Rock glacier inventories and kinematics (RGIK)

Guidelines for inventorying rock glaciers

Baseline and practical concepts

(Version 1.0)

www.rgik.org

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Authors and contributions

These guidelines are the outcome of a five-year work carried out by the International Permafrost Association (IPA) Action Group *Rock glacier inventories and kinematics* (RGIK). They are the result of the merging of previous complementary documents, which were prepared in their time with the specific contribution of Chloé Barboux, Aldo Bertone, Xavier Bodin, Francesco Brardinoni, Alessandro Cicoira, Reynald Delaloye, Thomas Echelard, Yan Hu, Nina Jones, Christophe Lambiel, Shelley MacDonell, Line Rouyet, Lucas Ruiz, Nicole Schaffer, Sebastián Vivero and Mishelle Wehbe. These guidelines also incorporate critical input from the participants in the RGIK Workshops I (Evolène, Switzerland on September 23–27, 2019), II (Fribourg, Switzerland on February 11–13, 2020), and III (Puigcerdà, Spain on June 17, 2023), as well as from the RGIK community through online consultations and various approval rounds.

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Cover Image: The Becs-de-Bosson rock glacier system visited during the 2019 RGIK Workshop I in the Western Swiss Alps.

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Content

Preamble

Between 2018 and 2023, the International Permafrost Association (IPA) Action Group on **Rock glacier inventories and kinematics (RGIK)** undertook an unprecedented effort **to develop widely accepted guidelines for inventorying rock glaciers, including kinematic information**. This mission involved three sub-tasks: defining main concepts and principles; establishing practical inventorying guidelines; and developing a technical manual for implementing rock glacier inventories in an open-access database. The present document represents the five-year effort of the RGIK Action Group to consolidate the **baseline and practical concepts** for rock glacier inventories in a globally consistent manner.

Illustrations/Atlas

The main text is supplemented by illustrations that help to better appreciate the rules and concepts described in this document. Numbers in brackets —e.g. [**1**]— are hyperlinks to these illustrations. Suggestions for additional or improved illustrations are always welcome (please write to rockglacier-ipa@unifr.ch).

1. Purpose of the guidelines

Until recently, the compilation of a Rock Glacier Inventory (RoGI) involved a disparate set of methodologies based on the experience of one or more operators (i.e., the inventory team), the availability of relevant source data (e.g., aerial or satellite imagery), and the different review procedures and objectives that motivated each individual study. As a result, a fully coherent integration of all these uncoordinated RoGIs has not been possible to date.

The increasing availability of open-access satellite imagery (e.g., optical and radar imagery) facilitates the development of new inventories and/or the updating of existing ones. The growing availability of remotely sensed data (e.g., Sentinel-1 SAR images) also facilitates the systematic detection of rock glacier surface movement and, consequently, the integration of kinematic information into consistent RoGIs.

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 automatically detection using remote sensing (e.g., GLIMS methodology). Additionally, relict rock glaciers have been systematically excluded from these inventories because they are unlikely to be part of the current cryosphere.

In this context, guidelines have been established for the inventorying of rock glaciers, which includes kinematic information. These guidelines facilitate the creation of new regional inventories and the adaptation of existing ones, ultimately leading to the integration of all inventories into a more uniform, open-access global database. Using common guidelines can help reduce, if not eliminate, discrepancies between rock glacier datasets that were originally compiled for different purposes.

Inventorying rock glaciers is a manual (visual) procedure that cannot yet be fully automated and requires geomorphological expertise by the operator or inventory team. 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. However, by establishing common guidelines, this document serves to minimize this inherent degree of variability. In addition, the increasing number of rock glaciers that are manually classified in accordance with widely accepted criteria and definitions can serve to calibrate automatic approaches (e.g., machine learning) and reinforce the process of manual identification.

2. Inventorying rock glaciers

Rock glaciers are landforms associated with mountain periglacial landscapes. They are prevalent periglacial features of the Earth's geomorphological heritage, although their identification (detection and delineation) can be challenging. Motivations for producing RoGIs and approaches to creating them vary.

