidence drawn from wetter physiographic regions, such as the European Alps (e.g., Scotti et al, Colucci et al, Kellerer-Pirklbauer) is not particularly reliable in arid regions of the Peruvian Andes, where hardly any vegetation can grow in similar dry settings.

This is explicitly stated in page 10 of RGIK (2023): "In arid regions, vegetation may nevertheless be lacking on relict rock glaciers due to unfavorable environmental conditions".

2) Ridge and furrows: this morphological element is not considered in the RGIK guidelines as diagnostic evidence for discriminating between active, transitional, and relict rock glaciers.

Based on the above, I wonder to what extent the morphological criteria detailed in Table 2 would lead to the compilation of an inventory consistent with existing (or forthcoming) RGIK-based inventories conducted elsewhere on Earth. Please elaborate.

We thank the reviewer for these important observations about activity classification criteria. We have implemented the following changes:

1. Title modification: Changed to "<u>4.2 Geomorphological identification and classification</u>**" to accurately reflect the content.**

2. Vegetation criterion clarification: We have added a qualification noting that vegetation is a secondary indicator with limited applicability in arid regions, citing the RGIK (2023) caution about arid environments.

3. Ridge and furrows context: We clarify that while ridge and furrow topography is optional in RGIK guidelines, it has been used as supporting evidence in multiple Andean studies, though not as a primary diagnostic criterion.

4. Criteria prioritization: We now emphasize that our classification relied primarily on frontal morphology and overall landform integrity, with other criteria serving as supplementary indicators.

4.4 Classification of rock glaciers

The first part of this section (lines 250-266) largely duplicates what described in section 4.2. Please move these 16 lines of text in section 4.2, ensuring to avoid repetitions.

The second part of this section is not entirely convincing, since it is mixing up the geometric characterization of simple/monomorphic landforms (termed units according to RGIK 2023) into lobate and tongue-shaped morphologies, with those of multilobe/polymorphic morphologies (termed systems according to RGIK 2023). Consequently, this hybrid system of classification does not deal solely with geometry, but also with the ability to distinguish (or not) different rock glacier units (in terms of front, lateral margins, and debris source) within a system, due to adjacency, coalescence, and overlapping of lobes.

The present classification scheme does not offer a clear protocol for consistently discriminating between complex and simple rock glacier configurations. In this context, the main rationale for proposing an RGIK hierarchical classification of rock glaciers into units and systems was exactly to mitigate mapping heterogeneity among operators when dealing with complex (multilobe) morphologies.

Please inform the reader about which geomorphic insights on rock glaciers may be gained by implementing the geometric characterization described in lines 273-280 and Table 5, and in particular the distinction between lobate and tongue-shaped morphologies. After reading section 5.2, which deals with the descriptive statistics on the above RG classification, I could not find any geomorphic insight that could help better understanding rock glacier occurrence (and relevant environmental controls) in the landscape.

We thank the reviewer for this important clarification about geometric classification. We have substantially revised this section to:

1. **Align with RGIK hierarchical framework: We explicitly connect our geometric classification to the RGIK unit/system hierarchy, clarifying that lobate and tongue-shaped forms represent Rock Glacier Units (RGUs), while coalescent and polymorphic forms represent Rock Glacier Systems (RGS).**
2. **Clarify classification protocol: We describe the specific criteria used to distinguish between simple units and complex systems based on debris source differentiation and lateral margin discernibility.**
3. **Justify geomorphic relevance: We explain how geometric classification provides insights into debris supply mechanisms, topographic constraints, and developmental history of rock glaciers in the Andean environment.**
4. **Connect to primary markers: We reference our implementation of RGIK primary markers that document this hierarchical classification.**

"4.4 Geometric classification

Our geometric classification aligns with the RGIK hierarchical framework, distinguishing between Rock Glacier Units (RGUs) representing individual landforms and Rock Glacier Systems (RGS) comprising multiple coalesced units. This approach addresses mapping consistency for complex morphologies while providing insights into debris supply patterns and topographic controls.

For simple/monomorphic landforms (RGUs), we classified geometry based on planform characteristics:

• Tongue-shaped: length-to-width ratio >1, indicating downslope-oriented flow (Harrison et al., 2008; Humlum, 1982).

• Lobate: length-to-width ratio <1, characteristic of cirque-floor or slope-base accumulation (Humlum, 1982).

For complex configurations (RGS), we identified:

• Coalescent: composite features formed by convergence of multiple tongue-shaped lobes with discernible individual sources (Humlum, 1982).

