Rock Glacier Inventories (RoGI) in 12 areas worldwide using a multi-operator consensus-based procedure

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Abstract. The Rock Glacier Inventories and Kinematics community (RGIK) has defined standards for generating Rock Glacier Inventories (RoGI). In the framework of the European Space Agency Climate Change Initiative for Permafrost (ESA CCI Permafrost), we set up a multi-operator mapping exercise in 12 areas around the world. Each RoGI team was composed of five to ten operators, involving 41 persons in total. Each operator performed similar steps following the RGIK guidelines (RGIK, 2023a) and using a similar QGIS tool. The individual results were compared and combined after common meetings to agree on the final consensus-based solutions. In total, 337 "certain" rock glaciers have been identified and characterised, and 222 additional landforms have been identified as "uncertain" rock glaciers.

The dataset consists of three GeoPackage files for each area: 1) the Primary Markers (PM) locating and characterising the identified Rock Glacier Units (RGU), 2) the Moving Areas (MA) delineating areas with surface movement associated with the rock glacier creep, based on spaceborne Interferometric Synthetic Aperture Radar (InSAR), and 3) the Geomorphological Outlines (GO) delineating the restricted and extended RGU boundaries. Here we present the procedure for generating consensus-based RoGI, describe the data properties, highlight their value and limitations, and discuss potential applications. The final PM/MA/GO dataset is available on Zenodo (Rouyet et al., 2024; https://doi.org/10.5281/zenodo.14501399). The GeoPackage (gpkg) templates for performing similar RoGI in other areas, and exercises based on the QGIS tool, are available on the RGIK website (https://www.rgik.org).

1   Introduction

35   Permafrost is defined as subsurface material remaining at or below 0 °C for at least two consecutive years (French, 2007). Due to its sensitivity to climate change, permafrost is an Essential Climate Variable (ECV), traditionally documented by the Ground Temperature (GT) and the Active Layer Thickness (ALT) (Streletskiy et al., 2017). In mountains, the permafrost distribution may be discontinuous and controlled by site-specific conditions with large variations over short distances. The investigation of mountain permafrost requires the development of dedicated products to complement to GT and ALT

40   measurements and models. Rock glaciers are obvious expressions of mountain permafrost, defined as debris landforms generated by the former or current creep of frozen ground (RGIK, 2023a). Although contrasting views exist in the genetic origin of rock glaciers, the distribution of rock glaciers may be regarded as a proxy of past or present permafrost occurrence. Rock glacier inventories (RoGI), including relict, transitional, and active landforms, are valuable to understand the evolution of periglacial environments, and to calibrate or validate mountain permafrost distribution models, where in situ

45   measurements are scarce (Azócar et al., 2017; Boeckli et al., 2012; Etzelmüller et al., 2020; Karjalainen et al., 2020; Marcer et al., 2017; Schmid et al., 2015). The distribution, sizes and dynamics of rock glaciers also have several operational implications for the management of geohazards and water resources, which have justified RoGI compilation in many mountain ranges (Hassan et al., 2021; Jones et al., 2018; Marcer et al., 2019; Rangecroft et al., 2015).

In addition, rock glacier creep rate is influenced by the permafrost thermal state and the ground ice/water contents (Cicoira et

50   al., 2019; Ikeda et al., 2008; Kenner et al., 2020). Several studies demonstrated that the interannual rock glacier velocity changes relate to the ground temperature variations (Delaloye et al., 2008; 2010; Kääb et al., 2007; Kellerer-Priklbauer et al., 2024; Schoeneich et al., 2015; Staub et al., 2016). In the context of climate change, cases of acceleration, destabilisation, and even collapse have been reported (Bodin et al., 2017; Delaloye et al., 2013; Eriksen et al., 2018; Hartl et al., 2023; Kellerer-Priklbauer et al., 2024; Scotti et al., 2017). Conversely, as degradation continues, rock glaciers tend to stabilize and transition

55   progressively into relict landforms (Ikeda & Metsuoka, 2002; Manchado et al., 2024; Necsoiu et al., 2016). Due to the link between temperature and rock glacier creep rate, Rock Glacier Velocity (RGV) became a new product of the ECV Permafrost (WMO, 2022; Streletskiy et al., 2021). In this context, RoGI compilation can be considered as a first necessary step to identify and select landforms to be monitored in a climate-oriented perspective. However, RoGI are not exhaustive worldwide and existing RoGI have been compiled with various methodologies. Owing to a lack of concerted international

60   rules for mapping and characterising rock glaciers, a RoGI compiled by different operators may lead to high levels of variability (Brardinoni et al., 2019), which hampers our ability to compare, merge, and analyse inventories across different regions.

With these motivations, the Rock Glacier Inventories and Kinematics (RGIK) initiative, launched in 2018, has focused on defining widely accepted standards and developing guidelines for the generation of RoGI and RGV products (Delaloye et al.,

65   2018). With the long-term objective to generate a homogenous open-access RoGI database, RGIK has released RoGI guidelines defining rules for inventory rock glaciers (RGIK, 2023a). In parallel, the European Space Agency Climate

Change Initiative for Permafrost (ESA CCI Permafrost) has worked on scaling up the generation and evaluation of ECV permafrost products using satellite remote sensing (Bartsch et al., 2023; Trofaier et al., 2017). For rock glacier products, ESA CCI Permafrost especially focuses on the use of spaceborne Interferometric Synthetic Aperture Radar (InSAR), an established remote sensing technique documenting ground surface movement and widely applied in the RoGI framework (Bertone et al., 2024; Brencher et al., 2021; Hu et al., 2023; Lambiel et al., 2023; Liu et al., 2013; Ma & Oguchi, 2024; Reinosch et al., 2021; Rouyet et al., 2021).

Previous studies highlighted the inherent subjectivity of operators to interpret the morpho-kinematic characteristics of rock glaciers based on optical and InSAR data (Bertone et al., 2022) and the benefits of designing multi-operator consensus-based procedures to reduce discrepancies and improve the final products (Way et al., 2021). In 2023, we therefore designed a mapping exercise with teams including operators from diverse institutions, countries, and backgrounds. This multi-operator RoGI exercise was performed in 12 areas around the world. Several operators performed similar steps individually and then discussed the results to provide consensus-based final products. This unique international initiative had four main objectives: 1) train the community for RoGI production, 2) test common RoGI rules and identify discrepancies to refine the existing guidelines, 3) develop standardized GIS templates and training tools for enhancing the production of comparable RoGI in new regions, and 4) compile and disseminate a homogenized set of RoGI from 12 diverse regions.

Here we present the multi-operator inventorying procedure (Section 2), describe the GIS tool and data properties (Section 3), summarize the main characteristics of the resulting dataset (Section 4), discuss the uncertainties and limitations (Section 5), and suggest ideas for future use and applications (Section 6).

2 Multi-operator inventorying procedure

2.1 RoGI areas and teams

The exercise was performed in 12 areas selected in ten countries and five continents (Table 1; Figure 1). Most RoGI areas have been selected within larger regions previously studied by Bertone et al. (2022), who included detailed descriptions of the regional settings in the supplementary material of the article. A Principal Investigator (PI) was designated to coordinate the work in each area (Table 1). The inventory teams were composed of five to ten operators (including the PI). Some operators worked in several areas. The exercise involved a total of 41 persons (see Acknowledgments).

Table 1. RoGI areas and teams (PI acronyms: see author list and affiliations).

Area numbers (ESA CCI Permafrost convention)	Area name *(country, code)* Approx. central lat./long. location	AOI km² *(# certain final RGU)*	PI (institution) *(# operators, incl. the PI)*
Area 5-1	Carpathians *(Romania, RO)* 45°23' N, 22°53' E	18 *(18)*	FS / WUT *(7 operators)*
Area 6-1	Western Alps *(Switzerland, CH)*	12	TE / UNIFR

	46°11' N, 7°30' E	*(30)*	*(5 operators)*
Area 7-1	Troms *(Norway, NO-T)*	47	LRo / NORCE
	69°23' N, 20°26' E	*(15)*	*(6 operators)*
Area 8-1	Finnmark *(Norway, NO-F)*	15	LRo / NORCE
	70°45' N, 27°50' E	*(17)*	*(7 operators)*
Area 9-1	Nordenskiöld Land *(Norway, NO-N)*	10	LRo / NORCE
	77°53' N, 13°54' E	*(18)*	*(6 operators)*
Area 10-1	Vanoise Massif *(France, FR)*	37	DC / USMB/UGA
	45°19' N, 6°37' E	*(49)*	*(6 operators)*
Area 11-1	Southern Venosta *(Italy, IT)*	19	FB / UniBo
	46°33' N, 10°36' E	*(39)*	*(10 operators)*
Area 12-1	Disko Island *(Greenland, GR)*	82	RC / GAMMA
	69°51' N, 52°33' W	*(29)*	*(6 operators)*
Area 13-1	Northern Tien Shan *(Kazakhstan, KA)*	59	TB / TU Graz
	43°0' N, 77°1' W	*(14)*	*(7 operators)*
Area 14-1	Brooks Range *(Alaska, U.S.A., US)*	21	MD / UAF
	68°6' N, 149°58' W	*(14)*	*(10 operators)*
Area 15-1	Central Andes *(Argentina, AR)*	55	LRu / IANIGLA
	32°59' S, 69.34° W	*(70)*	*(10 operators)*
Area 16-1	Southern Alps *(New Zealand, NZ)*	7	CL / UNIL
	43°59' S, 170°3' E	*(24)*	*(7 operators)*
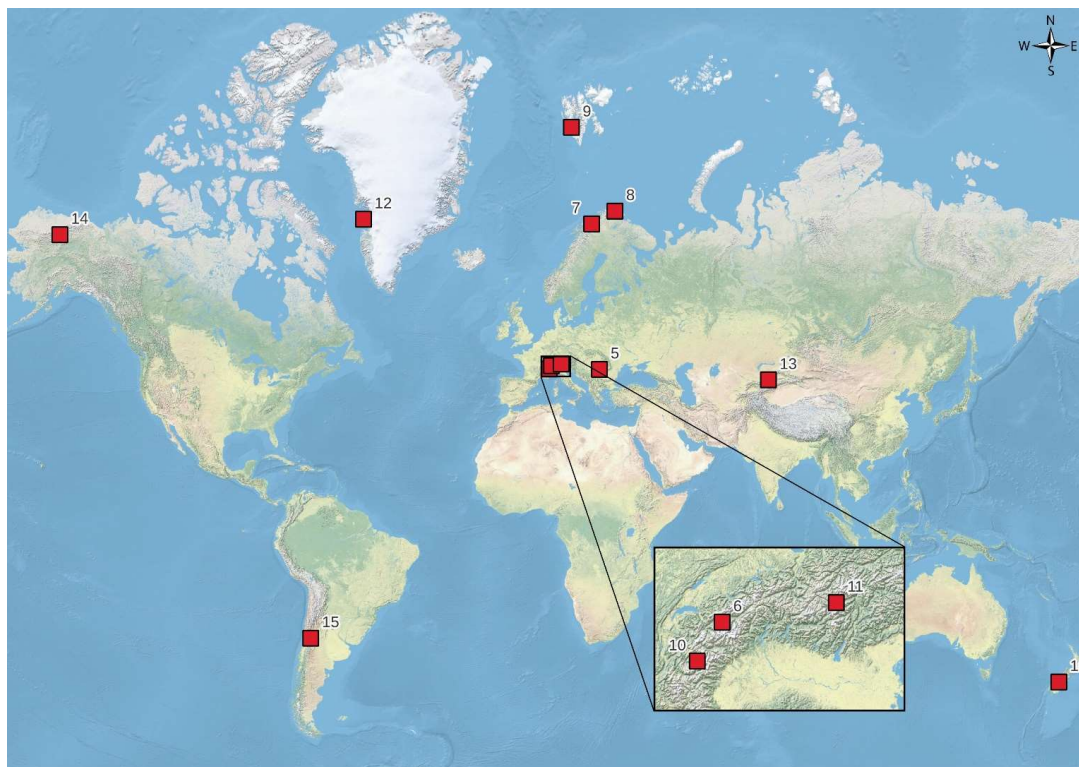
Figure 1. Location map of the RoGI regions, including the areas selected for the multi-operator RoGI exercise. Background map: ESRI Physical Web Map Service.

2.2 Consensus-based RoGI procedure

The RoGI exercise was performed between June and November 2023. The University of Fribourg (UNIFR), Switzerland, was responsible for providing the data packages and instructions, and coordinating the work between the teams. The volunteer operators were found within the involved institutions and after a call for participation using the RGIK mailing list (about 200 subscribers). For each area, the PI coordinated the work and had the responsibility for the final products. The PI also performed the work as an operator. Each operator received a common folder including a similar dataset organized within a QGIS project (see Section 3.1), along with the instructions for the exercise and the references to the RGIK guidelines applicable at the time (RGIK, 2022a; 2022b; 2022c; 2023b). The guidelines have since been merged into one reference document (RGIK, 2023a).
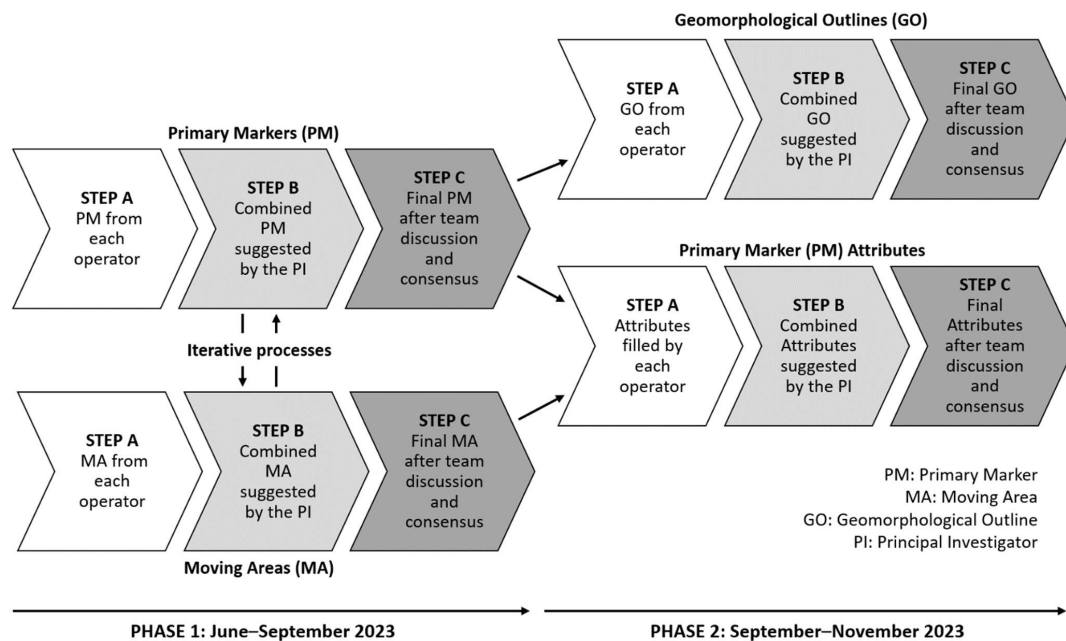
Figure 2. Consensus-based RoGI procedure.