2.1. Motivations for producing a RoGI

Basic and applied scientific motivations for producing an exhaustive RoGI 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 RoGI.
- **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. RoGIs 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). RoGIs 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 RoGIs will not be sufficient to entirely understand the issues related to permafrost degradation. However, this information can provide insight into assessing the presence or absence of permafrost within study areas.

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

2.2. Inventory compilation

Two main approaches are commonly used for compiling a RoGI:

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

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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.

the identification of rock glaciers in forested areas. It is possible to complement this remote sensing approach with local field validation. This approach allows the production of exhaustive inventories of presumed moving and non-moving landforms, whose discrimination (activity class) is primarily based on geomorphological characteristics.

- **Kinematic approach**: in a first stage, moving areas (*cf.* Section 6.2.1*)* 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 detect areas where the movement is apparently due to permafrost creep and to 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. Other types of moving landforms (e.g., landslides) that may be spatially connected to rock glaciers but should not be included in the inventory, can also be identified.

Although the two approaches are complementary and can be used in an integrated and iterative process, a RoGI is essentially a geomorphological inventory. Therefore, it is suggested to utilize the kinematic approach in addition to the geomorphological approach.

3. Rock glaciers

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

3.1. Technical definition of rock glaciers

The following definition of a rock glacier is provided for operational purposes. 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 enabling 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 (Fig. 1). The size of clasts composing rock glaciers is not specified.

Geomorphological criteria (*cf.* Sections 5.1 and 5.2):

- **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 main (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.

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[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 accordance with global glacier inventory 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.