• Polymorphic: heterogeneous assemblages displaying multiple geometric forms within a single system, often indicating complex developmental histories (Falaschi et al., 2015).

The distinction between units and systems was based on the discernibility of individual frontal and lateral margins, debris source differentiation, and spatial separation of constituent lobes. This geometric classification, documented through our RGIK-compliant primary markers, provides insights into:

- Debris supply mechanisms and source area characteristics
- Topographic constraints on rock glacier development.
- Spatial organization of periglacial processes in different Andean environments."

4.6 Uncertainty assessment

Besides evaluating between-operator heterogeneity in terms of polygon delineation, how was the uncertainty assessment conducted in terms of degree of activity?

We thank the reviewer for this important question about activity classification uncertainty. We have expanded this section to explicitly describe how we assessed and addressed uncertainty in activity classification through our consensus mapping protocol and multi-analyst validation process.

Subsection 5.1

Table 5: please consider moving this table in the supplementary file, while retaining just one line for the summary data relevant to each of the four climatic regions. Currently, the table contains basin-specific information which appear excessive, considering that the reader is not provided with any significant information on such drainage basins. For evaluating the relative spatial distribution of rock glaciers (abundance/paucity), I recommend that the authors use the number of rock glaciers per unit terrain area (rock glacier density) – as opposed to simple rock glacier count. Rock glacier density will be directly comparable across the relevant climatic regions. Presently, the reader does not know how large the different climatic regions are. In the text, the authors mention rock glacier density a few times, but no systematic analysis/evaluation is shown.

We thank the referee for these excellent and constructive suggestions. We have implemented both changes, which have significantly improved our spatial analysis.

1. **Moving Table 5: As recommended, we have moved the detailed basin-specific Table 5 to the Supplementary Material (now Table S2).**
2. **Creating a new summary table for the main text (new Table 5). To enhance clarity and comparability, we present the density as the number of rock glaciers per 100 km^2 and the area coverage as a percentage (%).**

Table 1. Count and density of rock glaciers by subregion.

Subregion	Count	Total area (km^2)	Subregion area (km^2)	Density (per 100 km^2)	Area coverage (%) (per 100 km^2)
NDOT	17	0.63	16 061.03	0.106	0.004
NWOT	47	1.89	91 321.86	0.051	0.002
SDOT	2135	87.73	107 643.97	1.983	0.082
SWOT	139	3.84	93 097.51	0.149	0.004

This new analysis provides a systematic and quantitative evaluation, clearly demonstrating that the Southern Dry Outer Tropics (SDOT) host a rock glacier density nearly 20 times higher than the other subregions. The text in Section 5.1 has been revised to discuss these findings.

Lines 322-325: "Lithology is also likely a key factor. The highest percentage of inventoried rock glaciers coincides with volcanic rock outcrops, where the type of chemical alteration increases the albedo of the surfaces and enhances permafrost development and preservation (Yoshikawa et al., 2020)". Please consider expanding on lithology or completely neglecting this factor in the manuscript. A sentence that relates RG abundance on chemical weathering (due to albedo) of volcanic rocks appears too much of a stretch. Lithological effects on rock glacier abundance have been difficult to isolate in the literature. I wouldn't try to solve or dismiss such a complicated topic with a similar sentence on volcanics, which by the way encompass a range of lithological types. For a brief discussion on the complexity of isolating lithological effects (due to spurious interactions with hypsometry and climate), the authors may have a look at Section 4.2 in Scotti et al (2024).

We thank the referee for this critical observation and for pointing us to the highly relevant discussion in Scotti et al. (2024). We agree that the original sentence in the Results section was an oversimplification of a complex factor. In accordance with the referee's suggestion and our own goal to separate results from interpretation, we have removed this sentence from Section 5.1 (Results). A brief discussion of the influence of lithology on the distribution and preservation of rock glaciers was included in the Discussion section, acknowledging the difficulties in isolating lithological effects from hypsometric and climatic controls, and citing both Yoshikawa et al. (2020) and Scotti et al. (2024).

Lines 332-333: "This suggests that even basins in close proximity, under the same broad climatic subregion, can exhibit different rock glacier densities and size distributions – possibly due to local geomorphological factors (such as basin lithology or glacial evolution)". As per prior comment, this sentence appears vague without adding significant information to the paper. Moreover, RG densities are mentioned, but I couldn't see any quantitative data on this variable. Please consider deleting this sentence.