The inventory procedure included two main phases, performed in June–September 2023 (Phase 1) and in September–November 2023 (Phase 2) (Figure 2). Each phase was divided into three steps:

- **Step A**: Individual work by each team operator. At the end of this step, all the operators sent their results to the PI.
- **Step B**: Compilation and summary by the PI. When discrepancies between operators were identified, the PI suggested a solution, to be discussed with the team.
- **Step C**: Discussion and consensus-based final decision by the inventory team. At the end of this step, the team agreed to the intermediate (first phase) or the final outputs (second phase).

During the first phase performed between June and September 2023, the team had to:

- **Identify and locate the Rock Glacier Units (RGU) with Primary Markers (PM)**. The operators were asked to include landforms following the technical definition of a rock glacier: "a debris landforms generated by the former or current creep of frozen ground, detectable in the landscape with the following morphologies: front, lateral margins and optionally ridge-and-furrow surface topography" (RGIK, 2023a, p.6). Based on this definition, a RoGI must include relict rock glaciers, but discard landforms that are primarily driven by other processes, such as glacial flow, solifluction,

ice melt, and sliding along a slip-surface. Different units are discriminated according to the RGIK guidelines (RGIK, 2023a). Orthoimages were the primary source of data used for this task, but additional datasets were used when
125   available (e.g., Digital Elevation Model, DEM) (see Section 3.1). InSAR data was useful to detect or confirm the location of moving rock glaciers. Each recognized RGU was identified with a point (primary marker, PM) in a dedicated vector layer. An uncertainty could be expressed by defining the landform as "uncertain rock glacier" in the case of geomorphological ambiguity or low data quality. The operators could optionally use a label "not a rock glacier" to indicate landforms that may be mistaken for rock glaciers, but are not driven by permafrost creep. These complex
130   cases were discussed during team meetings and sometimes kept in the final layer for educational purposes. The attribute table of the PM layer is shown in Appendix A. At this stage, only the first attributes of the table were applicable, as the detailed morpho-kinematic characterisation was performed during the second stage.

- **Detect, delineate, and classify Moving Areas (MA) using InSAR**. This task was performed in parallel, potentially iteratively, with the first bullet point (RGU identification with PM). The MA were identified, delineated, and
135   characterised based on InSAR data (see Section 3.1). The procedure is explained in the RGIK practical InSAR guidelines (RGIK, 2023b). Each recognized MA was delineated in a dedicated polygon vector layer. The attributes documenting the velocity class, the observation time window and validity time frame, and the reliability could be filled using a semi-automatic dialog box. The attribute table of the MA layer is shown in Appendix B.

In September 2023, the PI compared the individual results and suggested final solutions. After discussion and adjustment
140   during an online meeting with the team operators, the final consensus-based PM and MA layers were adopted.

During the second phase performed between September and November 2023, the team focused on the landforms categorized as "certain rock glaciers" in the final PM layer. For those landforms, the operators had to:

- **Document the RGU morpho-kinematic characteristics (Attributes).** The morpho-kinematic attributes characterising
145   the RGUs were filled using a semi-automatic dialog box in the final consensus-based PM layer from the first phase. All attributes refer to definitions described in the RGIK RoGI guidelines (RGIK, 2023a). All documented attributes are listed in Appendix A. For the geomorphologic attributes, orthoimages were the primary source of data, but additional datasets were used when available (e.g., DEM) (see Section 3.1). The kinematic attribute (KA) is based on the MA layer from the first phase. The procedure to convert velocity information from the MA to a KA category is explained in
150   RGIK guidelines (RGIK, 2023a; 2023b). The KA was used to assess the activity (active, transitional, relict), defined as the efficiency of sediment conveyance (expressed by the surface movement).

- **Delineate the RGU Geomorphological Outlines (GO).** The extended and restricted rock glacier GO were delineated in a dedicated polygon vector layer. The extended outlines include the front and lateral margins. The restricted outlines exclude the external parts (front and lateral margins) (RGIK, 2023a). For each polygon, attributes (outline type and
155   reliability of the delineation) could be filled using a semi-automatic dialog box. The attribute table of the GO layer is shown in Appendix C.

In November 2023, the PI compared the individual results and suggested final solutions. After discussion and adjustment during an online meeting with the team operators, the final consensus-based PM Attributes and the GO layer were adopted.

160 The compilation, data harmonization, and technical correction of the final set of PM, MA, and GO products were performed by the University of Fribourg, Switzerland (UNIFR) between November 2023 and February 2024. A final verification and approval by the PIs was performed between February and May 2024.

3 Data types, attributes and formats

3.1 Input data and GIS tool

165 The data packages delivered to the operators all had the same structure. The content was similar for each area. The main folder included four subfolders and a QGIS project:

- **Subfolder "INSTRUCTIONS"** with the documents and links to the applicable guidelines.
- **Subfolder "VECTOR"** including the polygon of the Area of Interest (AOI) that defined the boundaries in which the inventory work had to be performed, as well as the initial geopackage (gpkg) templates for digitalizing the PM, MA,
170 and GO.
- **Subfolder "INSAR-DATA"** including wrapped interferograms from Sentinel-1 (and potentially ALOS, SAOCOM, Cosmo-SkyMed, and/or TerraSAR-X depending on the data availability), potential complementary InSAR products (e.g., velocity maps from Stacking or Persistent Scatterer Interferometry algorithms), a layer displaying an index to reproject the line-of-sight displacement rate along the direction of the steepest slope (normalization factor), or a mask
175 highlighting N–S facing slopes where the InSAR data is likely to underestimate the real movement (see InSAR guidelines: RGIK, 2023b).
- **Subfolder "DEM-ORTHO"** in which the PI could add extra available background data before delivery to the operators (e.g., DEM-based products, high-resolution orthophotos, topographic maps).
- **QGIS project** structuring the available data and in which the operators performed the work. In addition to the AOI, the
180 InSAR data and initial vector files (gpkg templates), each GIS project incorporated links to Web Map Services (WMS) such as the Google Earth, Bing and ESRI orthomosaics.

The work was performed in similar QGIS projects, with common file structure, background data, and dialog boxes for filling the attribute tables. The QGIS structure is generic and allows for semi-automatic attribute selection to simplify the work of
185 the operators (Figure 3).
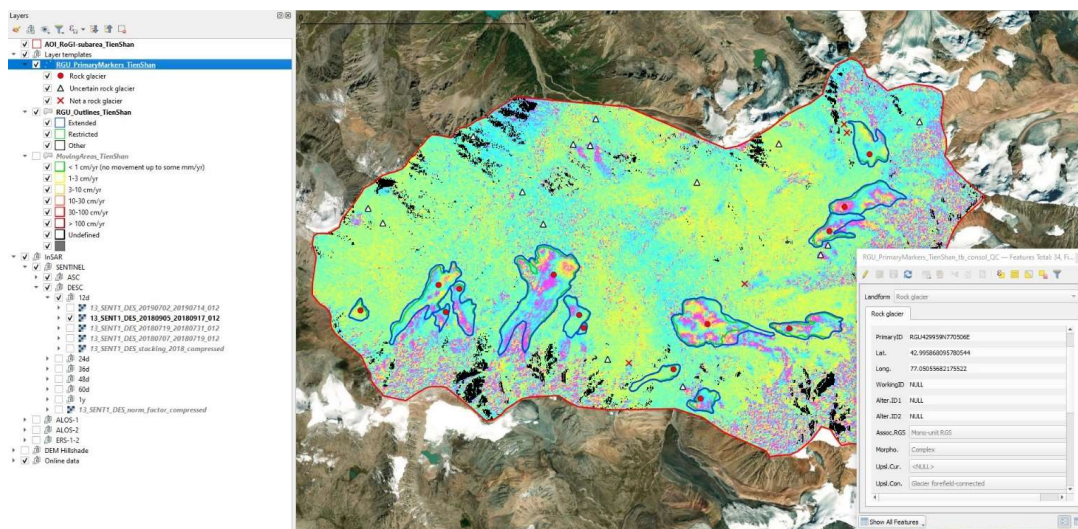
Figure 3. Example of QGIS data structure and dialog box for semi-automatic attribute filling in area 13-1 (Northern Tien Shan, Kazakhstan). ESRI satellite imagery is shown in the background. An example of Sentinel-1 wrapped interferogram is displayed within the AOI extent. The boundaries of the RoGI area (red polygon), the PM (red dots and white triangles), and the GO (blue and green polygons) are displayed as top layers. Background map: ESRI Satellite Web Map Service.

3.2 Output data: format and properties

The RoGI multi-operator exercise led to the generation of a set of three files for each area: the RGU Primary Markers (PM), the InSAR-based Moving Areas (MA), and the RGU Geomorphological Outlines (GO). All datasets are provided in a GeoPackage vector format (gpkg), a platform-independent database container. The Coordinate Reference System (CRS) used for the RoGI products is the World Geodetic System 1984 (WGS84). The coordinates are specified in decimal degrees.

For the RGU Primary Markers (PM), the following attributes are documented:

- ID (unique alpha-numerical identifier of the RGU).
- X and Y coordinates (WGS84 coordinate system).
- Morphological type (simple, complex).
  Additional related attribute: the "Completeness" field defining if the rock glacier is completely visible or not (complete, unclear connection to the upslope, truncated front, uncertain).

- Spatial connection to the upslope unit (talus-, debris mantle-, landslide-, glacier-, glacier forefield-, poly-connected,
205   other, uncertain, unknown).

  Additional related attributes: the "Upslope current" field defining if the rock glacier is currently connected to the upslope unit or not, and a "Comment" field to further describe morphological characteristics.

- Kinematic attribute (< cm/yr, cm/yr, cm/yr to dm/yr, dm/yr, dm/yr to m/yr, m/yr, > m/yr, undefined).

  Additional related attributes: the "Type of Data" field to define the type of data used to assign the kinematic attribute
210   (Optical, Radar, Lidar, Geodetic, Other), the "Kinematic Period" field to document the applicable period of the kinematic attribute (year(s) with available data), the "Reliability" of the kinematic attribute (low, medium, high, undefined), and a "Comment" field to document the applied method and the data quality.

- Activity (active, active uncertain, transitional, transitional uncertain, relict, relict uncertain, uncertain).

  Additional related attribute: the "Activity assessment" field documenting how the activity has been assessed
215   (morphological evidence only or with kinematic data).

- Destabilization signs (yes – ongoing, yes – completed, no, undefined).

For the Moving Areas (MA), the following attributes are documented:

- ID (unique alpha-numerical identifier of the moving area)
220 - Velocity class (< 1 cm/yr, 1–3 cm/yr, 3–10 cm/yr, 10–30 cm/yr, 30–100 m/yr, >100 cm/yr).
- Time observation window (text documenting the time period used for the MA detection and characterisation).
- Reliability of the detected moving area (low, medium, high).
- Additional comments.

225 **For the Geomorphological Outlines (GO)**, the following attributes are documented:

- ID (unique alpha-numerical identifier of the moving area)
- Outline type (extended, restricted, other).
- Reliability of the front, left margin, right margin, and upslope limit (0 – low, 1 – medium, 2 – high), and Reliability Index (automatic summation of the values assigned to the reliability attributes of these four different boundaries).
230 - Additional comments.

Each attribute is explained in detail in Appendixes A–C (including references to the applicable sections of the RGIK guidelines).

3.3 Output data: structure and naming convention

235 The data package available on Zenodo (Rouyet et al., 2024; https://doi.org/10.5281/zenodo.14501399) includes:

- **The folder 'ESACCI-PERMAFROST_ROGI_SINGLE-AREA'**, including the RoGI products for each area, for applications focusing on one specific region, with subfolders named as follows:

  - AREA_<AREA_NUMBER>_<AREA_NAME>_<COUNTRY_CODE>
  Example: AREA_5-1_Carpathians_RO

240
    - AOI, in a polygon vector layer in a gpkg format.
    Example: ESACCI-PERMAFROST-IND_SENTINEL1-INSAR_ROGI-AREA_5-1_AOI_2024-fv01.0.gpkg
    - Primary Markers (PM), in a point vector layer in a gpkg format.
    Example: ESACCI-PERMAFROST-IND_SENTINEL1-INSAR_ROGI-AREA_5-1_PM_2024-fv01.0.gpkg
    - Moving Areas (MA), in a polygon vector layer in a gpkg format.
245   *Example: ESACCI-PERMAFROST-IND_SENTINEL1-INSAR_ROGI-AREA_5-1_MA_2024-fv01.0.gpkg*
    - Geomorphological Outlines (GO), in a polygon vector layer in a gpkg format.
    Example: ESACCI-PERMAFROST-IND_SENTINEL1-INSAR_ROGI-AREA_5-1_GO_2024-fv01.0.gpkg

- **The file 'ESACCI-PERMAFROST_ROGI_ALL-AREAS_AOI-PM-MA-GO_2024_fv01.0.gpkg'**, including the AOIs and RoGI results (PM, MA and GO), merged for all areas, for applications requiring the combined use of all
250   inventories.

- **The file 'README.pdf' file**, describing the data structure and properties.

The naming convention of each gpkg file follows the product specifications defined by the ESA CCI Permafrost project and is meant to provide a generic structure allowing for updates and/or release of future additional products. All file names
255 follow the same structure: **ESACCI-<CCI Project>-<Processing Level>_<Data Type>_<Product String>-<Additional Segregator>_<Layer Type>_<Indicative Date>-fv<File version>.gpkg**

- **<CCI Project>:** PERMAFROST.
- **<Processing Level>**: Indicator (IND).
- **<Data Type>**: <SENSOR>-<METHOD>. <SENSOR> is the primary remote sensing data source used to document the
260   kinematics, in this case: SENTINEL-1. <METHOD> is the primary method used to process the kinematic data, in this case: INSAR.
- **<Product String>**: ROGI, for the product Rock Glacier Inventory.
- **<Additional Segregator>:** This should be structured as: AREA_<REGION_NUMBER>-<AREA_NUMBER>. <REGION_NUMBER> follows the generic CCI Permafrost numbering: 5–Carpathians (Romania); 6–Western Alps
265   (Switzerland); 7–Troms (Norway); 8–Finnmark (Norway); 9–Nordenskiöld Land (Svalbard, Norway); 10–Vanoise Massif (France); 11–Southern Venosta (Italy); 12–Disko Island (Greenland); 13–Northern Tien Shan (Kazakhstan); 14–

Brooks Range (Alaska, U.S.A.); 15–Central Andes (Argentina), 16–Southern Alps (New Zealand). <AREA_NUMBER> is a one- or more-digit(s) number, depending on the numbers of area(s) in the region. For merged products (RoGI in all areas), the additional segregator is: ALL-AREAS.