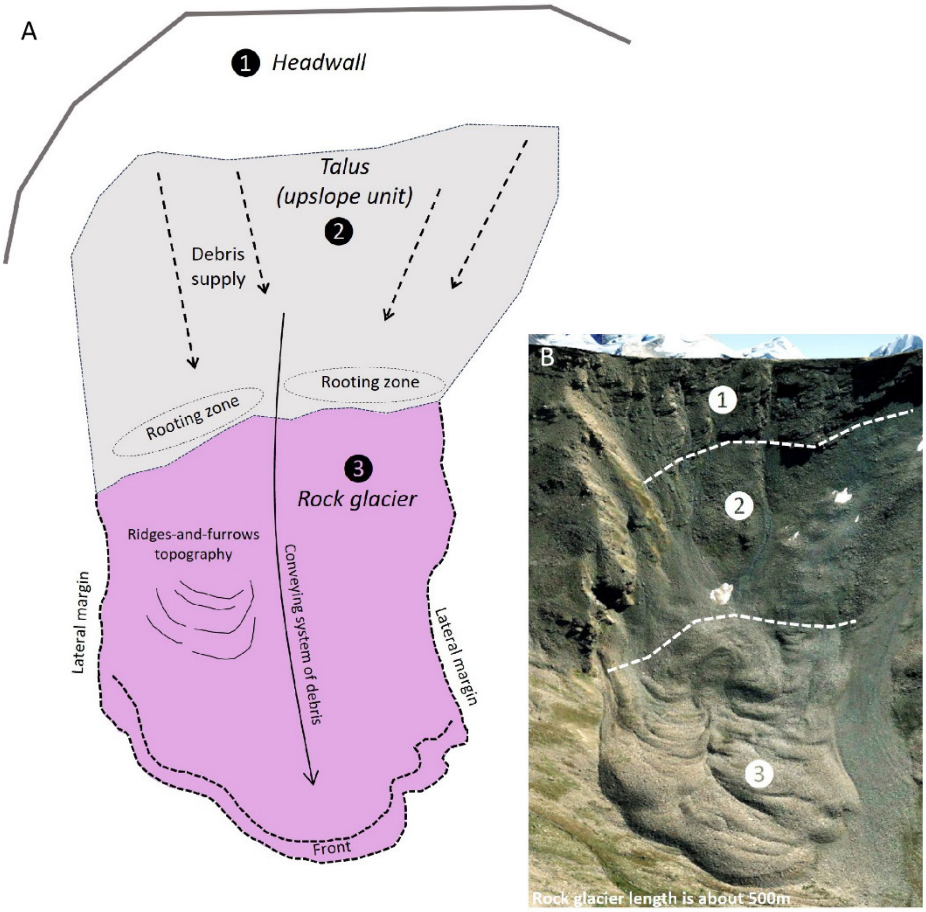

Fig. 1. Anatomy of a rock glacier showing the main geomorphologic features according to the technical definition. A: A rock glacier recognizable in the landscape by a front, lateral margins in continuity with the front, and ridge and furrow topography. The slope sequence of headwall, talus (upslope unit) and rock glacier is indicated. B: Oblique view of the corresponding rock glacier in Vallone di Sort (Italy), 45.5605°N, 7.1589°E, 2500–2800 m a.s.l. [1].

3.2. 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 systematically adopted.

- **Level 1 – Rock glacier unit**: a single rock glacier landform that can be unambiguously identified according to the technical definition provided in Section 3.1 and, in case of 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 3.3);
    - activity (or kinematics if available) is clearly different (*cf*. Section 3.4).

In addition, rock glacier units are classified as **simple** or **complex morphology**. A rock glacier unit of simple morphology shows homogeneous attributes corresponding to the criteria listed above [2]. A rock glacier unit of complex morphology shows some spatial variability within these criteria, but does not include sufficient evidence to unambiguously separate units [3, 4, 5].

- **Level 2 – Rock glacier system**: any landform composed of a single rock glacier unit or multiple units that are spatially connected, either in a downslope sequence or through coalescence. A rock glacier system including only one unit is classified as a **mono-unit** (sometimes called single-unit) system [2, 3, 4], else it is a **multi-unit** (sometimes called composite or multiple unit) system [6, 7, 8, 9, 10, 11].

3.3. Spatial connection of the rock glacier to the upslope unit

The geomorphological unit directly located upslope of a rock glacier unit or system can have implications for the characterization of the latter (e.g., internal structure, composition, ice origin and ice content), the assignment 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 imply a dynamic and/or genetic connection. The term “derived” is not used in this context 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 [12, 13]. In some cases, the talus slope is almost absent [14]. 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 several 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/glacierets (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 [13, 15, 16].

  Protalus ramparts are included in this category as “embryonic” rock glaciers if they are related to permafrost creep [17]. 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 a (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 [18, 19, 20].

- **Landslide-connected**: the rock glacier is situated in direct downslope connection of a landslide [21] or lies on a large and active deep-seated gravitational slope deformation. In these situations, the talus slope unit is usually absent.

- **Glacier-connected**: there is a continuity from a glacier, debris-covered glacier, or ice patch to a rock glacier feature. In the case of a glacier and ice patch, a debris-covered glacier transitional area always occurs between the debris-free ice and the rock glacier feature [22, 23, 24, 25, 26]. 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 features evidencing the presence of a debris-covered glacier upslope of the apparent rock glacier 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 today, the glacier has disconnected from the rock glacier or may have disappeared entirely. This category includes till-derived rock glaciers, which correspond to the classical debris rock glacier definition and to some push-moraines (glacitectonized frozen sediments) [27, 28, 29, 30].

For practical purposes, two other (unusual) categories are included.

- **Poly-connected**: two or more upslope connections (e.g., talus and glacier). The use of poly-connected should be restricted to cases where there is no obvious dominance of one connection type [31].
- **Other**: other types of geomorphological sequencing 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 [15, 16]. This attribute is noted only on **talus-connected** rock glaciers and allows rock glaciers that are currently connected to their upslope unit (i.e., efficient sediment connectivity) to be distinguished from those that have been disconnected from their original source.

3.4. Rock glacier activity

3.4.1. Historical background

The activity of rock glaciers has been traditionally and conceptually categorized based on the presumed flow behavior and, in relation to this, ice occurrence. Based primarily 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 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 campaigns, have been uncommon. Activity attribution based on geomorphological indicators is highly subjective, depending on the operator or inventory team skills. Due to the ongoing developments in remote sensing techniques, such as photogrammetry and Synthetic Aperture Radar Interferometry (InSAR), kinematic information on surface motion can henceforth be obtained for a large majority of rock glaciers. This additional information can also aid in refining the categorization of rock glacier activity.

