Answers to Referee #1

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

The authors of this paper produce the first national-scale rock glacier inventory for the Peruvian Andes region with a coverage over 300000 km^2 and use quality control and cross-check to improve the quality of the dataset. This dataset has high quality and is important for the permafrost and mountain hydrology studies in Peruvian Andes. However, the wording of this paper is too long with many places showing redundant and repetitive information. I suggest this paper should improve the organization, readability, and concreteness before publication.

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. According to the newest version of IPA guidelines, each rock glacier unit (RGU) and system (RGS) should have a primary marker, while this dataset only provides the footprint shapefile. Better to also incorporate the primary marker shapefile and suggest using Zenodo instead of PANGAEA to store the dataset.

   We thank the reviewer for this important suggestion. In accordance with the latest IPA/RGIK guidelines, we have generated and will include a new layer of primary markers (PM) as part of the revised dataset. This GeoPackage file contains point features for each rock glacier unit (RGU) and system (RGS), providing a unique ID for each landform, which improves the utility and standardization of our inventory. Regarding the data repository, we have decided to keep the dataset in PANGAEA, which, like Zenodo, is a reliable repository aligned with FAIR principles. This decision is based on PANGAEA's longstanding reputation as a specialized, high-quality repository for Earth sciences, its status as the recommended repository for the ESSD journal, and its proven track record in ensuring long-term data preservation and referability. We are confident that PANGAEA offers a robust and sustainable platform for our dataset, ensuring its full accessibility to the community.

2. In the results part, better to use figures instead of tables to show the results, and the presented figures are not high-quality enough. Suggest improving the figures.
   Thank you very much for your suggestions and comments. We have restructured the entire results section to make it more understandable. We have also removed a table and created a graph to facilitate better

interpretation. Finally, we have retained some figures because we believe they contribute to the reading of the results, and we have been more emphatic in highlighting the most relevant aspects of our study.

3. I have some concerns about discussing controlling factors on the distribution of rock glaciers as the emergence and development of rock glaciers typically need hundreds or thousands of years (i.e., rock glaciers are some landforms that happened at least hundreds of years ago). Is it reasonable to use the modern climate to judge the distribution of rock glaciers?

Specific comments:

Line 1: Please explain what makes this inventory 'high-resolution', if it is because that this inventory was created using Bing Map and Google Earth, I don't think the 'high-resolution' can be a highlight or advantage of this inventory as many previous inventories were also created using high-resolution Google Earth imagery.

Thank you very much for your 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: "<u>A comprehensive rock glacier inventory for the Peruvian Andes (PRoGI): dataset, characterization and topoclimatic attributes.</u>**"**

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.

Lines 43-63: These two paragraphs, first introduce rock glaciers, then permafrost, then rock glaciers, which reads wield. Suggest reorganizing the content, better to describe permafrost first, then introduce rock glaciers.

We thank the reviewer for this suggestion to improve logical flow. We have reorganized these paragraphs to follow a more natural structure: definition of

permafrost → mountain permafrost → rock glaciers as an expression of permafrost. This reorganization significantly improves readability.

"Mountain permafrost, defined as ground remaining ≤0 °C for at least two consecutive years (van Everdingen, 1998), underpins critical hydrological and geomorphological systems in high mountain environments. It stabilizes steep slopes, modulates groundwater flow, and sustains alpine ecosystems (Gruber and Haeberli, 2007). However, mountain permafrost is highly sensitive to warming; rising temperatures lead to permafrost degradation and can trigger the release of stored greenhouse gases (Biskaborn et al., 2019). In the Andes, where glacial retreat has increased the relative importance of permafrost as a water resource, its hydrological role remains critical yet poorly quantified due to sparse observations in remote high-altitude areas.

Among periglacial landforms, rock glaciers serve as direct visual indicators of mountain permafrost, with their presence delineating the occurrence of ground ice and the approximate lower limits of discontinuous permafrost (Brenning, 2005). These ice-debris landforms, formed by the creep of ice-rich permafrost and shearing at depth, optionally exhibit diagnostic steep fronts, lateral margins, and ridge-and-furrow surface topography (RGIK, 2023). 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. 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 (Schaffer et al., 2019; Janke et al., 2017; Rangecroft et al., 2015). 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). 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., 2022)—and hydrological buffers makes rock glaciers indispensable for understanding environmental change across multiple timescales. 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.

