IPA Action Group Rock glacier inventories and kinematics

Towards standard guidelines for inventorying rock glaciers

Baseline concepts

(Version 4.2.2)

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Authors and contributions

The document has been edited by Reynald Delaloye and Thomas Echelard (University of Fribourg, Switzerland) with the contribution of the participants at the workshop held in Evolène (Switzerland) on 23–27 September 2019 as well as further members of the Action Group after electronic consultation.

The purpose of this document is to serve as baseline for the practical establishment of standardized rock glacier inventories on a global scale.

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Updated versions including the renewed approval list and possibly very small changes and edits could be released at any time during the lifetime of the Action Group and renamed by adding a third digit in the versioning (e.g. 4.0.x). The last version will always be the one hosted on the Action Group website. There will be no specific information sent to the Action Group subscribers.

If minor content changes appear to be necessary, they will be adopted by the dedicated committee named in Evolène in September 2019, including Xavier Bodin (France), Francesco Brardinoni (Italy), Reynald Delaloye (Switzerland), Christophe Lambiel (Switzerland), Shelley MacDonell (Chile), Line Rouyet (Norway) and Lucas Ruiz (Argentina). The second digit of the versioning will be changed (4.x) and an information will be sent to the Action Group subscribers.

If major changes are required, a thorough revision of the document must be undertaken and the community will be questioned.

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Content

Preamble

Rock glacier inventories have been set up for decades all around the world, yet without any real coordination, making their global assemblage and uniform completion impossible. In the meantime, quantitative information about kinematics has been made available for numerous rock glaciers, particularly with the development of remote sensing techniques. The IPA (International Permafrost Association) Action Group *Rock glacier inventories and kinematics* (2018–2023) aims at **exploring the feasibility of developing widely accepted standard guidelines for inventorying rock glaciers on a global scale, including information on their kinematics**.

Defining standard guidelines for inventorying rock glaciers constitutes Task 1 of the Action Group, which has been divided into three Sub-Tasks:

- 1.1: definition of the *main concepts and principles* (the present document),
- 1.2: establishment of *practical inventorying guidelines*,
- 1.3: establishment of a *technical (operational) manual* on how to implement a rock glacier inventory in an open-access database.

The present document intends to set the necessary **baseline concepts** for inventorying rock glaciers on a global scale (Sub-Task 1.1). This document includes the contribution of the participants to the workshops held in Chambéry (March 2019) and Evolène (September 2019), as well as further members of the Action Group after electronic consultation.

What is new since version 4.2?

Illustrations have been added in Section 3 (working version 4.2.1, August 2021) - numbers in brackets (e.g. (**4**)) are active links to them. They have been revised according to comments received from the Action Group community. Suggestions for further illustrations are still always welcome.

Provisional timeline

The integration of the present document (RGI_BCv4.2.2) with the practical concepts (RGI_PCv2.0) and the baseline concepts of the optional kinematic attribute (RGI_KAv3.0) into one single document is foreseen at a later stage before the completion of the current Action Group phase in June 2023.

1. Purpose of standardized guidelines

Although many (published and unpublished) regional rock glacier inventories exist, they are not exhaustive worldwide. Existing rock glacier inventories have various ages and have been compiled using different methodologies, which mainly depend on the experience of the cartographer, review process and availability of appropriate source data (e.g. satellite imagery), as well on the varying objectives that motivated every single study. For these reasons, merging all existing inventories in a fully coherent way is presently not possible.

The increasing emergence of open-access satellite imagery (e.g. optical and radar imagery) facilitates the development of new inventories and/or the update of existing ones. The growing availability of remotely sensed data (e.g. Sentinel-1 SAR images) also makes the systematic detection of rock glacier surface motion, and consequently, the integration of kinematic information in standardized rock glacier inventories potentially feasible.