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 velocity, particularly in the European Alps, show that an acceleration of surface velocities by a factor of 2 to 10 has occurred between the 1980s and the 2020s. This acceleration has been a common trend, in response to increased permafrost temperature resulting from warmer air temperature, even if 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 very slowly, may accelerate in response to warming. These observations further support the need to refine and/or redefine the categorization of rock glacier activity.

3.4.2. 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 must be adapted regionally. If areal or point kinematic data are available, they should be integrated as a supplementary kinematic attribute (cf. Section 6.2.3) 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 [32, 33].
  - 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 [34].
- **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 [35, 36, 37].
  - 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) [38, 39, 40]. In arid regions, vegetation may nevertheless be lacking on relict rock glaciers due to unfavorable environmental conditions [41]. Relict rock glaciers are generally found at lower elevations than 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 to use kinematic data in a RoGI are developed in Chapter 6.

3.5. 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

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[4] This categorization is tailored to work with RoGIs and compliant with the technical definition of rock glaciers (*cf*. Section 3.1).

minimum of several years. The term ***destabilization*** has been progressively used since the 2000s to refer to rock glaciers with obvious signals of abnormally large displacements, often associated with by the opening of large transversal cracks and/or scarps [42, 43, 44, 45].

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, defining rock glacier destabilization can only be based 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. 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.

3.6. 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 or inventory team. It has been shown that the mapping styles may significantly vary between operators, which impacts RoGI exploitation. 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 to minimize subjectivity as much as possible. Nevertheless, the reliability of the outline should be estimated and documented.

To be able to address all inventorying motivations (*cf.* Section 2.1), two ways of delineating rock glacier boundaries are recommended: 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.* Sections 3.3 and 5.4).

3.7. 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 lobes, earth flows, moraines and lava flows) [46, 47], leading to inconsistent mapping.

Permafrost creeping areas that are detected to be moving using a kinematic approach, but do not express a typical rock glacier morphology (e.g., push-moraines and frozen debris lobes) are also excluded from this definition. Therefore, a RoGI includes only landforms that conform to the technical definition of rock glaciers (*cf*. Section 3.1) and exclude other ice-bearing landforms associated with permafrost and periglacial processes.

Since rock glaciers are landforms that are the result of permafrost creep, they should 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 3.3, glacier-connected). In the latter case, it is difficult to be recognized/delineated unambiguously in the absence of direct observations at depth. The arbitrary separation between rock glacier and debris-covered glacier in a continuous sequence can be based on morphological and textural criteria (*cf.* Section 5.4, Table 3).

4. Inventorying strategy

The development of RoGIs is driven by numerous motivations (*cf.* Section 2.1) and is thus highly dependent on both the aim and experience of the related operator or inventory team. To minimize this subjectivity, a strategy to systematize RoGIs 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 2.2) and may be iteratively refined depending on (newly) available data (Fig. 2).

- **Detection**: recognition of relevant landforms (unit/system) to be inventoried according to the technical definition of rock glaciers (*cf.* Sections 3.1 and 5.1).
- **Location**: attribution of a unique point identifier defining (ID attribution and georeferencing) any rock glacier system and unit (*cf.* Sections 3.2 and 5.2)
- **Characterization**: attribution of essential characteristics (attributes), including a kinematic attribute if adequate data is available (*cf.* Sections 3.3, 3.4 and 5.3).
- **Delineation**: outlining rock glacier units/systems (*cf.* Sections 3.6 and 5.4).