Along the higher South American Andes (>4000 m a.s.l.), studies in Argentina, Chile, and Bolivia have leveraged rock glacier inventories to map permafrost and assess water storage (Azócar and Brenning, 2010; Esper Angillieri, 2017; Falaschi et al., 2015; Rangecroft et al., 2015). However, knowledge gaps still persist in Peru: existing inventories are fragmented (Badillo-Rivera et al., 2021; León et al., 2021) and lacking standardized methods or detailed topoclimatic analyses. 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."

Line 68: "Splitting it up would reduce run-on complexity => What does it mean?

Thank you very much for your comment. We have deleted the sentence: "Splitting it up would reduce run-on complexity" **because it was not related to what was described in the paragraph.**

Line 100: In total, 2338 rock glaciers were mapped using these optical datasets (2095 from Bing and 243 from Google imagery) => These are results, should not appear in the Data section.

We thank the reviewer for this correction. The sentence reporting the total number of rock glaciers has been moved from the Data section to the Results section (Section 5.1) where it appropriately belongs. The Data section now focuses exclusively on describing the data sources and characteristics.

Line 101: Please explain what makes this dataset complete and high-resolution

We have removed the term "high-resolution" from the sentence and emphasized the coverage of Bing Maps and Google Earth images for our study area, based on the suggestion that using these images does not necessarily generate a high-resolution inventory.

Line 105: We compiled several auxiliary datasets => topoclimatic datasets?

Thank you for your comment. We have removed the term "auxiliary" because it refers to topoclimatic datasets and caused confusion with the following subsection.

Lines 137-140: We primarily used Bing Satellite...Google Earth imagery for that grid cell => similar information has appeared in section 3.1 Data sources Lines 93-96: Bing Maps Aerial imagery was used as the primary data source...geodatabase creation. Suggest merging the information and write it in one place, otherwise, the readability of the paper can be reduced with many redundant and repetitive information in different places.

We thank the reviewer for pointing out this redundancy. We have consolidated the information about imagery sources and usage into Section 3.1 Data sources, removing the repetitive description from Section 4.1.1. The Methodology section now focuses exclusively on the mapping workflow while the Data section contains the complete description of imagery sources and selection criteria.

“The entire study region was divided into a grid of 50 × 50 km cells to cover the Peruvian Andes uniformly. Each grid cell was examined in detail using the high-resolution satellite imagery described in Section 3.1, following the established protocol of primary Bing imagery with Google Earth supplementation for areas with visibility issues. This grid-based approach ensured that no areas were overlooked, and it helped organize the work among the mapping team.”

Line 149: Only longitudinal ridges and furrows? No latitudinal ridges and furrows?

Thank you very much for the clarification, except for adding the term to the original sentence: “e.g., longitudinal /latitudinal ridges and furrows, or a lobate debris structure”

Lines 190-217: Section 4.2 Geomorphological identification criteria: To me the Bullet point and the table are also redundant information, only keep one of them is enough (only the information in Table 2 is enough, no need to write repetitive words using Bullet points.

We thank the reviewer for this suggestion to reduce redundancy. We have eliminated the bullet points and retained only Table 2, which presents the geomorphological criteria in a more concise and organized format. The text now directly references the table without repetitive descriptions.

“4.2 Geomorphological identification criteriaand classification

Our classification approach builds upon the RGIK (2023) framework while implementing a simplified three-class activity system suited to national-scale mapping. When classifying rock glaciers by activity state, we employed a morphological scheme based on Barsch (1996) and RGIK guidelines (RGIK, 2023), distinguishing three categories: active, transitional, and relict (Fig. 3).

This simplified system addresses the practical challenges of large-scale inventorying while maintaining scientific rigor through our consensus validation process. In the absence of kinematic data, active rock glaciers are defined as landforms containing interstitial ice (Roer et al., 2005; Wirz et al., 2016). and typically exhibit pronounced ridges and furrows (Charbonneau and Smith, 2018; Sattler, 2016), frontal slopes steeper than 30–35°, and generally lack vegetation (Tielidze et al., 2023). Transitional rock glaciers may still contain ice but have ceased moving, displaying gentler frontal slopes (<30–35°), subdued microtopography (Kellerer-Pirklbauer et al., 2012), and may support some vegetation (Ahumada et al., 2014; Brenning, 2005). Relict rock glaciers show no evidence of recent movement, characterized by collapse structures, subtle micro-relief (Colucci et al., 2016), and often vegetated surfaces at lower elevations (Abdullah and Romshoo, 2024; RGIK, 2023; Scotti et al., 2013; Baroni et al., 2004).