270
- **<Layer Type>**: The individual layers of the vector product are provided in individual or merged files. The code of each individual layer is as follows:
    - AOI: extent of the ROGI area.
    - PM: layer 1, corresponding to the Primary Markers of the Rock Glacier Units.
    - MA: layer 2, corresponding to the InSAR-based Moving Areas.

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    - GO: layer 3, corresponding to the Geomorphological Outlines of the Rock Glacier Units.

    The merged data package combining the different layers includes the three codes (PM-MA-GO).

- **<Indicative Date>**: Format is YYYYMMDD, where YYYY is the year, MM is the month from 01 to 12, and DD is the day of the month from 01 to 31. Annual or multi-annual products are represented with YYYY only.

- **fv<File Version>**: File version number in the form n{1,}[.n{1,}] (two digits followed by a point and one or more

280
    digits).

4 RoGI results description

Figure 4 is an example of results of the RoGI multi-operator exercise for a selected area. It illustrates the similarities and differences between individual operator results (black dots for RGU PM; dashed lines for RGU GO) and the final products (coloured dots for RGU PM; solid lines for RGU GO). Due to the iterative and consensus-based procedure described in Section 2, the outcome is more than the sum of the individual results. The data package therefore includes the final consensus-based products only.

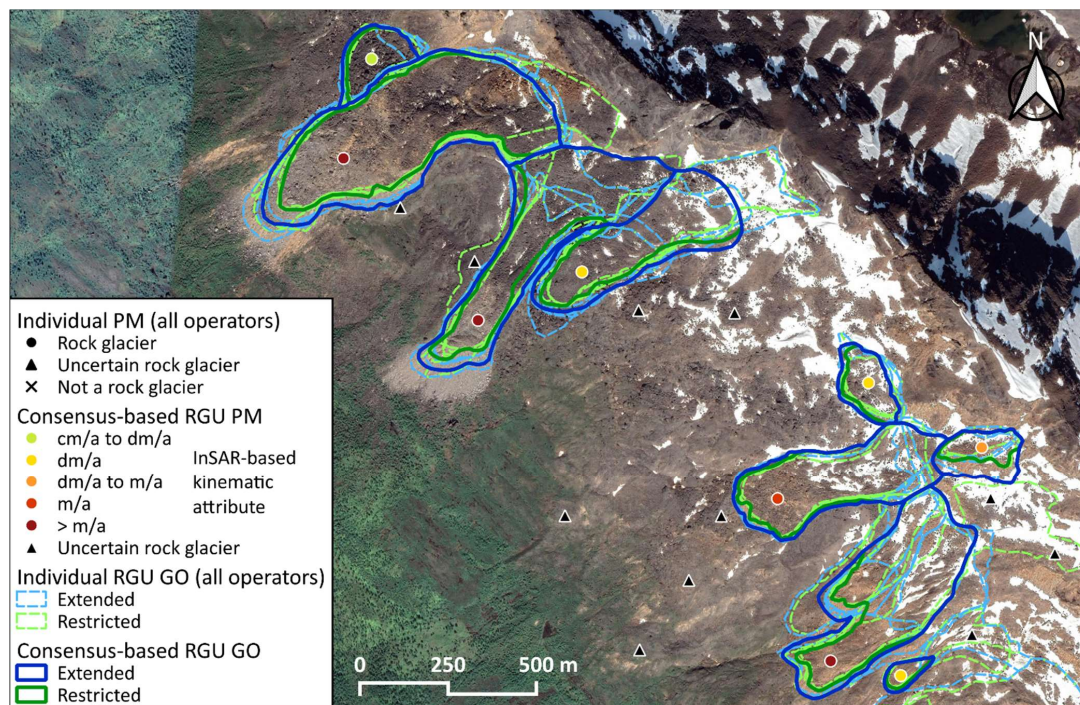



Figure 4: Example of RoGI results in part of area 7-1 NO-T (Troms, Norway), showing a selection of operator and final consensus-based results (Primary Markers: PM; Geomorphological Outlines: GO). For sake of visualisation, the MA layer is not shown, but was used to assign the PM kinematic attribute displayed here with a green–red colour scale. Background: NorgeiBilde orthophoto (2016-08-2016).

In total, 337 "certain" rock glaciers were identified and characterised, and 222 additional landforms were identified as

295   "uncertain" (Figure 5). The level of uncertainty varies and reflects the geomorphological complexity of each area. On average, about 40% of the landforms remain "uncertain". At these locations, the inventorying teams judged that we need more precise data and/or field visits to finalise the assessment.

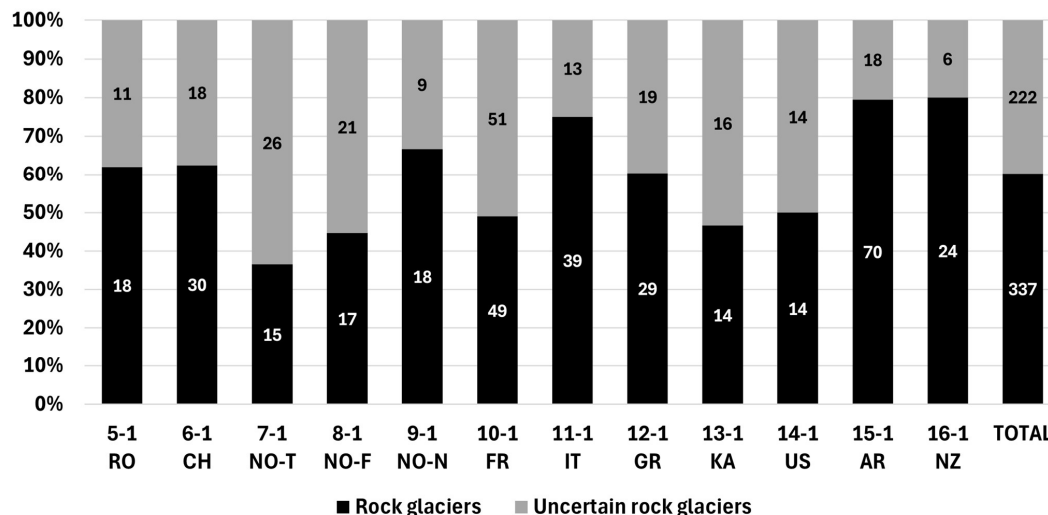



Figure 5: Relative distribution of the Rock Glacier Units (RGU) identified as "certain" (black) or "uncertain" (grey) in each RoGI

300   **area resulting from the consensus-based final Primary Marker (PM) layers. The numbers written in the bars correspond to the absolute numbers of landforms. The area numbers and the acronyms of the corresponding countries are used as x-axis legend (RO: Romania, CH: Switzerland, NO: Norway (NO-T: Troms, NO-F: Finnmark, NO-N: Nordenskiöld Land), FR: France, IT: Italy, GR: Greenland, KA: Kazakhstan; US: U.S.A.; AR: Argentina, NZ: New Zealand), according to Table 1 naming convention. Further analysis in the second phase of the exercise (outlining and characterisation of the attributes) was performed on the**

305   **"certain" rock glaciers only.**

The InSAR-based MA polygons have a wide range of velocities, both between and within the areas (Figure 6). The MA

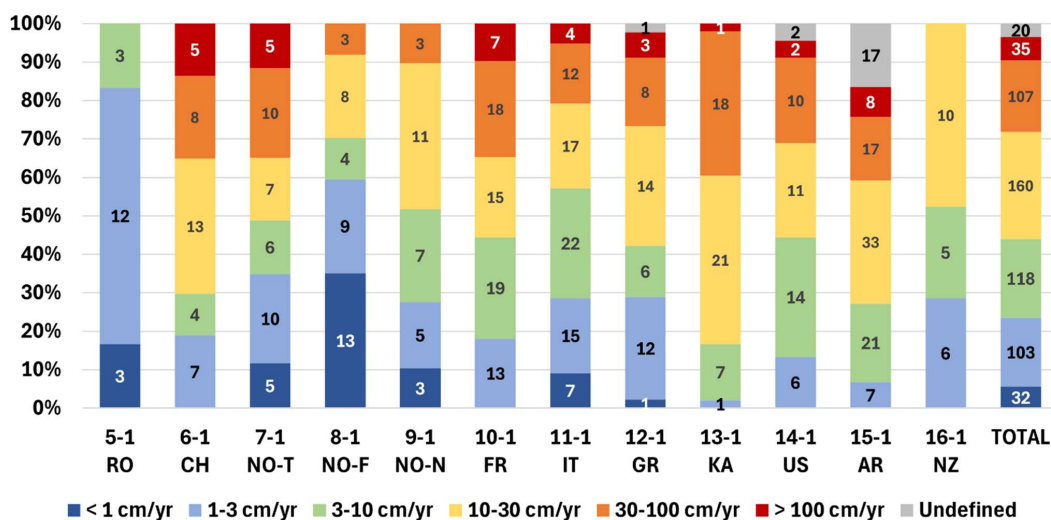
310 layers were used to assign the kinematic attribute (KA) of each RGU, which then was used to assess the activity (Figure 7). The kinematic and activity attributes of the PM files are therefore related to the MA layers, but the respective information is also complementary. While the activity is a convenient way to summary the rock glacier state, the MA layers provide a more comprehensive overview of the distribution of the rock glacier creep rate. There are overall more MA polygons than RGU PM due to spatial heterogeneities in velocity (i.e., several MA over the same RGU).

315

Figure 6: Relative distribution of the velocity classes of the InSAR-based Moving Areas (MA) in each RoGI area resulting from consensus-based final MA layers. The numbers written in the bars correspond to the absolute numbers of landforms. The area numbers and the acronyms of the corresponding countries are similar to Figure 5 and according to Table 1 naming convention.

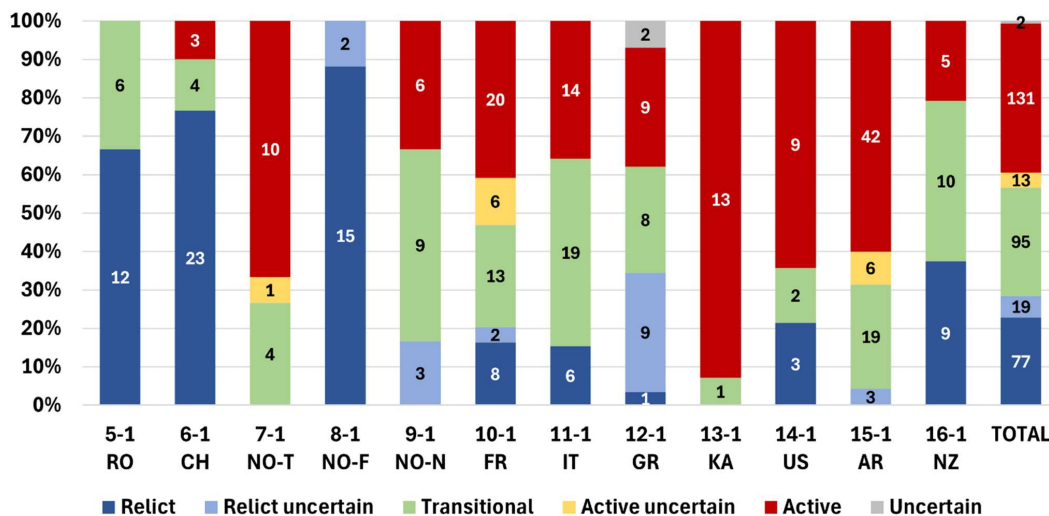



Figure 7: Relative distribution of the RGU activity (active, active uncertain, transitional, transitional uncertain, relict, relict uncertain, uncertain), documented as attribute in the consensus-based final Primary Marker (PM) layers. The numbers written in the bars correspond to the absolute numbers of landforms. The area numbers and the acronyms of the corresponding countries are similar to Figure 5 and according to Table 1 naming convention.

Based on the extended outlines, the RGU have a typical size ranging between 0.01 and 0.25 km^2 (median value of each area, Figure 8). The boxplots indicate large differences in size between and within the areas. It should be noted that in areas dominated by large rock glaciers (e.g., area 12-1 Disko Island, Greenland; area 13-1 Northern Tien Shan, Kazakhstan), small talus-connected rock glaciers may have been overlooked.

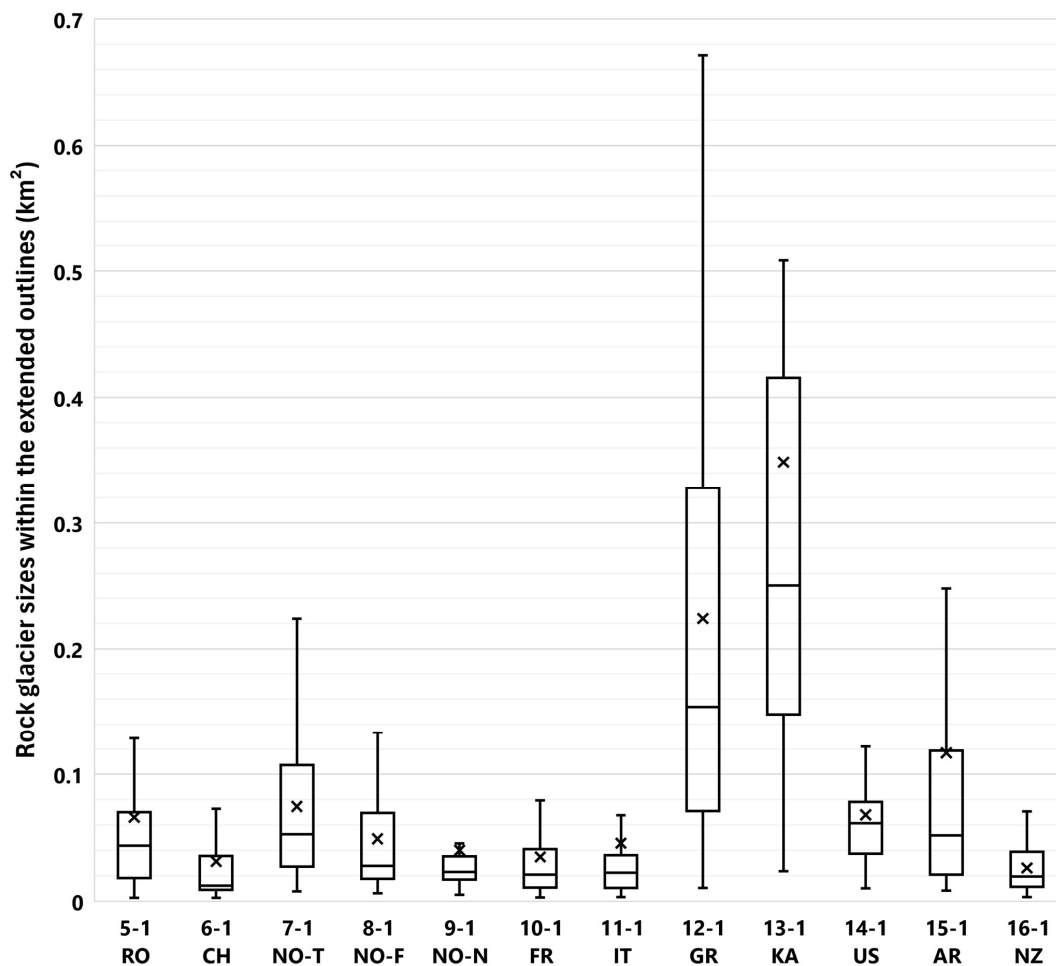



Figure 8: Range of RGU sizes within the extended Geomorphological Outlines (GO) in each RoGI area, resulting from the
330 **consensus-based final GO layers. The horizontal lines in the boxes indicate the median values. The lower and upper limits of the**
boxes indicate the 1st and 3rd quantiles. The whiskers highlight the maximum and minimum values. The crosses indicate the
averaged sizes. The area numbers and the acronyms of the corresponding countries are similar to Figure 5 and according to Table
1 naming convention.