Previous glacier-oriented initiatives, such as the World Glacier Inventory (WGI) or Global Land Ice Measurements from Space (GLIMS), tried to include rock glaciers but have not succeeded in being systematic and homogeneous. It has been particularly difficult to properly include rock glaciers due to the complexity of detecting them automatically by remote sensing (GLIMS methodology). Additionally, relict rock glaciers have been systematically excluded from these inventories, as they are not part of the current cryosphere.

The development of widely accepted standard guidelines for inventorying rock glaciers, including kinematic information, is becoming an urgent task to be fulfilled by the scientific community of concern. It will serve the compilation of new regional inventories and the adaptation of existing ones, hence leading – as a final objective – to the merging of all inventories in a more homogeneous open-access worldwide database. Standard guidelines should also help to avoid, or at least minimize, potential discrepancies between rock glacier datasets originally compiled for different purposes.

Inventorying rock glaciers is a manual (visual) procedure, which cannot be automatized yet and requires geomorphological expertise by the operators. Identifying and characterizing rock glaciers has often led to various and sometimes controversial mapping outcomes due to the complexity of morphologies (e.g. multiple generations, coalescent landforms, heterogeneous dynamics, interaction with glaciers) and the diversity of environments in which rock glaciers have developed. In order to overcome endless discussions, subjectivity must be acknowledged as part of the rock glacier mapping process. Establishing standard guidelines aims at minimizing this inborn degree of variability. It could even be envisaged that an increasing number of manually identified rock glaciers based on a widely accepted standard would support the development of automatic techniques (e.g. deep learning) as a complementary tool to compile inventories.

2. Inventorying rock glaciers

Rock glaciers are characteristic landforms associated with mountain periglacial landscapes. They are prevalent periglacial items of the Earth's geomorphological heritage, whose identification (detection and delineation) can be nevertheless challenging. Motivations for producing rock glacier inventories and approaches to creating them are various.

2a) Motivations for producing a rock glacier inventory

Basic and applied scientific motivations for producing an exhaustive rock glacier inventory at various scales can be summarized as follows:

- **Geomorphological mapping**: rock glaciers are identified and mapped as functional[1] or inherited[2] (relict) landforms of the geomorphological landscape: they are part of the mountain sediment cascade and as such contribute to control the pace of periglacial mountain landscape evolution. Enhancing the value of geomorphological heritage could also be the main motivation to compile a rock glacier inventory.

- **Proxy for permafrost occurrence**: functional rock glaciers are geomorphological indicators of the occurrence of permafrost. Even if it is accepted that functional rock glaciers may export perennially frozen ground outside of a permafrost prone area, they can be used to approximate the regional lower limit of the mountain permafrost belt and to validate spatial models of permafrost extent. Conversely, inherited (relict) rock glaciers are discriminative landforms of currently permafrost-free areas. Although functional rock glaciers attest to the occurrence of permafrost at depth, it must be considered that given the ongoing climate change, these features may gradually no longer reflect surface conditions favorable to permafrost occurrence.

- **Paleo-permafrost studies**: inherited (relict) rock glaciers can be used as proxies for various paleo-permafrost extents. Discrimination between inherited and functional state is often difficult, making the integration of inherited landforms in a global inventory indispensable.

- **Climate relevant variable**: rock glacier movement is particularly sensitive to changing permafrost temperature. Updating and comparing inventories of functional rock glaciers, which include temporally well-constrained kinematic information, can be used to assess the impact of ongoing climate change on the mountain periglacial environment over regions.

- **Hydrological significance**: functional rock glaciers are, by nature, ice (and water) storage features, which may play a prominent role in the hydrological regime of mountain catchments, especially in dry areas. Rock glacier inventories have been developed and/or used in particular for estimating their regional water-equivalent significance. In addition to being ice storage features, rock glaciers can affect water transit time and water chemistry in a catchment.

- **Geohazards**: functional rock glaciers may be the source of direct or indirect geohazards (e.g. destabilization, conveyance of loose debris into a gully) that may pose a risk to human activities and/or facilities (e.g. transport infrastructures, buildings, livelihoods). Rock glacier inventories and related kinematic data can be used to locate and assess some potential geohazards at local to regional scales. It must be noted that in the context of infrastructure construction/maintenance, the information from rock glacier inventories will not be sufficient to entirely understand the issues related to permafrost degradation. However, it may provide clues for assessing permafrost's occurrence (or absence) in the study area.