We prioritized frontal slope characteristics and overall landform preservation as primary classification criteria, as these show the most consistent relationship with activity status across different environmental settings. Ridge and furrow topography was considered as supporting evidence where clearly visible, acknowledging that this feature is optional in RGIK guidelines but has demonstrated utility in Andean contexts. Vegetation presence was used cautiously as a secondary indicator, with recognition of its limited applicability in arid high-elevation environments where vegetation may be absent regardless of activity status (RGIK, 2023).

For activity classification uncertainties, we implemented a consensus-based approach where borderline cases were reviewed by at least three team members. This process effectively internalized the classification uncertainty that RGIK addresses through 'uncertain' categories, providing a statistically robust alternative for large-scale inventories. This consensus approach specifically addressed the high inter-operator variability in activity classification reported in the literature (Brardinoni et al., 2019), ensuring consistent application of our modified three-class system across the entire inventory."

Lines 231-241: Again, Table 3 is sufficient to show everything clearly, no need to repeat the information using Bullet points.

Thank you very much for the suggestion, we have removed the duplicate information.

Lines 250-266: What is the difference between this paragraph and Section 4.2? In section 4.2 you already describe the geomorphological identification for rock glaciers of different activities, why mention the repetitive information here?

We thank the reviewer for identifying this duplication. We have removed the repetitive activity classification descriptions from Section 4.4 and consolidated all activity classification information in Section 4.2. Section 4.4 now focuses exclusively on the geometric classification of rock glaciers (tongue-shaped, lobate, coalescent, polymorphic), eliminating the redundancy while maintaining a clear organizational structure.

Line 291: The smallest rock glacier included in the inventory has an area of 0.001 km^2, the minimum area threshold for inclusion, according to the IPA guidelines (RGIK, 2023) => Are you sure the minimum area threshold suggested by IPA guidelines is 0.001 km^2 but not 0.01 km^2?

We thank the reviewer for catching this important discrepancy. The reviewer is correct - the RGIK (2023) guidelines recommend 0.01 km^2 (1 hectare) as the minimum area threshold, not 0.001 km^2. We have corrected this throughout the manuscript and provide justification for our decision to include smaller features given the specific context of the tropical Andes.

“The smallest rock glacier included in the inventory has an area of 0.001 km^2. While the RGIK (2023) guidelines suggest 0.01 km^2 as a general minimum area threshold for global inventories, we included smaller features because these smaller rock glaciers (14 % of our inventory) provide crucial information on permafrost distribution at lower altitudinal limits and under marginal conditions.”

Line 130: 4 Methodology => The Methodology part should be reconstructed, reducing the redundant and repetitive information and making the literature more concrete. Suggestions on the subsections could be 4.1 Identification and mapping of rock glaciers 4.2 Classification of rock glaciers 4.3 Topoclimatic features 4.4 Inventory compilation and validation 4.6 Uncertainty assessment

We appreciate the suggestion to restructure the subsection; we have changed the structure to the one suggested.

Line 350: Morphological types: => I suppose this should be a subsection 5.2.1 Morphological types? Also the Line 357 5.2.1 Rock glacier activity: => delete ‘:’

We thank the referee for this observation. In accordance with the comments from Referee #2 to reduce fragmentation and merge subsections, we have restructured Section 5.2. The text under "Morphological types" and "Rock glacier activity" has been integrated into a single, unified subsection now titled "5.2 Rock Glacier Characteristics: activity and geometry**". The colon in the original subheading has been removed in this new structure.**

Lines 350-356: Why the analysis of morphological types is not as long as rock glacier activity?

We thank the referee for this question. The morphological classification was conducted as a primary characterization to describe the inventory's diversity. A more extensive analysis was reserved for the activity status, as it is a more direct indicator of current permafrost conditions and hydrological function, which are central themes of this study. The activity classification therefore warranted a more detailed presentation, including its relationship with area, elevation, and spatial distribution.

Line 378: he NWOT and NDOT => I suppose it should be ‘The NWOT and NDOT’.

Thank you very much for your comment, we have restructured the section and these types of errors have been eliminated.

Line 392: Elevation distribution: => I suppose it should be a subsection 5.3.1 Elevation distribution here.

We've restructured the section and consolidated it into a single text (see section 5.3 Topographic and climatic attributes**) to avoid unnecessary fragmentation and facilitate reading flow.**

Lines 392-402: For the unit of elevation, some places are m a.s.l. Some places are m. Please keep them consistent.