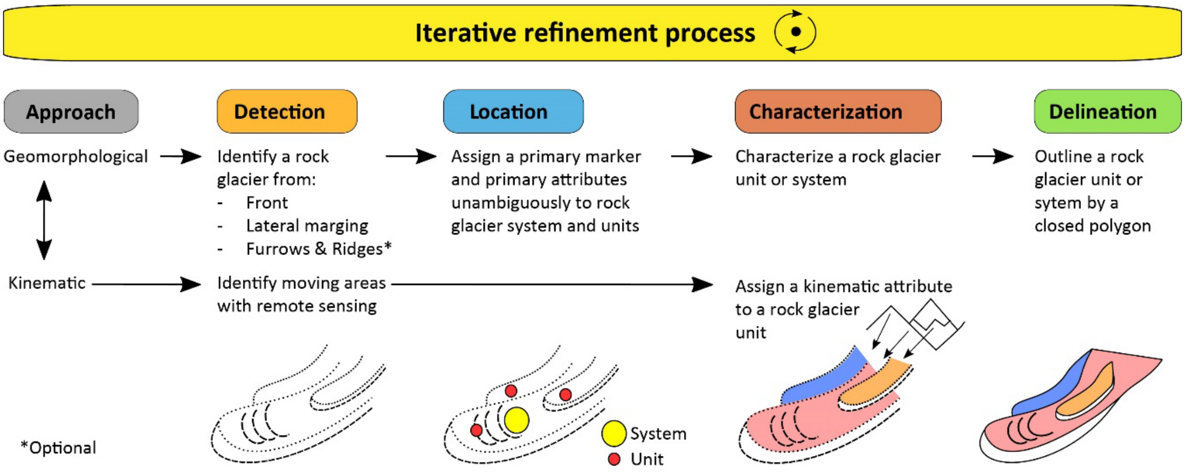

Fig. 2. An overview of the recommended strategy involved in compiling a RoGI using a conceptual workflow [48].

The initial two steps (detection and location) are mandatory. For most identified rock glaciers systems and units, they should be definitive. The subsequent two steps (characterization and delineation) consist in the optional assessment of morpho-kinematic variables, which may depend on the availability of adequate source data and/or may change over time due to the evolution on the rock glaciers.

A **consolidation step** is recommended for any set of inventoried rock glaciers or updated variables. This step requires the systematic control and validation of the data by at least one, preferably several further operators (i.e., inventory team). Adopting a consensus-based approach for inventorying rock glaciers as exemplified in [49] is highly recommended.

5. Practical concepts

The following chapter presents practical concepts that build upon Chapter 3 and follows the inventory strategy structure of Chapter 4. It serves as a fundamental framework for implementing consistent RoGIs on a global scale.

5.1. Detecting rock glaciers

Detecting rock glaciers consists **primarily of recognizing these landforms** according to the technical definition proposed in Section 3.1 and the system/units classification presented in Section 3.2. This should primarily be performed on the basis of optical imagery as well as DEM-derived products, but machine learning techniques and kinematic data (e.g., InSAR) can be used as complementary approaches.

The geomorphological criteria for identifying a rock glacier unit are based on the technical definition from Section 3.1 and described hereafter. They focus on details that will have implications for the inventorying process at later stages (e.g., outlining rules). As part of the workflow adopted to produce RoGIs, knowledge about rock glacier geomorphology is gathered and characteristics such as systems, units, spatial connections, activity, outlining is considered.

Front (mandatory criterion):

The front is the steep terminal part of any rock glacier unit. When the latter is in an active or transitional kinematic state, the rock glacier front is expected to be in motion down to a depth of about 15–30 m (permafrost creep). The uppermost moving frontal section is thus usually subject to reworking processes (e.g., crumbling), exposing "fresh" material at its surface. In most cases, the mobilized debris is deposited toward the bottom of the front and progressively overridden by the advancing rock glacier itself [50].

The front of active and relict rock glaciers[5] can exhibit a variety of longitudinal profiles (Fig. 3).

- **Talus**: the debris mobilized from the uppermost steeper section (>35–40° for active rock glaciers) builds up a talus accumulation of reduced extension at the foot of the rock glacier front. A talus-like front is delimited upslope by a front edge, which is quite sharp for active rock glaciers [52], but rounded for relict landforms.
- **Exaggerated talus**: if the rock glacier terminates in steep terrain, the reworking processes may create a frontal talus that is significantly greater than the thickness of the moving section of the rock glacier[6] [53, 54].
- **Bulgy**: a less common but distinct morphology characterized by a rounded and sometimes complex frontal topography, even for active rock glaciers [55].
- **Truncated**: the front position is constrained by the topography (e.g., connection to steep torrential gully or overriding of rock cliff) and stays almost invariant over time. The front edge is usually sharp, and the front profile develops as an exaggerated talus [56, 57].