4.1 RoGI area 5-1 RO (Carpathians, Romania)

335 RoGI area 5-1 is located in the Southern Carpathians, in Romania (central lat./long. location: 45°23' N, 22°53' E). The area covers an extent of approx. 18 km^2. The elevation ranges from peaks up to ~2500 m a.s.l along the southern mountain ridge, down to ~1070 m a.s.l. in the valley further north.

Previous research showed sporadic and isolated patches of permafrost, that are strongly linked with rock glaciers (Ardelean et al., 2015; Onaca et al., 2015; Popescu et al., 2024) and classified a small number of rock glaciers as active, with

340 displacement rates on the order of cm/yr for the past decades (Necsoiu et al., 2016).

The multi-operator RoGI exercise resulted in the identification of 18 certain rock glacier units, and 11 uncertain features. The InSAR-based MA indicate velocities ranging from < 1 cm/yr to 3–10 cm/yr. The assigned KA has contributed to classify the RGU activity as relict (12 RGU), and transitional (6 RGU). The averaged size of the mapped rock glaciers is ~0.07 km^2 based on the extended outlines.

345 4.2 RoGI area 6-1 CH (Western Alps, Switzerland)

RoGI area 6-1 is located in the upper part of the Réchy valley, in the Western Swiss Alps (central lat./long. location: 46°11' N, 7°30' E). The area covers an extent of approx. 12 km^2. The elevation ranges from peaks up to ~3000 m a.s.l along the southern mountain ridge, down to 2160 m a.s.l. in the valley further north.

Permafrost is still present in the upper part of the study area, whilst the lower area is mainly dominated by relict rock glaciers

350 (Lugon & Delaloye 2001; Marthaler et al. 2008; Tenthorey 1992). The kinematics of the Becs-de-Bosson rock glacier has intensively been monitored since the early 2000s (Kellerer-Pirklbauer et al., 2024; PERMOS 2024; Perruchoud & Delaloye, 2007) and displays velocities up to 2 m/yr. Staub et al. (2016) used this site to evidence the dependency of the interannual variation of the rock glacier creep rate to the multi-year ground surface temperature forcing.

The multi-operator RoGI exercise resulted in the identification of 30 certain rock glacier units, and 18 uncertain features.

355 The InSAR-based MA indicate velocities ranging from 1–3 cm/yr to > 100 cm/yr. The assigned KA has contributed to classify the RGU activity as relict (23 RGU), transitional (4 RGU) and active (3 RGU). The averaged size of the mapped rock glaciers is ~0.03 km^2 based on the extended outlines.

4.3 RoGI area 7-1 NO-T (Troms, Norway)

RoGI area 7-1 is located in the Kåfjord–Storfjord mountainous region, in Troms County, Northern Norway (central lat./long.

360 location: 69°23' N, 20°26' E). The area covers an extent of approx. 47 km^2. The elevation ranges from peaks up to ~1400 m a.s.l along the main Ádjit mountain ridge, down to ~400 m a.s.l. along the Skibotn valley flanks.

Previous research in this area indicated that the combination of seasonal frost and sporadic–discontinuous permafrost conditions in the region leads to a wide diversity of periglacial slope processes (Rouyet et al., 2021), including very high

velocity rock glaciers (Eriksen et al., 2018). The distribution of relict and active rock glaciers fits the extents of the modelled
365 Holocene and present-day permafrost extent in the region (Lilleøren et al., 2012).

The multi-operator RoGI exercise resulted in the identification of 15 certain RGU, and 26 uncertain features. The InSAR-based MA indicate velocities ranging from < 1 cm/yr to > 100 cm/yr. The assigned KA has contributed to classify the RGU activity as transitional (4 RGU), active (10 RGU), and active uncertain (1 RGU). The averaged size of the mapped rock glaciers is ~0.03 km² based on the extended outlines.

4.4   RoGI area 8-1 NO-F (Finnmark, Norway)

RoGI area 8-1 is located along Store Skogfjorden and Hopfjorden, in Finnmark country, Northern Norway (central lat./long. location: 70°45' N, 27°50' E). The area covers an extent of approx. 15 km². The elevation ranges from peaks up to ~535 m a.s.l in the southeastern part, down the sea level along the fjord.

The area is located at the limit of the modelled regional permafrost extent (Gisnås et al., 2017). Although most past research
375 has interpreted Finnmark rock glaciers as relict landforms (Lilleøren & Etzelmüller, 2011), a recent multi-methodological study suggests that some rock glaciers at sea-level are at a transitional stage (Lilleøren et al., 2022).

The multi-operator RoGI exercise resulted in the identification of 17 certain rock glacier units, and 21 uncertain features. The InSAR-based MA indicate velocities ranging from < cm/yr to 30–100 cm/yr. The assigned KA has contributed to classify the RGU activity as relict (15 RGU) and relict uncertain (2 RGU). The averaged size of the mapped rock glaciers is
380 ~0.05 km² based on the extended outlines.

4.5   RoGI area 9-1 NO-N (Nordenskiöld Land, Norway)

RoGI area 9-1 is located in the Western part of Nordenskiöld Land on Spitsbergen, the main island of Svalbard (central lat./long. location: 77°53' N, 13°54' E). The area covers an extent of approx. 10 km². The elevation ranges from peaks up to ~900 m a.s.l along the southeastern part of mountain ridge, down to ~50 m a.s.l. on the Nordenskiöldkysten strandflat.

385 Past rock glacier research in Svalbard identified low creep rates despite continuous permafrost and ice-rich conditions (Isaksen et al., 2000; Berthling et al., 1998). Along Nordenskiöldkysten, the apparent standstill of rock glaciers has been attributed to the low slope gradients where the rock glaciers flow onto the strandflat (Farbrot et al., 2005).

The multi-operator RoGI exercise resulted in the identification of 18 certain rock glacier units, and 9 uncertain features. The InSAR-based MA indicate velocities ranging from < cm/yr to 30–100 cm/yr. The assigned KA has contributed to classify the
390 RGU activity as relict uncertain (3 RGU), transitional (9 RGU), and active (6 RGU). The averaged size of the mapped rock glaciers is ~0.04 km² based on the extended outlines.

4.6   RoGI area 10-1 FR (Vanoise Massif, France)

RoGI area 10-1 is located in the Vanoise massif in France, in the Western European Alps (central lat./long. location: 45°19' N, 6°37' E). The area covers an extent of approx. 37 km². The elevation ranges from peaks up to ~3150 m a.s.l in the southern part, down to ~1710 m a.s.l in the valley further north.

Previous research in this area indicated that sporadic and discontinuous permafrost conditions in the region leads to a wide diversity and complexity of periglacial slope processes and several examples of rock glaciers destabilisation (Marcer et al., 2021).

The multi-operator RoGI exercise resulted in the identification of 49 certain rock glacier units, and 51 uncertain features. The InSAR-based MA indicate velocities ranging from 1–3 cm/yr to > 100 cm/yr. The assigned KA has contributed to classify the RGU activity as uncertain (2 RGU) relict (8 RGU), transitional (13 RGU), active (20 RGU), and active uncertain (6 RGU). The averaged size of the mapped rock glaciers is ~0.03 km² based on the extended outlines.

4.7   RoGI area 11-1 IT (Southern Venosta, Italy)

RoGI area 11-1 is located in Solda valley (Suldental), a tributary valley of the Venosta valley (Vinschgau), in western South Tyrol, Italy (central lat./long. location: 46°33' N, 10°36' E). The area hosts two hanging valleys and covers an extent of approx. 19 km². The elevation ranges from peaks up to ~3545 m a.s.l for Cima Vertana in the eastern divide, down to ~2120 m a.s.l further southwest.

According to a recently compiled geomorphological inventory, the area is characterised by highest rock glacier density within South Tyrol (~ 1.1 #/km² against a regional average of 0.54 #/km²) (Scotti et al., 2024). Prior work identified 803 rock glaciers across the broader Southern Venosta area, using InSAR to characterise the kinematics. Of these, 42% were classified as moving (> 1 cm/yr), 40% as not moving (< 1 cm/yr), and 18% as kinematically undefined. Rock glacier velocity, on average, was found to increase linearly with elevation up to the 2600–2800 m band, beyond which an inflection occurs, and consistent decimetre annual velocities are attained (Bertone et al., 2024). The activity that characterises rock glaciers in this region below and above 2600 m are consistent, respectively, with transitional and active rock glacier types.

The multi-operator RoGI exercise resulted in the identification of 39 certain rock glacier units, and 13 uncertain features. The InSAR-based MA indicate velocities ranging from < cm/yr to > 100 cm/yr. The assigned KA has contributed to classify the RGU activity as relict (6 RGU), transitional (19 RGU), and active (14 RGU). The averaged size of the mapped rock glaciers is ~0.05 km² based on the extended outlines.

4.8   RoGI area 12-1 GR (Disko Island, Greenland)

RoGI area 12-1 is located along the northeastern coast of Disko Island, Greenland (central lat./long. location: 69°51' N, 52°33' W). The area covers an extent of approx. 82 km². The elevation ranges from peaks up to ~1330 m a.s.l mountain tops in the southwestern part, down to sea level.

There is a high density of rock glaciers in the area, previously explained by the combination of continuous permafrost and the abundance of heavily weathered basaltic bedrock (Humlum, 1996). Previous studies have already pointed out that

425 tongue-shaped rock glaciers fed by glaciers in the hinterland are difficult to distinguish from debris-covered glaciers (Humlum, 1982).

The multi-operator RoGI exercise resulted in the identification of 29 certain rock glacier units, and 19 uncertain features. The InSAR-based MA indicate velocities ranging from < cm/yr to > 100 cm/yr. The assigned KA has contributed to classify the RGU activity as uncertain (2 RGU), relict (1 RGU), relict uncertain (9 RGU), transitional (8 RGU), and active (9 RGU).

430 The averaged size of the mapped rock glaciers is ~0.05 km^2 based on the extended outlines.

4.9 RoGI area 13-1 KA (Northern Tien Shan, Kazakhstan)

RoGI area 13-1 is located in the central part of Ile Alatau (also Zailiskiy Alatau), Northern Tien Shan in Central Asia (central lat./long. location: 43°0' N, 77°1' W). The area is located in Southern Kazakhstan, close to the border with Kyrgyzstan. The area covers an extent of approx. 59 km^2. The elevation ranges from peaks up to ~4365 m a.s.l in the eastern part, down to

435 ~2570 m a.s.l in the valley in the northwest.

Previous research has shown that rock glaciers are abundant in entire northern Tien Shan (Gorbunov and Titkov, 1989; Kääb et al. 2021; Titkov, 1988). More detailed investigations of the rock glaciers in the central part of northern Tien Shan highlighted the existence of several large complex rock glaciers, which originate in elevations where permafrost is very likely and flow down to elevations where permafrost is sporadic (Bolch & Gorbunov, 2014; Marchenko et al. 2001). Many

440 rock glaciers in this region are highly active with average surface velocities of 1 to more than 2.5 m/yr (Gorbunov et al. 1992, Kääb et al. 2021).

The multi-operator RoGI exercise resulted in the identification of 14 certain rock glacier units, and 16 uncertain features. The InSAR-based MA indicate velocities ranging from 1–3 cm/yr to > 100 cm/yr. The assigned KA has contributed to classify the RGU activity as transitional (1 RGU) and active (13 RGU). The averaged size of the mapped rock glaciers is

445 ~0.35 km^2 based on the extended outlines.

4.10 RoGI area 14-1 US (Brooks Range, U.S.A.)

RoGI area 14-1 is located in the Brooks Range, in Northern Alaska, U.S.A. (central lat./long. location: 68°6' N, 149°58' W). The area covers an extent of approx. 21 km^2. Elevation ranges from peaks up to ~2070 m a.s.l in the central part of the area, down to ~1120 m a.s.l. in the valleys further North.

450 The area is underlain by continuous permafrost. Limited previous research in this area mapped rock glaciers between 900 and 2000 m a.s.l., and occurring mainly on the north side of the Brooks Range (Calkin, 1987; Ellis and Calkin, 1979; Ikeda et al., 2008). Previous measured rates of two rock glaciers in the 1980s were 10 and 40 cm/yr (Calkin, 1987).

The multi-operator RoGI exercise resulted in the identification of 14 certain rock glacier units, and 14 uncertain features. The InSAR-based MA indicate velocities ranging from 1–3 cm/yr to > 100 cm/yr. The assigned KA has contributed to

455 classify the RGU activity as relict (3 RGU), transitional (2 RGU), and active (9 RGU). The averaged size of the mapped rock glaciers is ~0.07 km² based on the extended outlines.

4.11 RoGI area 15-1 AR (Central Andes, Argentina)

RoGI area 15-1 is located in the Central Andes, West from Mendoza, Argentina (central lat./long. location: 32°59' S, 69.34° W). The area covers an extent of approx. 55 km². Elevation ranges from up to ~5530 m a.s.l for the southernmost peaks,
460 down to ~3570 m a.s.l in the valley in the northern part of the area.

Previous studies reported an exceptional density of rock glaciers in the Central Andes of Argentina (Zalazar et al., 2020), where permafrost occurs from ~3600 m a.s.l. upwards (Trombotto Liaudat, 2000). Recently, significant surface displacements between 0.37 and 2.61 m/yr were assessed for large complex rock glaciers in the region (Blöthe et al.,2020), and short-term active layer monitoring documented the degradation of ice-rich permafrost in rock glaciers (Trombotto Liadat
465 and Bottegal, 2019).

The multi-operator RoGI exercise resulted in the identification of 70 certain rock glacier units, and 18 uncertain features. The InSAR-based MA indicate velocities ranging from 1–3 cm/yr to > 100 cm/yr. The assigned KA has contributed to classify the RGU activity as relict uncertain (3 RGU), transitional (19 RGU), active (42 RGU), and active uncertain (6 RGU). The averaged size of the mapped rock glaciers is ~0.12 km² based on the extended outlines.