It is very important to note that the original motivation for producing a rock glacier inventory may differ from that of a subsequent third-party user. Therefore, standardized guidelines should help to avoid, or at least minimize, potential discrepancies.

2b) Inventory compilation

Two main approaches have been commonly used for compiling a rock glacier inventory:

- **Geomorphological approach**: <u>rock glaciers</u> are recognized by systematic visual inspection of the landscape (image interpretation) and DEM-derived products. For this purpose, surface texture and morphometric analysis could be used. LiDAR DEM surveys, when available, also facilitate the

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[1] In a geomorphological slope sequence, a functional rock glacier is a landform that currently conveys sediments from a rooting zone towards its front.

[2] In a geomorphological slope sequence, an inherited rock glacier is a landform that today no longer conveys sediments from a rooting zone towards its front, due to permafrost exhaustion.

identification of rock glaciers in forested areas. This is the classical approach, locally complemented by field visits. It allows the production of exhaustive inventories of presumed moving and non-moving landforms, whose discrimination (activity classes) is primarily based on geomorphological characteristics. Development in deep-learning techniques could also complement this approach.

- **Kinematic approach**: in a first stage, moving areas are detected and characterized using multi-temporal remotely sensed data (e.g. SAR-derived products, airborne LiDAR, high-resolution optical satellite and aerial images). In a second stage, the moving areas are compared with optical images to exclude areas where the movement is not due to permafrost creep and focus exclusively on rock glaciers (geomorphological assessment). If the study does not include a systematic visual inspection of the landscape, it is limited to the non-exhaustive identification and characterization of moving rock glaciers, whereas non-moving rock glaciers are missed. The approach also allows for identifying other types of moving landforms (e.g. landslides), that may be spatially connected to rock glaciers but should not be included in the inventory.

Although the two approaches are complementary and can be used in an integrated and iterative process, a rock glacier inventory is essentially a geomorphological inventory.

3. Rock glaciers

The following section defines rock glaciers in the perspective of generating standardized inventories and details various significant aspects related to their characterization.

3a) Technical definition of rock glaciers

The following definition of rock glacier is provided for operational (technical) purpose. It is exclusively addressed to frame the process of rock glacier inventorying and lies beyond any outstanding controversy (e.g. about rock glacier genesis and ice origin). It relies on the most common geomorphological evidence allowing the identification of rock glaciers in the landscape:

Rock glaciers are debris landforms generated by the former or current creep of frozen ground (permafrost)[3], detectable in the landscape with the following morphologies: front, lateral margins and optionally ridge-and-furrow surface topography. In a geomorphological slope sequence, rock glaciers are landforms conveying (or having conveyed) debris from an upslope area (rooting zone) towards their front (**3**). The debris grain size is not specified.

Geomorphological criteria (*cf.* Sections 5a, 5b):

- **Front** (mandatory criterion): discernable talus delimiting the terminus of a (formerly) moving part of the rock glacier and usually displaying a convex morphology perpendicular to the principal (former) flow direction. For a rock glacier developing on a steep slope, the front may be difficult to recognize.
- **Lateral margins** (mandatory criterion): discernible lateral continuation of the front. Lateral margins may be absent, particularly in the upper part of the landform.
- **Ridge-and-furrow topography** (optional criterion): pronounced convex-downslope or longitudinal-surface undulations associated with current or former compressive flow.

[3] Rock glacier (or permafrost) creep has to be understood here as a generic term referring to the variable combination of both internal deformation within the crystalline structure of the frozen ground (creep stricto sensu) and shearing in one or several horizons at depth.

In coherence with global glacier inventories standards, and given the technical limitations (that may evolve in the future), it is recommended that the minimum rock glacier size to be included into a global compilation should be 0.01 km^2. Nevertheless, inventories at higher resolution are encouraged.