In the three first typologies, the front line of the rock glacier unit generally draws a curved downward, convex (*lobate*) morphology perpendicular to the principal rock glacier flow direction (Fig. 3A–C). In the truncated case, the front line has a non-lobate morphology (Fig. 3D).

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[5] In the case of transitional rock glaciers, they may exhibit longitudinal profiles that lie between active and relict landforms and are therefore not explicitly described in the following frontal typologies.

[6] An arbitrary value is given in Section 5.4.1 to standardise the process of outlining exaggerated rock glacier fronts.

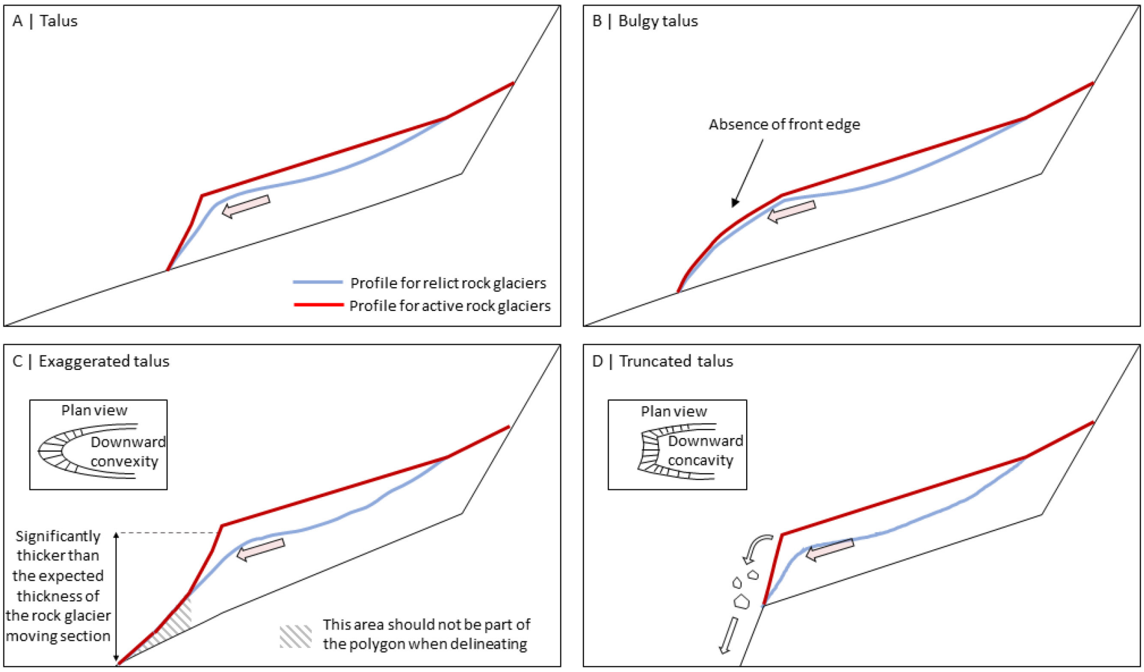

Fig. 3. Common morphology(ies) of the fronts of both active and relict rock glaciers [51].

Lateral margins (mandatory criterion):

Lateral margins are the continuation of the front on the sides of the rock glacier. Three different types of margins typically occur: talus-margins, levees and shear-margins, or a combination of these [58]. Well-developed lateral margins may not always occur, particularly in the upper part of the landform.

- **Talus-margin** designates a morphology similar to a talus-like front, which can even form an exaggerated talus and, in some uncommon cases, be truncated.
- **Levee** is a former talus-margin that has ceased growing/building up, due to the lowering of the rock glacier surface. It could sometimes be confused with glacier lateral moraines, especially in the case of relict rock glaciers, and disentangling the two is not always possible.
- **Shear-margin** is a shallow and elongated furrow that develops along the moving part of the rock glacier in association with shearing processes. It develops mostly at the inner bottom side of the levees and in the uppermost part of rock glaciers.