Thank you very much for the clarification. We've standardized the elevation units to avoid confusion for the reader.

Lines 434-439: This paragraph is not about Aspect, may you use miss the subsection?

We've restructured the section and consolidated it into a single text (see section 5.3 Topographic and climatic attributes**) to avoid unnecessary fragmentation and facilitate reading flow.**

Lines 439-443: 'This distribution reveals that elevation is the primary control on the presence of rock glaciers, with secondary hydrothermal modulation - evidenced by inverse AP-MAAT relationships in NDOT/SDOT/SWOT (where aridity and snow redistribution at elevation increase cooling) versus the direct correlation of NWOT (driven by thermal depression mediated by microclimatic processes). Such systematic variations underscore how Andean rock glaciers integrate macroscale climatic gradients with local topoclimatic processes.' => Why elevation is the primary control and climatic conditions are secondary? I don't understand how this conclusion was drawn from the results.

Thank you very much for the question. We have removed this paragraph, but we have added a more detailed analysis on this topic in the discussion section of the results.

Lines 453-454: Individual rock glacier area uncertainty was found to range from as low as ~0.001 km^2 for small, clearly defined features to up to ~0.3 km^2 for very large or diffuse features, with a mean uncertainty of ~0.06 km^2. => A figure between uncertainty and area would be helpful.

We thank the referee for this suggestion. The requested relationship between rock glacier area and mapping uncertainty is precisely captured and presented in the Bland-Altman plot included in the Supplement (Figure S1). In this plot, the x-axis (mean area from multiple mappers) represents the rock glacier size, and the y-axis (difference in mapped area) represents the absolute uncertainty between operators. The figure clearly shows the relationship described in the text, where larger areas are associated with greater absolute discrepancies. At this point in the text (lines 453-454), we have explicitly referenced Figure S1 to guide the reader toward this visualization.

Lines 504-514: I would expect more results about the comparison between the rock glacier distribution (active, transitional, relict) and the distribution of permafrost from Obu et al. (2018) instead of just stating the elevation and MAAT. Maybe better to show some example figures showing this distribution comparison, see whether the active ones are within the permafrost and the relict ones are out.

We thank the reviewer for this suggestion. We have removed references to MAGT, since, as described in the data section, it has been used as a complementary variable and does not provide data for an analysis of subsurface thermal conditions, as it is an invalid model for the mountainous region of Peru.

Lines 518-519: “The comparisons with global inventories (see Table 8) show that while Peru’s rock glaciers are extreme in elevation, other characteristics like slope and aspect are broadly similar to rock glaciers elsewhere” => But Table 1 only shows the elevation and does not show other characteristics like slope or aspect?

We apologize for this error. The text referring to comparisons with other parameters has been limited and, in other cases, removed from the text.

Line 537: see my general comments, not sure whether it is reasonable to use modern climate to discuss the distribution of rock glaciers as these landforms are something happened hundreds of years ago.

This is a valid point. We refined our argument in Section 6.2 to make it clearer. We now explicitly state that while rock glaciers are relict landforms whose formation can be traced back to earlier cold periods, their current state of activity (active, transitional, relict) directly reflects contemporary permafrost conditions. Therefore, using modern climate data to interpret their current state and distribution is justified, as it helps explain why some remain active while others degrade or have become relict.

Lines 555-557: “The correlation of the inventory with modelled MAGT data (Obu et al. 2019) provides an independent check: nearly all active, rock glaciers lie in grid cells where MAGT is at or below 0°C, whereas relict rock glaciers occupy cells where MAGT is just above 0°C (indicating marginal permafrost conditions).” => See my comments above, I would expect more elaboration on this part. Maybe a statistics on the MAGT of the rock glaciers with different activities, or some examples showing the distribution of rock glaciers and the permafrost.

As mentioned in the previous comment, these data have been used as complementary and do not necessarily represent the thermal variability in our inventory.

Line 675: ‘his opens’ => This opens?

Fixed "This opens" error

Line 692-694: “Looking forward, several lines of future work are planned based on this inventory: Temporal monitoring: now that this baseline is set, repeat satellite observations (e.g., in 5–10 years) or the analysis of time series (like the 2017 vs 2024 imagery) could reveal if any rock glaciers are retreating at the margins or if new ones are forming” => The development of rock glaciers typically take hundreds of years (totally different from glaciers), I don’t think you would see significant changes on rock glaciers on decadal scale.

We agree with the referee and thank him for this correction. We have removed the mention of decadal-scale monitoring for margin retreat or new formation.