Discriminating rock glaciers from other landforms

Without knowing the environmental context and/or limited mapping experience, some landforms may express rock glacier-like morphology (e.g. solifluction lobe, earth flow, moraine and lava flow) (**97**, **98**), leading to inconsistent mapping.

Permafrost creeping areas that can be detected as moving in a kinematic approach but do not express the morphology typical of a rock glacier (as it is for many push-moraines and frozen debris lobes) are also excluded from this definition. Therefore, a rock glacier inventory is an inventory of rock glaciers only, but is neither an inventory of any ground ice occurrences, nor any other mountain permafrost-related landforms.

As landforms resulting from permafrost creep processes, rock glaciers should also not be confused with debris-covered glaciers, which are glaciers partially or completely covered by supraglacial debris. Typically, there are two main examples of misrecognition: either the entire debris-covered glacier is confused with a rock glacier (or the reverse), or the rock glacier is located in front of a glacier in a “debris-covered glacier to rock glacier” sequence (*cf*. Section 3.c, glacier-connected). In the latter case, it is difficult to be recognized/delineated unambiguously in the absence of direct observations at depth. An arbitrary separation between rock glacier and debris-covered glacier or between the debris-covered glacier and the rock glacier section in a continuous sequence can be based on morphological and textural criteria. A “checklist table” will be provided in the *practical inventorying guidelines* helping the distinction.

3b) Rock glacier morphological system and units

Rock glaciers with a complex morphology (e.g. multiple generations, multiple lobes, coalescent lobes and heterogeneous dynamics) are common and difficult to characterize unequivocally. The scale of discrimination depends on the study motivations, the operator, the available data, and the landform’s complexity.

To address this issue, the following hierarchical **classification scheme** is adopted.

- **Level 1 – Rock glacier unit**: a single rock glacier landform that can be unambiguously discerned according to the technical definition provided in Section 3a and, in case of a spatial connection, can be differentiated from other (adjacent or overlapping) rock glacier units according to any of the following criteria:

    - Morphological expression and/or land cover suggest a distinct timing of formation (e.g. overlapping lobes).
    - Connection to the upslope unit can be discriminated (*cf*. Section 3c).
    - Activity (or kinematics if available) is clearly different (*cf*. Section 3d).

    Rock glacier units are classified as ***simple*** or ***complex***. A simple rock glacier unit shows homogeneous attributes corresponding to the criteria listed above (**4**). A complex unit shows some spatial variability within these attributes, but does not include sufficient evidence to unambiguously separate units (**8**, **5**, **65**).

- **Level 2 – Rock glacier system**: any landform composed either of a single rock glacier unit or of multiple units that are spatially connected, either in a topo-sequence or through coalescence. A rock glacier system including only one unit is classified as a **mono-unit** (sometimes called single-unit) system (4, 8, 5), else it is a **multi-unit** (sometimes called composite or multiple unit) system (6, 9, 7, 10, 11, 69).

3c) Spatial connection of the rock glacier to the upslope unit

The geomorphological unit located directly upslope of a rock glacier unit or system can hold implications for the characterization of the latter (e.g. internal structure and composition, ice origin, ice content), the designation of attributes (e.g. landform outlining, definition of the rooting zone) as well as the analysis of the kinematic behavior. The focus is set on the spatial (structural) connection because it is generally discernable in optical images. The spatial connection of the rock glacier to an upslope unit does not necessarily mean a dynamic and/or genetic connection. The term "derived" is not used because it implies an interpretation of the origin of both debris and/or ice.

- **Talus-connected**: The rock glacier is part of a downslope sequence, including headwall – talus slope – rock glacier (sometimes the talus slope is almost lacking) (12, 70). The rock glacier unit is subjacent and connected to a talus slope unit, which is dominantly fed by rock fall activity, but may also be fed by surface runoff, debris flow and/or avalanche events from the headwall unit. Sediment transfer across the talus slope unit can be operated by a number of interrelated processes. The area connecting the talus slope to the rock glacier is often characterized by a concave morphology, where, considering the landform history, the episodic to frequent development of long-lasting avalanche cones, snow/ice patches or even small glaciers (relative to the rock glacier size) may occur. In the latter case, although the episodic disappearance of the glacier implies a lack of efficient sedimentary connection with the relevant upslope unit, the rock glacier is still classified as talus-connected (14, 70, 13).