Ridges and furrows (optional criterion):

Ridges and furrows are pronounced, convex transverse or longitudinal surface undulations associated with the current or former cohesive flow of the rock glacier. Transversal features are consecutive to compression, whereas longitudinal features reflect either flow convergence, or shearing, and deformation occurring between areas moving at different rates [59]. These linear features should not be confused with transversal cracks and scarps [42, 43], which display a downward concavity associated with extensive flow and a high longitudinal velocity gradient usually associated with destabilization (*cf.* Section 3.5).

5.2. Locating rock glaciers

Any rock glacier unit and system (*cf.* Section 3.2) must be identified by a **Primary Marker** (PM) at a point. The PM is a mandatory requirement in any RoGI. Any other characteristics (attributes) related to a rock glacier unit/system are subsequently linked to the PM.

The **primary attributes** of a **PM** enable the user to:

- locate the rock glacier unit/system in a georeferenced coordinate system;
- discriminate each rock glacier unit/system from neighboring ones; and
- associate a rock glacier system to its constituting unit(s) and vice-versa.

The positioning of the PM on the rock glacier unit/system should avoid, as far as possible, any temporal variation and updating. It must not refer to anything else than the location of the rock glacier unit/system and its unambiguous discrimination from neighboring ones. The positioning does not require following any precise rule except that the point must be located somewhere in the lower half of the rock glacier unit/system. It should be arbitrarily placed upslope of, yet not far from, the rock glacier front and within the identified rock glacier unit/system extent.

Each PM is named by a unique code (primary ID) according to its hierarchical identification as a unit (RGU) or a system (RGS), followed by its WGS84 coordinates in decimal degrees with four digits. The primary ID code will necessarily be 18 characters. For example, a rock glacier unit located at 46.9435°N, 12.3693°E (decimal degrees) will be coded RGU469435N0123693E [60]. Note that every RGU must only be associated with one single RGS.

5.3. Characterizing rock glaciers

Various attributes (e.g., connection to upslope unit, activity) can be assigned to any rock glacier unit defined by a PM. Some attributes can also be allocated to rock glacier systems by combining the characteristics of their composing units.

The following tables encompass the main attributes of rock glacier units (Table 1) and systems (Table 2) that should be included in an inventory. Apart from the mandatory primary attributes, all other attributes are optional but recommended. The value "n.a." (not available) is used for any attribute that has not been assessed.

Table 1. Main attributes - Rock Glacier Unit (RGU) [61].

Attribute	**Values / Units**	**Description**
Primary (mandatory)		
Primary ID	RGU + 15 digits	(*cf.* Section 5.2)
Associated RGS	RGS + 15 digits	(*cf.* Section 5.2)
Metadata		Source data, date of mapping, mapper's name, reviewer's name, etc.
Optional		
Rock Glacier Morphology	Simple, Complex, n.a.	(*cf.* Section 3.2)
Rock Glacier Completeness	Yes, No, n.a.	
Upslope Connection	Talus, Debris-mantled slope, Landslide, Glacier, Glacier-forefield, Other, Poly-connected, Uncertain, Unknown, n.a.	(*cf.* Section 3.3)
Upslope Currently	Yes, No, Uncertain, Unknown	(*cf.* Section 3.3)
Activity Assessment	Geomorphological, Kinematic, n.a.	(*cf.* Section 3.4.2)
Kinematic Attribute	Undefined, < cm/yr, cm/yr, cm/yr to dm/yr, dm/yr, dm/yr to m/yr, m/yr, >m/yr	(*cf.* Section 6.2.3)
Activity	Active, Transitional, Relict, Active uncertain, Relict uncertain, Uncertain, n.a.	(*cf.* Section 3.4.2)
Destabilization	Yes (ongoing), Yes (completed), No, n.a.	(*cf.* Section 3.5)
Delineation type	Restricted, Extended, Restricted and extended, Other, n.a.	(*cf.* Sections 3.6 and 5.4)

Table 2. Essential attributes - Rock Glacier System (RGS) [62].