470 **4.12 RoGI area 16-1 NZ (Southern Alps, New Zealand)**

RoGI area 16-1 is located in the Ben Ahau Range, part of the Southern Alps of New Zealand (central lat./long. location: 43°59' S, 170°3' E). The study area covers an extent of approx. 7 km². Elevation ranges from peaks up to 2431 m a.s.l for the highest peak in the north, down to ~1600 m a.s.l in the westernmost valley.

In two previous studies in the study area, Sattler et al. (2016) identified two relict, four inactive, and six active rock glaciers,
475 based on aerial image analysis only, while Lambiel et al. (2023) reported the presence of ten transitional and two active rock glaciers, using Sentinel-1 InSAR data.

The multi-operator RoGI exercise resulted in the identification of 24 certain rock glacier units, and 6 uncertain features. The InSAR-based MA indicate velocities ranging from 1–3 cm/yr to > 10–30 cm/yr. The assigned KA has contributed to classify the RGU activity as relict (9 RGU), transitional (10 RGU), and active (5 RGU). The averaged size of the mapped rock
480 glaciers is ~0.03 km² based on the extended outlines.

5 Uncertainties and limitations

5.1 Documentation of uncertainties

In the attribute tables of the three GeoPackage files, various fields document the reliability of the mapping and morpho-kinematic assessment:

- 485 For the PM files, an attribute "uncertain" describes ambiguous areas that should be investigated in the future (need for additional data and/or field visit). For educational purposes, an attribute "not a rock glacier" could also be used to highlight landforms that are likely to be misinterpreted as rock glaciers. The level of uncertainty and complexity can be highlighted for many morpho-kinematic attributes, either in the selectable categories (for example "active uncertain", "transitional uncertain", and "relict uncertain" for the attribute "Activity") or using an additional reliability attribute

- 490 (for example for the "Kinematic" attribute). Additional comments describing the error sources and ambiguities in the interpretation can be written in "Comment" fields.

- For the MA files, the reliability (or the degree of confidence) of the results is qualitatively documented in accordance with the quality of the detection, the velocity classification and the delineation of the moving areas based on the available InSAR data. When medium–low reliability is set (uncertain InSAR signal and/or unclear MA outlines),

- 495 information on the uncertainty sources can be described in a "Comment" field.

- For the GO files, the reliability of the delineation at different locations of the rock glacier (front, left/right lateral margins, upslope boundary) is estimated with a score of 0 (low), 1 (medium), or 2 (high). The summation of the scores (0–8) gives a general estimate of the outline reliability for the entire landform.

5.2 Quality assessment of the RoGI products

500 Here we summarize the observations about the quality of the three output files, based on the results in the 12 areas and the feedback of the operator teams.

5.2.1 Quality of the PM products

- The quality of the PM products depends on the availability, resolution, and quality of the source data, which varies among the areas. Optical imagery affected by shadows, clouds, or snow cover led to increased uncertainty in some

- 505 areas (e.g., area 12-1 Disko Island, Greenland; area 14-1 Brooks Range, U.S.A.). In warm regions in the marginal permafrost zone (e.g., area 5-1 Carpathians, Romania), relict landforms with vegetation cover were hard to identify without detailed analysis of terrain hillshades (from LiDAR DEM to filter out the vegetation). In areas dominated by large glacier-connected or glacier-forefield-connected rock glaciers, small talus-connected rock glaciers tended to be overlooked, which may explain the different size distribution between the areas (see Figure 8). The identification of

- 510 small and relatively shallow rock glaciers developed on debris-mantled slopes might be challenging, as they often do not exhibit well-defined rooting zones and lateral margins (e.g., in area 11-1 Southern Venosta, Italy).

- The level of geomorphological complexity and the interactions with other glacial and periglacial processes vary among the areas. Several teams reported the challenges of discriminating landforms due to the glacier–rock glacier continuum (e.g., area 13-1 Northern Tien Shan, Kazakhstan; area 14-1 Brooks Range, U.S.A.; area 15-1 Central Andes, Argentina)

- 515 or between rock glacier landforms and complex morainic systems in the case of rock glaciers derived from former (late-

glacial) glacier-forefield (e.g., in area 6-1, Western Alps). The imbrication with other types of periglacial processes also leads to ambiguities in the landform discrimination (e.g., large coarse solifluction lobes and rockslide deposits, e.g., in area 8-1 Finnmark, Norway). In such cases, the final products include many "uncertain" PM and several cases with unclear upslope connections. In areas with landslides (e.g., area 7-1 Troms, Norway; area 10-1 Vanoise Massif, France), there were difficulties in assigning the type of upslope connection. The "landslide-connected" upslope unit is somewhat ambiguous, as it often practically means that there is a poly-connection (talus+landslide). In such cases, the high level of discrepancy between operators required some discussions to agree on a final category.

- The main challenge reported by all teams is related to the variable level of details applied to discriminate landforms with complex morphology. There were discrepancies among the operators in the way to interpret multi-unit systems and discriminate the units. In complex cases, some operators considered the landforms as one main complex unit (one PM), while others identified several units (several PM). After discussions, consistent solutions were found within each area. There are remaining differences between the areas due to the variable geomorphological complexity.

- The quality of the attribute characterisation depends on the complexity of the study area. In cold-climate regions with continuous permafrost (e.g., area 9-1 Nordenskiöld Land, Norway), one challenge is related to the kinematic and activity attributes. Although the landforms are "active" in the traditional sense (i.e., intact, with presence of permafrost), some are very slowly creeping and so fall into the transitional–relict category according to the current RGIK definition (low efficiency of sediment conveyance). The activity is also challenging to assess in areas where the contrast in surface material between the rock glacier surface and the front is generally low (e.g., area 16-1 Southern Alps, New Zealand). In such cases, the front is generally smooth, which makes it is hard to discriminate active from transitional rock glaciers without kinematic information.

5.2.2 Quality of the MA products

- InSAR was useful for identifying moving rock glaciers, in addition to providing a semi-quantitative information about their creep rates. When used iteratively with PM detection (see Figure 2), the MA step allowed for including landforms that may have been overlooked when only applying a geomorphological approach. It was especially valuable in areas where optical imagery was affected by shadows, clouds, or snow cover.

- The accuracy of the kinematic analysis varied between areas due to unequal data availability. Some areas had a variety of InSAR data from different SAR sensors and processed with different algorithms (single interferograms, stacking and PSI), providing a wide range of detection capabilities. In such cases, the areas with no MA could reliably be interpreted as "no movement" (i.e., movement < cm/yr), and high to very high velocity can be discriminated (dm–m/yr, m/yr or > m/yr). However, some areas had fewer datasets and longer Sentinel-1 repeat-pass time interval (extra-European areas, e.g., area 14-1 Brooks Range, U.S.A.), which led to reduced maximal detection capability. Using Sentinel-1 12d repeat-pass only, it is indeed not possible to discriminate m/yr to > m/yr kinematic categories.

- The InSAR interpretation resulted in discrepancies between operators. All teams reported that it was the hardest step of the RoGI procedure due to variable backgrounds of the operators. A consensus-based process was difficult to perform, due to variable levels of experience with InSAR, the different ways to look at all available datasets, and the variable levels of details in systematically outlining the MAs. In most cases, the same MA were similarly identified and delineated, but the velocity classes were sometimes assigned differently. Despite this challenge, many operators reported that the work was highly educative, and all teams had at least one operator well-experienced with InSAR, which ensured high quality in the final results.

- In general, major fast-moving MA were detected with few variabilities among operators, while small and slow MA were more difficult to interpret. In marginal permafrost zones (e.g., area 5-1 Carpathians, Romania; area 8-1 Finnmark, Norway), there is a dominance of transitional and relict rock glaciers characterised by little (or no) movement. The MA are small and with low velocity, and therefore hard to identify compared to other areas characterised by strong InSAR signal on interferograms with short time intervals between the compared images.

- In cold regions with continuous permafrost, the ground is highly dynamic during the thawing season, which makes it difficult to dissociate the InSAR signal on the rock glacier from surroundings areas that also move. When analysing small and slowly creeping talus-connected rock glaciers, it was sometimes challenging to discriminate the movement associated with rock glacier creep from other processes, such as thaw subsidence in ice-rich lowlands located directly at the foot of the mountain ridges (e.g., area 9-1 Nordenskiöld Land, Norway).

5.2.3 Quality of the GO products

- The main difficulty was to delineate the boundary between the rock glacier and its contributing area, depending on the type of upslope connection. For glacier-connected or glacier-forefield-connected rock glaciers, the location of the upper boundary was often ambiguous, and the corresponding outline reliability therefore set to "low" in the attribute table (e.g., area 13-1 Northern Tien Shan, Kazakhstan; area 15-1 Central Andes, Argentina). For talus-connected rock glaciers, there were discrepancies on how to draw the upper outline: straight line on the upslope area of the rock glacier, versus a curved connection to avoid the inclusion of talus cones feeding the rock glacier. The teams discussed this challenge and agreed on drawing a curved line, continuing the delineation of the front and margins while following the topography.

- In some cases, the delineation of the front was challenging, especially if the toe of the rock glacier was reworked by other processes, such as solifluction (e.g., area 14-1 Brooks Range, U.S.A.). Some problems were identified in cases of exaggerated fronts blended with the downside talus slope (e.g., area 16-1 Southern Alps, New Zealand). Small debris-mantled rock glaciers often had ambiguous margins, challenging for outlining (e.g., area 11-1 Southern Venosta, Italy). Such complicated cases were discussed during team meetings to find a mutually agreeable solution. When the location of the boundary was uncertain, the corresponding outline reliability was set to "low" or "medium" in the attribute table.

580 • Complex rock glacier systems with several rock glacier units were the most challenging landforms to outline. The delineation was especially difficult in the case of adjacent landforms or several generations of partly overlapping rock glacier units. In some cases, several units initially identified with different PM in the first phase of the exercise were not outlined separately in the second phase (too complex). The two phases (PM identification and GO delineation) were performed iteratively. When the outlining process highlighted that multi-unit discrimination was bringing too much

585 uncertainty, the PM numbers and locations were revised (simplification) (e.g., area 7-1 Troms, Norway; area 13-1 Northern Tien Shan, Kazakhstan; area 15-1 Central Andes, Argentina).

• Combining different data sources with variable acquisition times, snow/vegetation covers, and sunlight directions helped interpreting and mapping some rock glaciers. On the other hand, some areas are affected by georeferencing shifts between the different optical data sources available in the online services (e.g., area 8-1 Finmark, Norway; area 9-

590 1 Nordenskiöld Land, Norway). These shifts may explain some discrepancies among operators, depending on the main source used to digitalise the boundaries. The scale and level of details used to perform the outlining work also varied between the operators. This challenge did not affect the consistency and quality of the final products that were discussed within the teams and accordingly revised by each PI. The data source used for the final outlines is specified in the attribute table.

595 **5.3 Quality assessment of the multi-operator RoGI procedure**

Here we summarize the observations about the multi-operator RoGI procedure, based on the results in the 12 areas and the feedback of the operator teams.

5.3.1 Value of the RoGI exercise and the multi-operator procedure

• The steps and instructions of the exercise were generally assessed as clear and easy to follow. The operators reported

600 that they liked the structure and clarity of the provided GIS and data packages. Thus, it is promising to apply the same structure in new regions and therefore ensure consistency in future RoGI data compilation.

• Each team had two multi-operator meetings, with 3–10 people attending. The size of the teams proved ideal for such an exercise, as more people would have been challenging to manage and ensure efficient discussions. In some cases, the digital meetings were complemented with email interactions (e.g., sharing of comments in documents, prints screens,

605 powerpoints, and sending recording of meetings). All types of communication were found valuable, both for personal learning purpose and for improving the quality of the final products.

• Having operators with different skills and backgrounds was found to bring in added value to the final results. The combination of different points of view and experiences from several regions around the world ensured that various morpho-kinematic elements were identified and taken into consideration.

610 • Although InSAR interpretation has been identified as the most challenging step due to little experience for some operators, several teams report that the data were useful at different levels, for example simply to detect moving landforms that may not be so obvious on optical images only.

5.3.2 Challenges and suggestions to improve the RGIK procedure and guidelines

• The consensus-based procedure generally worked well for the PM identification, the GO delineation, and the
615 categorisation of key attributes (e.g., upslope connection, kinematics, and activity). However, some steps cannot be comprehensively assessed during team meetings. It is for example not feasible to collectively discuss all details of the InSAR interpretation. Practically, the PIs compared their own results with those of the other operators, and corrected their results when mistakes were found. A comprehensive consensus-based process can work but only on a small set of rock glaciers, which could then be used for adjusting the assessment criteria before upscaling.

620 • The InSAR interpretation was challenging for operators without past experience with these types of data. Despite discrepancies in the quality of some individual results, that issue did not impact the final products, as each team included at least one person with InSAR experience. Nevertheless, the teams suggested various ways to improve this part in the future, such as 1) adding new examples in the guidelines on how to read the interferograms, 2) splitting the multi-operator process into two separate teams (one with InSAR expertise focusing on the MA part, one with
625 geomorphological expertise focusing on the PM/GO and using the final MA for the kinematic assessment), 3) pre-processing the data and providing the velocity products in formats that are easier to interpret by non-experts.

• The assignment of the activity attribute based on geomorphological and/or kinematic criteria requires clarification in the guidelines. It was for instance recommended to avoid overinterpreting the absence of movement, because no MA can also mean no data. In such case, some operators only focused on geomorphological criteria without documenting
630 the kinematic attribute. A kinematic attribute with low velocity and low reliability index may have been documented, but was not used to set the activity. For other operators, the lack of movement has been used in synergy with geomorphological evidence, as an additional indicator confirming the geomorphological interpretation.

• As part of the GO step, the upper outline between rock glacier and its contributing area was identified as the most challenging part to delineate. The way to draw the upper outline when there is a high level of uncertainty could be
635 improved in the RGIK guidelines, based on additional examples, for different landform types and from different places around the world. The scale of digitalisation was not specified at the beginning of the exercise, which led to discrepancies in the outlining level of details and size of the considered landforms. The way to document the data source, imagery date and scale of analysis could be improved. When using Bing, Google or ESRI WMS imagery, it is important to specify the date that work has been performed as these open services have frequent updates. It was
640 encouraged to do it in the field "Comments" or "Kin.Comments" but other elements could be written in these fields, which led to variable metadata documentation depending on the operator.

- Several operators commented that there were many variables to document. The entire inventory process was consequently time-consuming, which led to variable levels of details. It should be noted that in the framework of this exercise, all steps were required although several elements are presented as "optional" in the guidelines. For example,

645   the GO are valuable but are not mandatory to draw. A combination of PM with and without GO is possible within the same RoGI. One could decide to delineate a large system and mark the locations of several units using PM only (i.e., without outlining at the same level). More compact versions of the RoGI protocol could be developed to avoid discouraging some groups to follow it. Alternative ways to summarize the essential information contained in the RGIK guidelines (short check-list document, flow-chart with link to necessary definitions, video tutorial, etc.) may also help

650   RoGI operators to quickly have a clear overview on the tasks to perform.

Overall, despite discrepancies in the individual results, the above issues did not impact the final products. Consistent solutions were found after discussion within and among the team(s).