  Protalus ramparts are included in this category as "embryonic" rock glaciers if they are related to permafrost creep (66). They should not be confused with protalus-looking landforms related to (former or present) snow accumulation (i.e. pronival ramparts).

- **Debris-mantled slope-connected**: The rock glacier lacks any (significant) headwall. The debris is dominantly produced by in-situ bedrock weathering (debris mantle) and gradually put into motion by shallow, surficial mass movement processes (e.g. solifluction) before developing into a rock glacier feature (16, 72, 17).

- **Landslide-connected**: The rock glacier is located in direct downslope spatial connection to a landslide (i.e. rock or debris slide) (19) or lies on a large and active deep-seated gravitational slope deformation. In these situations, where the talus slope unit is usually lacking, identifying the rock glacier can be ambiguous.

- **Glacier-connected**: There is a continuity from a glacier, debris-covered glacier or ice patch to a rock glacier feature. In the case of glacier and ice patch, a debris-covered glacier transitional area always occurs between the debris-free ice and the rock glacier feature (22, 23, 73, 102, 103). The delimitation between the glacier or the ice patch section and the rock glacier section is not feasible without further direct or geophysical prospection. Embedded glacier ice within the rock glacier is likely to occur. Geomorphological indices evidencing the presence of a debris-covered glacier upslope of the apparent rock glacier feature may be observed (e.g. crevasses, thermokarst, meltwater channels).

- **Glacier forefield-connected:** The rock glacier develops within or from a (formerly) glaciated area. Interaction between the glacier or ice patch and the rock glacier feature is prevalent, but essentially restricted to phases of glacier advance (e.g. Little Ice Age). Embedded glacier ice within the rock glacier is possible. When receding, which is a common pattern nowadays, the glacier has disconnected from the rock glacier or may have disappeared entirely. This category includes tillderived rock glaciers, which correspond to the classical debris rock glacier definition and some push-moraines (glacitectonized frozen sediments) (**24**, **25**, **27**, **26**).

For practical issues, two (unusual) other categories are included:

- **Poly-connected:** two or more upslope connections (e.g. talus- and glacier-connected). The use of poly-connected should be restricted to cases where there is no large dominance of one type of upslope connection.
- **Other**: Other types of geomorphological sequence related to a rock glacier landform.

An attribute defining whether the rock glacier is currently connected to the upslope unit or not must be added (**13**, **14**).

3d) Rock glacier activity

Historical background

The activity of rock glaciers has been traditionally and conceptually categorized regarding the presumed flow behavior and, in relation to this, the ice occurrence. Primarily based on the observation of geomorphological (e.g. front slope angle) and vegetation-related indicators, which differ locally and regionally due to lithological and climatic settings, rock glaciers have been most commonly classified into the following categories of activity:

- Intact:
  - Active: rock glaciers bearing excessive ice that are in effective motion.
  - Inactive: rock glaciers that remain (almost) motionless yet still contain ice.
- Relict: rock glaciers that have stopped moving, often several hundreds to thousands of years ago, due to the loss of (almost) all their ice.

Historically, regional inventories of rock glaciers have been based on a *geomorphological approach*. In-situ or remotely sensed kinematic data, as well as field visualizations, have remained occasional. Activity attribution based on geomorphological indicators is highly subjective, depending on the operators' skills. As a result of the continuous development of remote sensing techniques (e.g. photogrammetry, satellite-borne InSAR), kinematic information on surface motion can henceforth be obtained for a large majority of rock glaciers. This additional information could allow the refinement of rock glacier activity categories.