Thank you very much for your comment. Following the instructions for restructuring this subsection, we have removed and added new text to better define the study's findings and avoid writing assumptions.

Table 6: 1) what was the rationale for the selection of the size bins shown in this table? Two categories contain respectively just 3 and 1 rock glaciers only. The current binning does not seem appropriate. 2) What is the underlying hypothesis for presenting RG size categories as a function of RG mean elevation and slope? I don't understand why slope and elevation should change systematically with RG size, neither I recall any empirical relation constrained along these lines in other inventories. Please consider deleting from Table 6 columns reporting mean elevation and mean slope.

We thank the referee for these insightful comments. We agree that the size bins in the original Table 6 were suboptimal and that the inclusion of mean elevation and slope within those arbitrary categories was not well-justified.

In response, we have removed Table 6 entirely. Instead, we have created a new Figure 5 (provided below) that provides a more integrated and spatially explicit overview of key rock glacier attributes. This new figure includes maps of rock glacier distribution colored by:

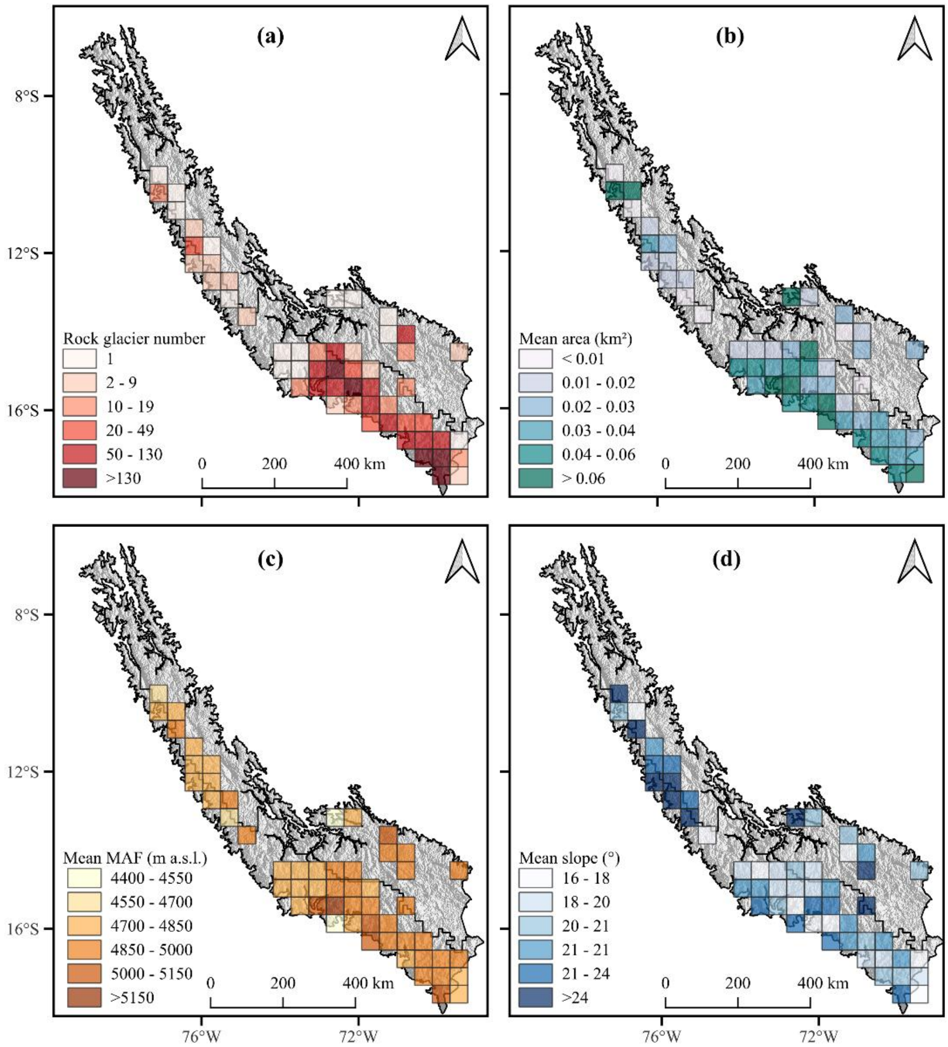
(a) Total count

(b) Mean area

(c) Mean Minimum Altitude of the Front (MAF)

(d) Mean slope

This approach avoids the problematic and arbitrary size-class binning and allows the reader to visually assess the spatial patterns of these characteristics without implying a direct or systematic functional relationship between them. We believe this is a more robust and informative way to present the data.