6   Conclusion: potential use and applications

The multi-operator RoGI exercise performed in 2023 involved 41 people who applied the RGIK guidelines in 12 areas

655 spread around the world. This unique international initiative fulfilled the four initial objectives outlined at the end of Section 1. First, we demonstrated that it was feasible to apply common RoGI guidelines and procedure in various mountainous environments. All teams acknowledged that the initiative was highly instructive, thanks to the lively discussions in team meetings, the diversity of backgrounds and experiences, and the possibility to perform the work in various geomorphological contexts. Second, we identified various limitations (see Section 5) that will serve to improve the RGIK guidelines in the

660 future. Third, we developed standardized GIS templates for homogenizing the production of future RoGI and providing training tools for the community. The GIS templates and two online exercises are already available on the RGIK website. Fourth, we compiled and disseminated a homogenized set of RoGI in 12 diverse regions.

The resulting dataset has the potential to be used for several applications. Here we discuss four potential uses:

665 - **Further investigation in the selected areas and RoGI upscaling**: The exercise was performed on relatively small areas (7–82 km^2) to make it feasible to apply the demanding procedure described in Section 2. All PIs and involved research groups acknowledged the educational value of the process and the lessons learnt during the exercise will contribute to continue their work in the regions, with the long-term objective to upscale the RoGI to entire mountain ranges. The landforms, for which the current characterisation was uncertain with the applicable data, may be

670   investigated further during future targeted fieldwork campaigns or when new datasets become available.

- **Rock glacier selection for Rock Glacier Velocity (RGV) monitoring:** Following the recent acceptance of RGV as a new parameter of the ECV Permafrost (WMO, 2022; Streletskiy et al., 2021), one important task of the community is to monitor the interannual velocity changes of selected rock glaciers, using in situ and/or remote sensing techniques. It

675 is highly recommended to have a good understanding of the rock glaciers selected for long-term monitoring and exploitations as climate change indictor. The development of comprehensive RoGI in several regions is therefore a valuable first step to design monitoring strategies in each area (RGIK, 2023c).

- **Educational training tools for enhancing the systematic generation of RoGI worldwide:** The international multi-operator exercise highlighted the variety of rock glacier morphologies and characteristics across the selected mountain ranges, showing the importance of illustrating the RGIK guidelines with examples from different regions. The operator
680 comments show the need to promote the guidelines with alternative tools (e.g., compact version of the RoGI protocol, short check-list document, flow-chart summarizing the main steps with links to necessary definitions, video tutorial, additional GIS training tools based on the present dataset, etc.). New training material, partly based on our RoGI dataset, may contribute to promoting and supporting the generation of RoGI in under-studied regions.

- **Training data for automated inventorying techniques:** There is a growing interest in the community for developing
685 automated solutions for RoGI generation at a large scale, using machine learning (Erharter et al., 2022; Mahanta et al., 2024; Robson et al., 2020; Sun et al., 2024). Per definition, machine learning requires high-quality datasets to train the model. Transferability is typically a challenge. If the input data is clustered in a small area, the model may fail to map rock glaciers in another region with different conditions. In this respect, despite the few landforms in each area, our dataset covers a wide range of topographic, geological, and climatic conditions. To our knowledge, this is the first
690 publicly released dataset that combines RoGI in ten different countries and five continents, which will hopefully be valuable for machine learning applications.

Data availability

The final PM/MA/GO dataset is available on Zenodo (Rouyet et al., 2024; https://doi.org/10.5281/zenodo.14501399). The GeoPackage (gpkg) templates for performing similar RoGI in other areas, and exercises based on the QGIS tool are available
695 on the RGIK website (https://www.rgik.org).

Author contributions

The mountain permafrost component of the ESA CCI Permafrost project is led by TS and RD. The multi-operator exercise was designed by RD, TE and LRo. The RoGI instructions and GIS generic tool were prepared by TE, RD and LRo. The InSAR datasets were processed by TS and LRo. LRo set the timeline of the exercise, led coordination meetings with the PIs
700 and oversaw the work between the areas. LS assisted the coordination of the PI meetings. The multi-operator work in each area was coordinated by the PIs: FS (area 5-1), TE (area 6-1), LRo (area 7-1, 8-1, 9-1), DC (area 10-1), FB (area 11-1), RC (area 12-1), TB (area 13-1), MD (area 14-1), LRu (area 15-1) and CL (area 16-1). The PIs finalised the products for their area. Technical correction and final data package compilation was performed by TE, LRo, LS and RD. LRo led the work on

writing the manuscript and wrote the first draft. Figures and tables were made by TE and LRo. All authors contributed to the final version of the paper.

Completing interests

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

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References

Ardelean, A. C., Onaca, A. L., Urdea, P., Serban, R. D., and Sirbu, F.: A first estimate of permafrost distribution from BTS measurements in the Romanian Carpathians (Retezat Mountains). Geomorphologie-Relief Processus Environnement, 21(4), 297–312. doi:10.4000/geomorphologie.11131, 2015.

Azócar, G. F., Brenning, A., and Bodin, X.: Permafrost distribution modelling in the semi-arid Chilean Andes, The Cryosphere, 11(2), 877–890, doi:10.5194/tc-11-877-2017, 2017.

Bartsch, A., Strozzi, T., and Nitze, I.: Permafrost monitoring from space, Surveys in Geophysics, 44(5), 1579–1613, doi:10.1007/s10712-023-09770-3, 2023.

Berthling, I., Etzelmüller, B., Eiken, T., and Sollid, J. L.: Rock glaciers on Prins Karls Forland, Svalbard. I: internal structure, flow velocity and morphology, Permafrost and Periglacial Processes, 9(2), 135–145, doi:10.1002/(SICI)1099-1530(199804/06)9:2<135::AID-PPP284>3.0.CO;2-R, 1998.

730 Bertone, A., Barboux, C., Bodin, X., Bolch, T., Brardinoni, F., Caduff, R., Christiansen, H. H., Darrow, M. M., Delaloye, R., Etzelmüller, B., Humlum, O., Lambiel, C., Lilleøren, K. S., Mair, V., Pellegrinon, G., Rouyet, L., Luiz, L., and Strozzi, T.: Incorporating InSAR kinematics into rock glacier inventories: insights from 11 regions worldwide, The Cryosphere, 16(7), 2769–2792, doi:10.5194/tc-16-2769-2022, 2022.

Bertone, A., Jones, N., Mair, V., Scotti, R., Strozzi, T., and Brardinoni, F.: A climate-driven, altitudinal transition in rock
735 glacier dynamics detected through integration of geomorphological mapping and synthetic aperture radar interferometry (InSAR)-based kinematics, The Cryosphere, 18, 2335–2356, 10.5194/tc-18-2335-2024, 2024.

Blöthe, J. H., Halla, C., Schwalbe, E., Bottegal, E., Trombotto Liaudat, D., and Schrott, L.: Surface velocity fields of active rock glaciers and ice-debris complexes in the Central Andes of Argentina, Earth Surface Processes and Landforms, 46, 504–522, doi:10.1002/esp.5042, 2021.

740 Bodin, X., Krysiecki, J. M., Schoeneich, P., Le Roux, O., Lorier, L., Echelard, T., Peyron, M., and Walpersdorf, A.: The 2006 collapse of the Bérard rock glacier (Southern French Alps), Permafrost and Periglacial Processes, 28(1), 209–223, doi:10.1002/ppp.1887, 2017.

Boeckli, L., Brenning, A., Gruber, S., and Noetzli, J.: A statistical approach to modelling permafrost distribution in the European Alps or similar mountain ranges, The Cryosphere, 6(1), 125–140, doi:10.5194/tc-6-125-2012, 2012.

745 Bolch, T., and Gorbunov, A. P.: Characteristics and origin of rock glaciers in Northern Tien Shan (Kazakhstan/Kyrgyzstan), Permafrost Periglac. Process., 25, 320–332, doi:10.1002/ppp.1825, 2014.

Brardinoni, F., Scotti, R., Sailer, R., and Mair, V.: Evaluating sources of uncertainty and variability in rock glacier inventories, Earth Surface Processes and Landforms, 44(12), 2450–2466, doi:10.1002/esp.4674, 2019.

Brencher, G., Handwerger, A. L., and Munroe, J. S.: InSAR-based characterization of rock glacier movement in the Uinta
750 Mountains, Utah, USA, The Cryosphere, 15(10), 4823–4844, doi10.5194/tc-15-4823-2021, 2021.

Calkin, P. E.: Rock glaciers of central Brooks Range, Alaska, USA, In: J. R. Giardino, J. F. Shroder, and J. D. Vitek (Eds), Rock glaciers, 65–82, Allen & Unwin, Boston, 1987.

Cicoira, A., Beutel, J., Faillettaz, J., and Vieli, A.: Water controls the seasonal rhythm of rock glacier flow, Earth and Planetary Science Letters, 528, 115844, doi:10.1016/j.epsl.2019.115844, 2019.

755 Delaloye, R., Perruchoud, E., Avian, M., Kaufmann, V., Bodin, X., Hausmann, H., Ikeda, A., Kääb, A., Kellerer-Pirklbauer, A., Krainer, K., Lambiel, C., Mihajlovic, D., Staub, B., Roer, I., and Thibert, E.: Recent interannual variations of rock glacier creep in the European Alps, In: 9th International Conference on Permafrost, Fairbanks, Alaska, 29 June – 3 July 2008, 343–348, doi:10.5167/uzh-7031, 2008.

Delaloye, R., Lambiel, C., and Gärtner-Roer, I.: Overview of rock glacier kinematics research in the Swiss
760 Alps, Geographica Helvetica, 65(2), 135–145, doi:10.5194/gh-65-135-2010, 2010.

Delaloye, R., Barboux, C., Bodin, X., Brenning, A., Hartl, L., Hu, Y., Ikeda, A., Kaufmann, V., Kellerer-Pirklbauer, A., Lambiel, C., and Liu, L.: Rock glacier inventories and kinematics: A new IPA Action Group, In: Proc. EUCOP5 – 5th European Conference of Permafrost, Chamonix, France, Vol. 23, 392–393, 2018.

Ellis, J. M., and Calkin, P.E.: Nature and distribution of glaciers, neoglacial moraines, and rock glaciers, east-central Brooks Range, Alaska, Arct. Alp. Res. 11, 403–420, doi:10.1080/00040851.1979.12004149, 1979.

Erharter, G. H., Wagner, T., Winkler, G., and Marcher, T.: Machine learning–an approach for consistent rock glacier mapping and inventorying–example of Austria, Applied Computing and Geosciences, 16, 100093, doi:10.1016/j.acags.2022.100093, 2022.

Eriksen, H. Ø., Rouyet, L., Lauknes, T. R., Berthling, I., Isaksen, K., Hindberg, H., Larsen, Y., and Corner, G. D.: Recent acceleration of a rock glacier complex, Adjet, Norway, documented by 62 years of remote sensing observations, Geophysical Research Letters, 45(16), 8314–8323, doi:10.1029/2018GL077605, 2018.

Etzelmüller, B., Patton, H., Schomacker, A., Czekirda, J., Girod, L., Hubbard, A., Lilleøren, K. L., and Westermann, S.: Icelandic permafrost dynamics since the Last Glacial Maximum–model results and geomorphological implications, Quaternary Science Reviews, 233, 106236, doi:10.1016/j.quascirev.2020.106236, 2020.

Farbrot, H., Isaksen, K., Eiken, T., Kääb, A., and Sollid, J. L.: Composition and internal structures of a rock glacier on the strandflat of western Spitsbergen, Svalbard, Norsk Geografisk Tidsskrift - Norwegian Journal of Geography, 59(2), 139–148, doi:10.1080/00291950510020619, 2005.

French, H. M.: The Periglacial Environment, Third Edition, John Wiley & Sons, 2007.

Gisnås, K., Etzelmüller, B., Lussana, C., Hjort, J., Sannel, A. B. K., Isaksen, K., Westermann, S., Kuhry, P., Christiansen, H. H., Frampton, A., and Åkerman, J.: Permafrost map for Norway, Sweden and Finland, Permafrost and Periglacial Processes, 28(2), 359–378, doi:10.1002/ppp.1922, 2017.

Gorbunov, A. P., Titkov, S. N. und Polyakov, V.: Dynamics of the rock glaciers of the Northern Tien Shan and the Djungar Alatau, Kazakhstan, Permafrost Periglac. Process., 3, 29–39, doi:10.1002/ppp.3430030105, 1992.

Gorbunov, A. und Titkov, S.: Kamennye Gletchery Gor Srednej Azii: (Rock glaciers of the Central Asian mountains), Akademia Nauk SSSR, Irkutsk, 1989.

Hartl, L., Zieher, T., Bremer, M., Stocker-Waldhuber, M., Zahs, V., Höfle, B., Klug, C., and Cicoira, A.: Multi-sensor monitoring and data integration reveal cyclical destabilization of the Äußeres Hochebenkar rock glacier, Earth Surf. Dynam., 11, 117–147, doi:10.5194/esurf-11-117-2023, 2023.

Hassan, J., Chen, X., Muhammad, S., and Bazai, N. A.: Rock glacier inventory, permafrost probability distribution modeling and associated hazards in the Hunza River Basin, Western Karakoram, Pakistan, Science of The Total Environment, 782, 146833, doi:10.1016/j.scitotenv.2021.146833, 2021.

Hu, Y., Liu, L., Huang, L., Zhao, L., Wu, T., Wang, X., and Cai, J.: Mapping and characterizing rock glaciers in the arid Western Kunlun Mountains supported by InSAR and deep learning, Journal of Geophysical Research: Earth Surface, 128(9), e2023JF007206, doi:10.1029/2023JF007206, 2023.

Humlum, O.: Rock glacier types on Disko, Central West Greenland. Geografisk Tidsskrift - Danish Journal of Geography, 82(1), 59–66, doi:10.1080/00167223.1982.10649152, 1982.

Humlum, O.: Origin of rock glaciers: Observations from Mellemfjord, Disko Island, Central West Greenland. Permafrost and Periglacial Processes, 7, 361–380, doi:10.1002/(SICI)1099-1530(199610)7:4<361::AID-PPP227>3.0.CO;2-4, 1996

Ikeda, A., and Matsuoka, N.: Degradation of talus-derived rock glaciers in the Upper Engadin, Swiss Alps, Permafrost and
800 Periglacial Processes, 13(2), 145–161, doi:10.1002/ppp.413, 2002.

Ikeda, A., Matsuoka, N., and Kääb, A.: Fast deformation of perennially frozen debris in a warm rock glacier in the Swiss Alps: An effect of liquid water, Journal of Geophysical Research: Earth Surface, 113(F1), doi:10.1029/2007JF000859, 2008.