Whereas the classical categorization may have considered the activity of rock glaciers as almost constant over time at the scale of decades to centuries, observations of rock glacier kinematic behavior, in particular in the European Alps, show that an acceleration by a factor of 2 to 10 of the surface velocities between the 1980s and 2010s. This acceleration has been a common feature, probably in response to increased permafrost temperature resulting from warmer air temperature. Some single features manifest singular behaviors (e.g. reactivation, rapid acceleration, destabilization or decrease in velocity). In cold permafrost regions (e.g. Arctic or high Andes), rock glaciers, which are almost stationary or moving only very slowly, may accelerate in response to warming. These observations reveal the need of refining and/or redefine the categorization of rock glacier activity.

Updated categorization of activity

The following conceptual categorization of rock glacier activity refers exclusively to **the efficiency of sediment conveyance (expressed by the surface movement) at the time of observation**[4]**. It should not be used to infer any ground ice content**. The categories are still based on geomorphological indicators, which have to be adapted regionally or contextually. If areal or point kinematic data are available, they should be integrated as a supplementary attribute and must be considered in order to assign the category of activity, which is defined as:

- **Active:** rock glacier moving downslope over most of its surface.
  - If no kinematic data is available: an active rock glacier shows geomorphological evidence of downslope movement such as a steep front (steeper than the angle of repose) and possibly lateral margins with freshly exposed material on top (**28**, **30**).
  - If adequate kinematic data is available: an active rock glacier shows coherent downslope movement over most of its surface. As an indication, the displacement rate can range from a decimeter to several meters per year (**71**).
- **Transitional:** rock glacier with slow movement only detectable by measurements or movement restricted to areas of non-dominant extent. According to the topographic and/or climatic context, transitional rock glaciers can either evolve towards a relict (degraded) or an active state.
  - If no kinematic data is available: a transitional rock glacier has less distinct geomorphological evidence of current downslope movement than active rock glaciers in the same regional context (**31**, **33**, **32**).
  - If adequate kinematic data is available: a transitional rock glacier shows little to no downslope movement over most of its surface. As an indication, the average displacement rate is less than a decimeter per year in an annual mean over most of the rock glacier. The downslope movement must not be confused with subsidence.
- **Relict:** rock glacier with neither geomorphological evidence nor detection of current movement associated with permafrost creep.
  - If no kinematic data is available: a relict rock glacier shows no geomorphological evidence of recent movement. The relict state could be indicated by subdued topography, smoothed lateral and frontal slopes/margins, and by the development of vegetation and soil cover (e.g. lichen, grass, forest) (**34**, **35**, **67**). In arid regions, vegetation may nevertheless be lacking on relict rock glaciers due to unfavorable environmental conditions (**92**). Relict rock glaciers are generally found at lower elevations than the active ones.
  - If adequate kinematic data is available: a relict rock glacier shows no detectable downslope movement over most of its surface, and the geomorphological characteristics are as described above.

Any activity assessment must be defined (i.e. based on geomorphological identifiers only or supported by kinematic data) and dated.

The principles about using kinematic data in a standardized inventory are developed in a separate document (Kinematics as an optional attribute in standardized rock glacier inventories).

[4] This categorization is tailored to work with rock glacier inventories and compliant with the technical definition of rock glaciers (*cf*. Section 3a).

3e) Rock glacier destabilization

The motion rate of some rock glaciers may be characterized by a drastic acceleration that can lead the landform, or a part of it, to behave abnormally fast (i.e. no longer following the regional trend) for a minimum of several years. The term ***destabilization*** has been progressively used since the 2000s to refer to rock glaciers with obvious signals of abnormally fast displacements, often associated with by the opening of large transversal cracks and/or scarps (**36**, **37**, **29**, **84**).

Destabilized rock glaciers generally display an initial acceleration phase, followed by a high-velocity phase and finally a deceleration phase. Destabilized morphology can be preserved for a long time after the high-velocity phase has ended. Whereas this surface expression can be documented in an inventory as evidence of a current or past destabilization phase, an actual state of destabilization can only rely on kinematic data. Multiannual time series showing displacement rates of several meters per year and departing from the regional trend (if known) can attest to the current destabilization phase. Rock glaciers experiencing an ongoing destabilization phase constitute a sub-category of active rock glaciers and must be inventoried as such.