Subsection 5.2.1:

Considering that RG degree of activity in PRoGI relies on the visual assessment/interpretation of landforms, I suggest reducing substantially the length of the analysis (and accompanying text of the Results and the Discussion) concerned with the classification of rock glaciers into active, transitional, and relict. My suggestion is motivated by the high degree of uncertainty that is typically associated with the morphologically based classification of inactive/transitional rock glacier activity (e.g., Table 3 and Figure 11 in Brardinoni et al., 2019), and the rate of reclassification rock glaciers may undergo, once InSAR kinematic data are integrated (e.g., Table 4 and Figure 11b in Bertone et al., 2024).

Bertone A, Jones N, Mair V, Scotti R, Strozzi T, Brardinoni F. 2024. A climate-driven, altitudinal transition in rock glacier dynamics detected through integration of geomorphologic mapping and InSAR-based kinematic information. The Cryosphere, 18, 2335–2356, https://doi.org/10.5194/tc-18-2335-2024

Indeed, Bertone et al found that 15% of the rock glaciers western South Tyrol were reclassified from relict to intact (or vice versa), as a result of InSAR data integration.

This reclassification rate is likely to increase even more when 3 activity classes (as opposed to just the intact and relict ones) are considered.

We sincerely thank the referee for this critical observation and for bringing the highly relevant studies of Brardinoni et al. (2019) and Bertone et al. (2024) to our attention. We fully acknowledge the significant uncertainty inherent in morphology-based activity classification, especially for distinguishing transitional and relict forms.

In direct response to this comment, we have substantially revised the respective subsection in the Results (5.2 Rock glacier characteristics: activity and morphology).

Line 362: “inactive”. Please replace or remove the term inactive, as it would confound the reader. Traditionally, inactive and relict have been used to differentiate two distinct classes of activity.

We have removed the term inactive from the text.

Lines 369-372: “Indeed, we found that relict rock glaciers have the smallest mean size (mean area ~0.03 km^2), compared to ~0.04 km^2 for transitional and ~0.06 km^2 for active rock glaciers. This pattern is consistent with expectations: once a rock glacier loses its ice (becoming relict), it may slump and shrink over time, whereas active ones are buttressed by internal ice and can maintain larger extents.”

Technically, the above sentences belong to the Discussion, as they contain interpretation of the results. Most importantly, please consider rethinking your possible explanation, since rock glaciers are complex landforms associated with millennial time scales of development. Indeed, RG size has to do with age of formation, length of (continuous or discontinuous) activity through millennia, rate of sediment supply, and available room within a valley/slope for growing in planimetric size. Attributing the smaller size of relict rock glaciers to slumping (or other mass wasting styles of obliteration) appears simplistic, considering that the vast majority of rock glaciers degrade (non-catastrophically) through subsidence. Incidentally, this interpretation contrasts with prior results from the Italian Central Alps (Scotti et al 2013), where relict RGs were found to be systematically larger than intact counterparts (i.e., Figure 8, and Figure 6a, cf. gray (intact) and white (relict) box whiskers).

Thank you very much for your comment, and we agree with you. We've removed this sentence and placed a brief discussion in the next section. However, recognizing that long and complex processes can determine the size of rock glaciers and associate them with their activity, we've tried not to be so emphatic in that regard.

Subsection 5.3.1

Lines 410-412: “This suggests that slopes around 15–20° are especially conducive to rock glacier formation/preservation, likely because they are steep enough for debris-ice creep but not so steep as to cause frequent avalanching or debris removal.”

Technically, the above sentence belongs to the Discussion, as it provides an interpretation of the results.

We have moved the prayer to the discussion section.

Subsection 5.3.2

Figure 8: from the description of how mean RG aspect was computed in QGIS, I suspect that this variable might be biased. The main issue when calculating the average aspect of a surface is that aspect is a circular variable, meaning that the mean is incorrect due to the discontinuity that occurs around 360 degrees for northerly aspects (i.e., aspects approaching single-digit degrees are adjacent to aspects approaching 360 degrees). Typically, this results in underestimating the number of RGs that are dominantly facing north. Please double-check whether adequate transformation was conducted during aspect calculation and elaborate on this in the methods.

We have verified the aspect calculation in our inventory and it has been estimated correctly. Thanks to your suggestion, we have included the description of how it was done in the methods section:

"The mean aspect was calculated using a circular mean transformation (e.g., calculating the mean of sine and cosine components) rather than a simple arithmetic average."