Isaksen, K., Ødegård, R. S., Eiken, T., and Sollid, J. L.: Composition, flow and development of two tongue-shaped rock
805 glaciers in the permafrost of Svalbard, Permafrost and Periglacial Processes, 11(3), 241–257, doi:10.1002/1099-1530(200007/09)11:3<241::AID-PPP358>3.0.CO;2-A, 2000.

Jones, D. B., Harrison, S., Anderson, K., Selley, H. L., Wood, J. L., and Betts, R. A.: The distribution and hydrological significance of rock glaciers in the Nepalese Himalaya, Global and Planetary Change, 160, 123–142, doi:10.1016/j.gloplacha.2017.11.005, 2018.

810 Kääb, A., Frauenfelder, R., and Roer, I.: On the response of rockglacier creep to surface temperature increase, Global and Planetary Change, 56(1-2), 172–187, doi:10.1016/j.gloplacha.2006.07.005, 2007.

Kääb, A., Strozzi, T., Bolch, T., Caduff, R., Trefall, H., Stoffel, M., und Kokarev, A.: 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, doi:10.5194/tc-15-927-2021, 2021.

815 Karjalainen, O., Luoto, M., Aalto, J., Etzelmüller, B., Grosse, G., Jones, B. M., Lilleøren, K. S., and Hjort, J.: High potential for loss of permafrost landforms in a changing climate, Environmental Research Letters, 15(10), 104065, doi:10.1088/1748-9326/abafd5, 2020.

Kellerer-Pirklbauer, A., Bodin, X., Delaloye, R., Lambiel, C., Gärtner-Roer, I., Bonnefoy-Demongeot, M., Carturan, L., Damm, B., Eulenstein, J., Fischer, A., Hartl, L., Ikeda, A., Kaufmann, V., Krainer, K., Matsuoka, N., Morra Di Cella,
820 U., Noetzli, J., Seppi, R., Scapozza, C., Schoeneich, P., Stocker-Waldhuber, M., Thibert, E., and Zumiani, M.: Acceleration and interannual variability of creep rates in mountain permafrost landforms (rock glacier velocities) in the European Alps in 1995–2022, Environmental Research Letters, 19(3), 034022, doi:10.1088/1748-9326/ad25a4, 2024.

Kenner, R., Pruessner, L., Beutel, J., Limpach, P., and Phillips, M.: How rock glacier hydrology, deformation velocities and ground temperatures interact: Examples from the Swiss Alps. Permafrost and Periglacial Processes, 31(1), 3–14,
825 doi:10.1002/ppp.2023, 2020.

Lambiel, C., Strozzi, T., Paillex, N., Vivero, S., and Jones, N.: Inventory and kinematics of active and transitional rock glaciers in the Southern Alps of New Zealand from Sentinel-1 InSAR, Arctic, Antarctic, and Alpine Research, 55(1), 2183999, doi:10.1080/15230430.2023.2183999, 2023.

Lilleøren, K. S., and Etzelmüller, B.: A regional inventory of rock glaciers and ice-cored moraines in Norway. Geografiska
830 Annaler: Series A, Physical Geography, 93(3), 175–191, doi:10.1111/j.1468-0459.2011.00430.x, 2011.

Lilleøren, K. S., Etzelmüller, B., Schuler, T. V., Gisnås, K., and Humlum, O.: The relative age of mountain permafrost—estimation of Holocene permafrost limits in Norway, Global and Planetary Change, 92, 209–223, doi:10.1016/j.gloplacha.2012.05.016, 2012.

Lilleøren, K. S., Etzelmüller, B., Rouyet, L., Eiken, T., Slinde, G., and Hilbich, C.: Transitional rock glaciers at sea level in northern Norway, Earth Surface Dynamics, 10(5), 975–996, doi:10.5194/esurf-10-975-2022, 2022.

Liu, L., Millar, C. I., Westfall, R. D., and Zebker, H. A.: Surface motion of active rock glaciers in the Sierra Nevada, California, USA: inventory and a case study using InSAR, The Cryosphere, 7(4), 1109–1119, doi:10.5194/tc-7-1109-2013, 2013.

Lugon, R., and Delaloye, R.: Modelling alpine permafrost distribution, Val de Réchy, Valais Alps (Switzerland), Norwegian Journal of Geography, Vol. 55/4, 224–229, doi:10.1080/00291950152746568, 2001.

Ma, Q., and Oguchi, T.: Rock Glacier Inventory of the Southwestern Pamirs Supported by InSAR Kinematics, Remote Sensing, 16(7), 1185, doi:10.3390/rs16071185, 2024.

Mahanta, K. K., Pradhan, I. P., Gupta, S. K., and Shukla, D. P.: Assessing Machine Learning and Statistical Methods for Rock Glacier-Based Permafrost Distribution in Northern Kargil Region, Permafrost and Periglacial Processes, doi:10.1002/ppp.2240, 2024.

Manchado, A. M.-T., Allen, S., Cicoira, A., Wiesmann, S., Haller, R., and Stoffel, M.: 100 years of monitoring in the Swiss National Park reveals overall decreasing rock glacier velocities, Communications Earth & Environment, 5, 138, doi:10.1038/s43247-024-01302-0, 2024.

Marcer, M., Bodin, X., Brenning, A., Schoeneich, P., Charvet, R., and Gottardi, F.: Permafrost favorability index: spatial modeling in the French Alps using a rock glacier inventory, Frontiers in Earth Science, 5, 105, doi:10.3389/feart.2017.00105, 2017.

Marcer, M., Serrano, C., Brenning, A., Bodin, X., Goetz, J., and Schoeneich, P.: Evaluating the destabilization susceptibility of active rock glaciers in the French Alps, The Cryosphere, 13(1), 141–155, doi:10.5194/tc-13-141-2019, 2019.

Marcer, M., Cicoira, A., Cusicanqui, D., Bodin, X., Echelard, T., Obregon, R., and Schoeneich, P.: Rock glaciers throughout the French Alps accelerated and destabilised since 1990 as air temperatures increased. Communications Earth & Environment, 2(1), 81, doi:10.1038/s43247-021-00150-6, 2021.

Marchenko, S. S.: A model of permafrost formation and occurrences in the intracontinental mountains, Norsk Geografisk Tidsskrift, 55, 230–234, doi:10.1080/00291950152746577, 2001.

Marthaler, M., Sartori, M., and Escher, A.: Feuille 1307 Vissoie, Atlas géol. Suisse 1:25 000, Carte 122 (Sheet 1307 Vissoie, Swiss Geological Atlas 1:25 000, Map 122), 2008.

Necsoiu, M., Onaca, A., Wigginton, S., and Urdea, P.: Rock glacier dynamics in Southern Carpathian Mountains from high-resolution optical and multi-temporal SAR satellite imagery, Remote Sensing of Environment, 177, 21–36, doi:10.1016/j.rse.2016.02.025, 2016.

Onaca, A., Ardelean, A. C., Urdea, P., Ardelean, F., and Sirbu, F.: Detection of mountain permafrost by combining conventional geophysical methods and thermal monitoring in the Retezat Mountains, Romania, Cold Regions Science and Technology, 119, 111–123, doi:10.1016/j.coldregions.2015.08.001, 2015.

PERMOS: PERMOS Database, Swiss Permafrost Monitoring Network, Davos and Fribourg, Switzerland, doi:10.13093/permos-2024-01, 2024.

Perruchoud, E. and Delaloye, R.: Short-term changes in surface velocities on the Becs-de-Bosson rock glacier (western Swiss Alps), In: Proceedings HMRSC-IX, Graz, 14-15 Sept. 2006, Grazer Schriften der Geographie und Raumforschung 43, 131–136, 2007.

Popescu, R., Filhol, S., Etzelmüller, B., Vasile, M., Pleșoianu, A., Vîrghileanu, M., Onaca, A., Șandric, I., Săvulescu, I., Cruceru, N., Vespremeanu-Stroe, A., Westermann, S., Sîrbu, F., Mihai, B., Nedelea, A., and Gascoin, S.: Permafrost Distribution in the Southern Carpathians, Romania, Derived From Machine Learning Modeling, Permafrost and Periglacial Processes, 35(3), 243–261, doi:10.1002/ppp.2232, 2024.

Rangecroft, S., Harrison, S., and Anderson, K.: Rock glaciers as water stores in the Bolivian Andes: an assessment of their hydrological importance, Arctic, Antarctic, and Alpine Research, 47(1), 89–98, doi:10.1657/AAAR0014-029, 2015.

Reinosch, E., Gerke, M., Riedel, B., Schwalb, A., Ye, Q., and Buckel, J.: Rock glacier inventory of the western Nyainqêntanglha Range, Tibetan Plateau, supported by InSAR time series and automated classification, Permafrost and Periglacial Processes, 32(4), 657–672, doi:10.1002/ppp.2117, 2021.

RGIK: Towards standard guidelines for inventorying rock glaciers: baseline concepts (version 4.2.2, 31.03.2022). IPA Action Group Rock Glacier Inventories and Kinematics (RGIK), 13 pp, www.rgik.org, 2022a.

RGIK: Towards standard guidelines for inventorying rock glaciers: practical concepts (version 2.0, 11.04.2022). IPA Action Group Rock Glacier Inventories and Kinematics (RGIK), 10 pp, www.rgik.org, 2022b.

RGIK: Optional kinematic attribute in standardized rock glacier inventories (version 3.0.1, 22.07.2022). IPA Action Group Rock Glacier Inventories and Kinematics (RGIK), 8 pp, www.rgik.org, 2022c.

RGIK: Guidelines for inventorying rock glaciers: baseline and practical concepts (version 1.0, 28.12.2023). IPA Action Group Rock glacier inventories and kinematics, 25 pp, doi:0.51363/unifr.srr.2023.002, 2023a.

RGIK: InSAR-based kinematic attribute in rock glacier inventories. Practical InSAR Guidelines (version 4.0., 31.05.2023), IPA Action Group Rock Glacier Inventories and Kinematics (RGIK), 33 pp, www.rgik.org, 2023b.

RGIK: Rock Glacier Velocity as an associated parameter of ECV Permafrost: baseline concepts (version 3.2, 22.05.2023) IPA Action Group Rock Glacier Inventories and Kinematics (RGIK), 13 pp, www.rgik.org, 2023c.

Robson, B. A., Bolch, T., MacDonell, S., Hölbling, D., Rastner, P., and Schaffer, N.: Automated detection of rock glaciers using deep learning and object-based image analysis, Remote Sensing of Environment, 250, 112033, doi:10.1016/j.rse.2020.112033, 2020.

Rouyet, L., Lilleøren, K. S., Böhme, M., Vick, L. M., Delaloye, R., Etzelmüller, B., Lauknes, T. R., Larsen, Y., and Blikra, L. H.: Regional morpho-kinematic inventory of slope movements in northern Norway, Frontiers in Earth Science, 9, 681088, doi:10.3389/feart.2021.681088, 2021.

900   Rouyet, L., Bolch, T., Brardinoni, F., Caduff, R., Cusicanqui, D., Darrow, M., Delaloye, R., Echelard, T., Lambiel, C., Ruiz, L., Schmid, L., Sirbu, F., and Strozzi, T.: Rock Glacier Inventories (RoGI) in 12 areas worldwide using a multi-operator consensus-based procedure [Data set], Zenodo, doi:10.5281/zenodo.14501399, 2024.

Sattler, K., Anderson, B., Mackintosh, A., Norton, K., and de Róiste, M.: Estimating permafrost distribution in the maritime southern alps, New Zealand, based on climatic conditions at rock glacier sites. Frontiers in Earth Science, 4, 1–17, doi:10.3389/feart.2016.00004, 2016.

905   Schmid, M.-O., Baral, P., Gruber, S., Shahi, S., Shrestha, T., Stumm, D., and Wester, P.: Assessment of permafrost distribution maps in the Hindu Kush Himalayan region using rock glaciers mapped in Google Earth, The Cryosphere, 9, 2089–2099, doi:10.5194/tc-9-2089-2015, 2015.

Schoeneich, P., Bodin, X., Echelard, T., Kaufmann, V., Kellerer-Pirklbauer, A., Krysiecki, J.-M., and Lieb, G. K.: Velocity Changes of Rock Glaciers and Induced Hazards. In: Lollino, G., Manconi, A., Clague, J., Shan, W., Chiarle, M. (eds),

910   Engineering Geology for Society and Territory - Volume 1, Springer, Cham, doi:10.1007/978-3-319-09300-0_42, 2015.

Scotti, R., Crosta, G. B., and Villa, A.: Destabilisation of Creeping Permafrost: The Plator Rock Glacier Case Study (Central Italian Alps), Permafrost and Periglacial Processes, 28, 224–236, doi:10.1002/ppp.1917, 2017.

Scotti, R., Mair, V., Costantini, D., and Brardinoni, F.: A high-resolution rock glacier inventory of South Tyrol: Evaluating

915   lithologic, topographic, and climatic effects. In: Beddoe, R.A. and Karunaratne, K.C. (Eds.) 12th International Conference on Permafrost. 16–20 June 2024, Whitehorse, Canada: International Permafrost Association, pp. 382–389, doi:10.52381/ICOP2024.176.1, 2024.

Staub, B., Lambiel, C., and Delaloye, R.: Rock glacier creep as a thermally-driven phenomenon: A decade of inter-annual observations from the Swiss Alps, In: 11th International Conference on Permafrost, 20–24 June 2016, Potsdam,

920   Germany, Bibliothek Wissenschaftspark Albert Einstein, 96–97, 2016.

Streletskiy, D., Biskaborn, B., Smith, S. L., Noetzli, J., Viera, G., and Schoeneich, P.: Strategy and Implementation Plan 2016–2020 for the Global Terrestrial Network for Permafrost (GTN-P), library.arcticportal.org/id/eprint/1938, 2017.

Streletskiy, D., Noetzli, J., Smith, S. L., Vieira, G., Schoeneich, P., Hrbacek, F. and Irrgang A. M.: Strategy and Implementation Plan 2021–2024 for the Global Terrestrial Network for Permafrost (GTN-P),

925   doi:10.5281/zenodo.6075467, 2021.

Sun, Z., Hu, Y., Racoviteanu, A., Liu, L., Harrison, S., Wang, X., Cai, J., Guo, X., He, Y., and Yuan, H.: TPRoGI: a comprehensive rock glacier inventory for the Tibetan Plateau using deep learning, Earth System Science Data Discussions, 2024, 1–32, doi:10.5194/essd-2024-28, 2024.

Tenthorey, G.: Perennial névés and the hydrology of rock glaciers, Permafrost and Periglacial Processes, Vol. 3/3, 247–252,
930   doi:10.1002/ppp.3430030313, 1992.

Titkov, S. N.: Rock Glaciers and glaciation of the Central Asian Mountains, In: Proceedings of the 5th International
Permafrost Conference, Vol. 1, Trondheim, 259–262, 1988.