It is worth noting that destabilization is not used here in a geotechnical, slope stability context, but solely to qualify the above described temporal variability in rock glacier deformation.

3f) Rock glacier outline

Technically, defining a rock glacier as a landform implies setting a distinct outline, and for various practical issues (e.g. area calculation) this outline has to be a polygon. Mapping an outline retains some degree of subjectivity, i.e. it is dependent on the operator. It has been shown that the operators' mapping styles may highly differ and significantly impact the exploitation of any rock glacier inventory data. For example, a rock glacier specific area directly affects a first-order assessment of inherent water content, or maximum and minimum rock glacier elevations directly influence altitudinal thresholds derived for modelling past or present occurrence of mountain permafrost. Therefore, "outlining rules" must be clearly defined in order to minimize subjectivity as much as possible. Nevertheless, this uncertainty should be specified and highlighted in the database if boundaries are uncertain.

In order to address all inventorying motivations (*cf.* Section 2a), two ways of delineating rock glacier boundaries are recommended to be included as standards: the ***extended*** and the ***restricted geomorphological footprints***. If only one footprint is chosen, it must be clearly specified.

- **Extended geomorphological footprint**: the outline embeds the entire rock glacier up to the rooting zone and includes the external parts (front and lateral margins).
- **Restricted geomorphological footprint**: the outline embeds the entire rock glacier up to the rooting zone and excludes the external parts (front and lateral margins).

The delineation of the upper part of the rock glacier footprint and the definition of the rooting zone depends on the spatial connection of the rock glacier to the upslope unit (*cf.* Section 3c). The details of this procedure are described in the practical inventorying concepts (*cf.* RGI_PC Section 5d).

4. Inventorying strategy

The development of rock glacier inventories is driven by numerous motivations (*cf.* Section 2a) and is thus highly dependent on both the aim and experience of the related operator. To minimize this subjectivity, a strategy to standardize the rock glacier inventories and make them comparable is summarized hereafter.

The inventorying strategy follows four consecutive steps, which are based on a combination of both geomorphological and kinematic approaches (*cf.* Section 2b) and may be iteratively refined depending on (newly) available data:

- *Detecting rock glaciers*: recognition of relevant landforms (system/unit) to be inventoried according to the technical definition of rock glaciers (*cf.* Section 3a).
- *Locating rock glaciers*: attribution of a unique point identifier defining (ID attribution and georeferencing) any rock glacier system and unit.
- *Characterizing rock glaciers*: attribution of essential characteristics (attributes), including a kinematic attribute if adequate data is available.
- *Delineating rock glaciers*: outlining rock glacier units.

The first two steps (detecting and locating rock glaciers) are mandatory. For most identified rock glaciers systems and units, they should be definitive. The two other steps (characterizing and delineating rock glaciers) are conversely assessments of variables, which may depend on the availability of adequate source data and/or may change over time alongside the rock glacier evolution.

Finally, a *consolidation step* is recommended for any set of inventoried rock glaciers or updated variables. The consolidation is basically the systematic control and validation of the data by at least one, preferably several further operators.

Practical concepts for inventorying rock glaciers are detailed in a dedicated document (RGI_PC), as well as the concepts for integrating a kinematic attribute (RGI_KA).

Acronyms

DEM	Digital Elevation Model
ESA CCI+	European Space Agency, Climate Change Initiative (link)
GLIMS	Global Land Ice Measurements from Space (link)
InSAR	Interferometric Synthetic Aperture Radar
IPA	International Permafrost Association (link)
LiDAR	Light Detection And Ranging
RGI-PC	Towards standard guidelines for inventorying rock glaciers: practical concepts (link)
SAR	Synthetic Aperture Radar
WGI	World Glacier Inventory (link)