Trofaier, A. M., Westermann, S., and Bartsch, A.: Progress in space-borne studies of permafrost for climate science:
Towards a multi-ECV approach, Remote Sens. Environ., 203, 55–70, doi:10.1016/j.rse.2017.05.021, 2017.

935 Trombotto-Liaudat, D.: Survey of cryogenic processes, periglacial forms and permafrost conditions in South America,
Revista do Instituto Geológico 21, 33–55, doi:10.5935/0100-929X.20000004, 2000.

Trombotto-Liaudat, D., and Bottegal, E.: Recent evolution of the active layer in the Morenas Coloradas rock glacier, Central
Andes, Mendoza, Argentina and its relation with kinematics, CIG, doi:10.18172/cig.3946, 2019.

Way, R. G., Wang, Y., Bevington, A. R., Bonnaventure, P. P., Burton, J. R., Davis, R., Garibaldi, M. C., Lapalme, C. M.,
940   Tutton, R., and Wehbe, M. A.: Consensus-Based Rock Glacier Inventorying in the Torngat Mountains, Northern
Labrador. In: Proc. Regional Conference on Permafrost 2021 and the 19th International Conference on Cold Regions
Engineering, 130–141, Reston, VA, American Society of Civil Engineers, 2021.

WMO: The 2022 GCOS ECVs Requirements, GCOS – 245, World Meteorological Organization (WMO),
library.wmo.int/idurl/4/58111, 2022.

945 Zalazar, L., Ferri, L., Castro, M., Gargantini, H., Gimenez, M., Pitte, P., Ruiz, L., Masiokas, M., Costa, G., and Villalba, R.:
Spatial distribution and characteristics of Andean ice masses in Argentina: results from the first National Glacier
Inventory, Journal of Glacialology, 66(260), 938–949, doi:10.1017/jog.2020.55, 2020.

Appendix A: Attribute Table of the Primary Marker (PM) files

950 Attributes of the Primary Marker (PM) gpkg files (M: mandatory attribute; O: optional attribute). The last column refers to the sections of the RGIK guidelines documenting the recommendations for identifying rock glaciers and assigning values to each attribute. At the time of the exercise, the table referred to the sections of several dedicated documents (RGIK, 2022a; 2022b; 2022c). The RGIK RoGI guidelines have since been merged into one reference document (RGIK, 2023a). The following table has therefore been updated accordingly.

Attribute	Description	Values	RGIK guidelines
fid (M)	Unique identifier of the Primary Marker.	Automatic filling	
Landform (M)	This attribute allows the operators to point out some landforms that look like rock glaciers, but which are not. 'Uncertain rock glacier' is an option in case of suspected rock glacier but still uncertain based on the available data. 'Rock glacier' is the default value.	0. Uncertain rock glacier 1. Rock glacier 2. Not a rock glacier	RoGI guidelines chap. 3 (sections 3.1 and 3.7) RoGI guidelines chap. 5 (section 5.1)
WorkingID (O)	Practical identifier chosen by the operator (e.g., TYR001, TYR002, ... for an inventory in Tyrol).	Text	
Lat. (M)	Latitude of the Primary Marker in decimal degrees.	Automatic filling	
Long. (M)	Longitude of the Primary Marker in decimal degrees.	Automatic filling	
PrimaryID (M)	RGU + 12 to 15 digits depending on the "Lat.", "Long." values. Always 4 digits after the degrees. (e.g., RGU34567S123456E means 3,4567° South and 12,3456° East)	Automatic filling	RoGI guidelines chap. 5 (section 5.2)
Alter.ID1 (O)	Alternative local or regional name	Text	
Alter.ID2 (O)	Identifier used in a previous inventory.	Text	
Assoc.RGS (O)	Defines if the Primary Marker is part of a mono-unit system ('Mono-unit RGS') or a multi-unit system ('Multi-unit RGS').	1. Mono-unit RGS 2. Multi-unit RGS	RoGI guidelines chap. 3 (section 3.2)
RGS.Primar (O)	Primary ID of the associated rock glacier system. RGS + 12 to 15 digits depending on the "Lat.", "Long" values. Always 4 digits after the degrees.	Automatic filling	
Morpho. (O)	Defines if the rock glacier identified by the primary marker is a rock glacier with simple or complex morphology.	1. Simple	RoGI guidelines chap. 3

		2. Complex	(section 3.2)
			RoGI guidelines chap. 5 (section 5.3)
Complet. (O)	Defines if the rock glacier identified by the Primary Marker is completely visible or not. 'No, Ups.Con' means that it is not complete due unclear upslope connection (e.g., overlapping of several rock glaciers generations). 'No, truncated front' means that it is not complete due to truncated front. 'Uncertain' when data or analysis do not allow to decide.	1. Yes 2. No unclear connection to the upslope 3. No, truncated front 4. Uncertain	RoGI guidelines chap. 5 (section 5.3)
Upsl.Con. (O)	Defines the geomorphological unit directly located upslope of a rock glacier unit or system (5 categories). When dealing with uncertain or intermediate situations, 4 additional categories are included: 'Poly-connected', 'Other', 'Uncertain' and 'Unknown'. See related documentation for further information.	1. Talus-connected 2. Glacier forefield-connected 3. Glacier-connected 4. Debris-mantled slope-connected 5. Landslide-connected 6. Poly-connected 7. Other 8. Uncertain 9. Unknown	RoGI guidelines chap. 3 (section 3.3) RoGI guidelines chap. 5 (section 5.3)
Upsl.Cur. (O)	Defines if the rock glacier is currently connected to the upslope unit or not.	1. Yes 2. No 3. Uncertain 4. Unknown	RoGI guidelines chap. 3 (section 3.3) RoGI guidelines chap. 5 (section 5.3)
Comment (O)	Comment on possible poly-connection and uncertainty	Text	
Acti.Ass. (O)	Defines how the activity assessment was performed: based on geomorphologic evidence only, or with additional kinematic data.	1. Kinematic 2. Geomorphologic	RoGI guidelines chap. 3 (section 3.4)

			RoGI guidelines chap. 5 (section 5.3)
Acti.Cl. (O)	Activity class assigned to the rock glacier. See related documentation for further information. Already pre-filled if "Kin.Att." is filled. It is also possible to change the value manually from the drop-down list, e.g., in case of low reliability of the kinematic attribute due to unideal slope orientation (N/S) compared to InSAR LOS measurements, the "Kin.Att." may not be representative of the real activity of the rock glacier (based on geomorphologic evidence).	1. Active 2. Active uncertain 3. Transitional 4. Relict uncertain 5. Relict 6. Uncertain	RoGI guidelines chap. 3 (section 3.4) RoGI guidelines chap. 5 (section 5.3) RoGI guidelines chap. 6 (sections 6.1, 6.2 and 6.3)
Kin.Att. (O)	Kinematic Attribute (KA) assigned to the rock glacier. Only if "Acti.Ass." is 'Kinematic'.	0. Undefined 1. < cm/a 2. cm/a 3. cm/y to dm/a 4. dm/a 5. dm/a to m/a 6. m/a 7. > m/a	RoGI guidelines chap. 6 (sections 6.1, 6.2 and 6.3)
TypeOfData (O)	Type of data used for kinematic assessment. Use "Kin.Comment" if you want to add more details about the type of date used (e.g., InSAR or SAR offset tracking for 'Radar'). Only if "Acti.Ass." is 'Kinematic'. 'Other' can be used if there is a combination of methods (add comments in "Kin.Comment").	Optical Radar Lidar Geodetic Other	RoGI guidelines chap. 6 (sections 6.1, 6.2 and 6.3)
Kin.Period (O)	Period of the data used to assign the KA (e.g., 2018–2020). Only if "Acti.Ass." is 'Kinematic'.	yyyy–yyyy	RoGI guidelines chap. 6 (sections 6.1, 6.2 and 6.3)
Destabili. (O)	Describes if the rock glacier unit is (ongoing) or has been (completed) destabilized.	0. No 1. Yes, ongoing 2. Yes, completed 3. Uncertain	RoGI guidelines chap. 3 (section 3.5) RoGI guidelines chap. 5 (section 5.3)

Kin.Comment (O)	Comment regarding kinematic information, data type and quality, spatial representativeness, etc. Especially when the reliability is low or medium.	Text	
Rel.Kin. (O)	Reliability of the assignment of the KA Only if "Acti.Ass." is 'Kinematic'	0. Low 1. Medium 2. High	RoGI guidelines chap. 6 (sections 6.1, 6.2 and 6.3)
Country (O)	Country Code of the RoGI area.	RO: Romania CH: Switzerland NO: Norway (T: Troms, F: Finnmark, N: Nordenskiöld Land) FR: France IT: Italy GR: Greenland KA: Kazakhstan US: U.S.A. AR: Argentina NZ: New Zealand	See Table 1 and Section 3.3 (naming convention).

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Appendix B: Attribute Table of the Moving Area (MA) files

Attribute table of the Moving Area (MA) gpkg files (M: mandatory attribute; O: optional attribute). The recommendations for delineating MA based on InSAR and assigning values to each attribute are documented in RGIK (2023b).

Attribute	Description	Values
Fid (M)	Unique identifier of the polygon.	Automatic filling
MA.ID. (M)	MA + 12 to 15 digits depending on the "Lat.", "Long" values. Always 4 digits after the degrees. (e.g., MA34567S123456E means 3,4567° South and 12,3456° East)	Automatic filling
WorkingID (O)	Practical identifier chosen by the operator (e.g., MA_TYR001, TYR002, ... for a moving areas inventory in Tyrol).	Text
Ref.PrimaryID (O)	PrimaryID of the related Rock Glacier Unit in the PM attribute table.	Text
Vel.Class (M)	Velocity class: variable characterising the surface displacement rate. Using InSAR, it refers to velocity observed in the LOS during a specified observation time window ("Time.Obs.").	0. Undefined 1. < 1 cm/yr (no movement up to some mm/yr) 2. 1–3 cm/yr (some cm/yr) 3. 3–10 cm/yr 4. 10–30 cm/yr (some dm/yr) 5. 30–100 cm/yr 6. > 100 cm/yr (m/yr and higher)
Time.Obs. (O)	Sensor type used to perform the characterisation is documented here. Observation time window (period during which the detection and characterisation is computed/measured, i.e., which months/seasons), and temporal frame (total duration during which the periodic measurements/computations are repeated and aggregated for defining the moving area, i.e.,	Text containing: SENSOR(s)_OBSERVATION-TIME-WINDOW TEMPORAL-FRAME e.g., with InSAR data: S1 Summer Y1–Y2 (velocity observed from Sentinel-1 with an observation time window in summer, each year between year Y1 to year Y2) TSX Summer Y1, Y2, ... (velocity observed from TerraSAR-X with an observation time window in summer, at year Y1, year Y2, etc.)

	which year(s)).	CSK Annual Y1–Y2 (velocity observed from Cosmo-SkyMed with an observation time window of one year, each year in between year Y1 to year Y2) ALOS 08–10 Y1–Y2 (velocity observed from ALOS with an observation time window between August and October each year between year Y1 and year Y2) S1 Summer Y1–Y2 and TSX 10 Y3 (velocity observed from Sentinel 1 with an observation time window in summer, each year between year Y1 to year Y2 and TerraSAR-X with an observation time window centred in October of the year Y3) Note: "Summer" period must be described into the metadata, and it should be at least 2–3 months
Rel.MA (O)	Reliability of the detected moving areas.	0. Low: signal interpretation (velocity estimation) and outline are uncertain but there is evidence of movement that needs to be considered. 1. Medium: signal interpretation (velocity estimation) or outline is uncertain. 2. High: obvious signal, best appropriate configuration (back-facing slope)
Comment (O)	Comments regarding the detection and characterization (if needed).	Text (250 characters maximum)
Country (O)	Country Code of the RoGI area.	RO: Romania CH: Switzerland NO: Norway (T: Troms, F: Finnmark, N: Nordenskiöld Land) FR: France IT: Italy GR: Greenland KA: Kazakhstan US: U.S.A. AR: Argentina NZ: New Zealand See Table 1 and Section 3.3 (naming convention).

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Appendix C: Attribute Table of the Geomorphological Outlines (GO) layers

Attribute table of the Geomorphological Outlines (GO) gpkg files (M: mandatory attribute; O: optional attribute). The last column refers to the sections of the RGIK guidelines documenting recommendations for outlining rock glaciers and assigning values to each attribute. At the time of the exercise, the table referred to the sections of several dedicated documents (RGIK, 2022a; 2022b). The RGIK RoGI guidelines have since been merged into one reference document (RGIK, 2023a). The following table has therefore been updated accordingly.

Attribute	Description	Values	RGIK guidelines
Fid (M)	Unique identifier of the polygon.	Automatic filling	
PrimaryID (M)	Unique identifier of the rock glacier unit in the PM attribute table. The digitized polygon in this table is necessarily associated to the previously created Primary Marker (point geometry). The "PrimaryID" must, therefore, be the same as the associated Primary Marker.	Automatic filling	RoGI guidelines chap. 5 (section 5.2)
WorkingID (O)	Practical identifier chosen by the operator (e.g., TYR001, TYR002, ... for an inventory in Tyrol).	Text	
Out.Type (M)	Outline type.	1. Extended 2. Restricted 3. Other	RoGI guidelines chap. 3 (section 3.6) RoGI guidelines chap. 5 (section 5.4)
Rel.Fr. (O)	Reliability of the front outline digitalisation.	2. High 1. Medium 0. Low	RoGI guidelines chap. 5 (sections 5.4.1 and 5.4.4)
Rel.LeftLM (O)	Reliability of the left lateral margin (i.e., orographic perspective) outline digitalisation.	2. High 1. Medium 0. Low	RoGI guidelines chap. 5 (sections 5.4.2 and 5.4.4)
Rel.RightLM (O)	Reliability of the right lateral margin (i.e., orographic perspective) outline digitalisation.	2. High 1. Medium 0. Low	RoGI guidelines chap. 5 (sections 5.4.2 and 5.4.4)
Rel.Ups.Con. (O)	Reliability of the upslope connection outline digitalisation.	2. High 1. Medium	RoGI guidelines chap. 5 (sections 5.4.3 and 5.4.4)

		0. Low	
Rel.Index (O)	Outline reliability index summing the values assigned to the reliability attributes "RelFr", "Rel.LeftLM", "Rel.RightLM" and "Rel.Ups.Con.".	Automatic filling From 0 (Low) to 8 (High)	RoGI guidelines chap. 5 (section 5.4.4)
Comment (O)	Comments regarding the outline.	Text (250 characters maximum)	
Country (O)	Country Code of the RoGI area.	RO: Romania CH: Switzerland NO: Norway (T: Troms, F: Finnmark, N: Nordenskiöld Land) FR: France IT: Italy GR: Greenland KA: Kazakhstan US: U.S.A. AR: Argentina NZ: New Zealand	See Table 1 and Section 3.3 (naming convention).