Attribute	Values / Units	Description
Primary (mandatory)		
Primary ID	RGS + 15 digits	(*cf.* Section 5.2)
Associated RGU(s)	RGS + 15 digits	(*cf.* Section 5.2)
Metadata		Source data, geographical and map coordinates, date of mapping, mapper's name, reviewer's name, etc.
Optional		
Rock Glacier Composition	Mono-unit, Multi-unit, n.a.	(*cf.* Section 3.2)
Delineation	Yes, Partial, n.a.	
Delineation Type	Restricted, Extended, Other, Various, n.a.	(*cf.* Sections 3.6 and 5.4)

Rock Glacier Morphology (RGU only)

Describes the complexity of the morphology of a RGU according to Section 3.2.

Rock Glacier Composition (RGS only)

Describes the composition of a RGS according to Section 3.2.

Rock Glacier Completeness (RGU only)

Describes whether the delineable area of a rock glacier unit corresponds to the entire landform (yes) or only to part of it (no), responding to the question: does the rock glacier unit comprise the entire sequence of a rock glacier landform from its rooting zone to its front? Masking is typically caused by the overriding of a rock glacier unit by another [63] or by any other landform that has developed at a later stage (e.g., talus slope, large rock-fall deposit) [64].

Upslope Connection

Describes the connection of the rock glacier unit to its geomorphological upslope unit according to Section 3.3. The value "Uncertain" is allocated when the geomorphological assessment cannot be performed with confidence. The value "Unknown" is used when a rock glacier unit has been overridden by another one and the former connection to the upslope unit cannot be assessed with confidence anymore [65].

Upslope currently

Describes whether or not the rock glacier is currently connected to the upslope unit (noted only for talus-connected) according to Section 3.3.

Activity Assessment

Describes whether the activity assessment is performed based on geomorphological criteria only or with the support of kinematic data. In the latter case, the type and date of the source data must also be provided.

Kinematic Attribute

Describes semi-quantitative (order of magnitude) velocity information according to Section 6.2.3 (Table 4).

Activity

Describes the displacement rate of the rock glacier unit according to Section 3.4. The value "active uncertain" indicates that the rock glacier unit is not in a relict state, but that there is not sufficient data or geomorphological evidence to distinguish between an "active" and "transitional" state. "Relict uncertain" means that the rock glacier unit is not in an active state, but there is not sufficient data or geomorphological evidence to distinguish between a "transitional" and "relict" state. The value "uncertain" is used when the data quality is insufficient to determine any activity status.

Destabilization

Describes the occurrence of a destabilization phase of the rock glacier unit as defined in Section 3.5. The term "ongoing" means that the geomorphological evidence and/or kinematic data signal to an ongoing phase of destabilization, whereas "completed" means that the geomorphological evidence and/or kinematic data confirm a completed destabilization phase. The latter statement could also apply to relict rock glacier units. In both ongoing and completed cases of destabilization, the data used for the assessment must be dated.

Delineation (RGS only)

Describes whether the delineation process of a rock glacier system is completed or not. The value "Yes" means that all constituting units are delineated, whereas "Partial" means that only some are outlined.

Delineation Type

Describes if and how the delineation of a rock glacier unit or system has been performed (*cf.* Sections 3.6 and 5.4). If delineation has been performed, the type and date of the source data must also be provided.

"Extended and restricted" means that both outlines are available. "Other" means that none of the rules for extended and restricted outlining have been strictly followed. "Various" means different rules have been used depending on the constituting units (RGS only). This might be the case of older inventories or inventories that do not comply with the present guidelines.

5.4. Delineating rock glaciers

Delineating rock glaciers consists of drawing a polygon around the rock glacier unit/system. Two ways of delineating rock glacier boundaries are recommended as standard: the **extended** and the **restricted** geomorphological footprints (*cf.* Section 3.6). Outlines, which remain optional, may be drawn for each rock glacier unit identified by a PM. At the system level, the outline is composed by the combined perimeter of the relevant rock glacier units.

A rock glacier footprint is a polygon, whose position and properties represent the spatial extent of the landform and its associated uncertainty. If the delineation is subject to large uncertainty around most of the landform, it is recommended not to attribute any footprint to the rock glacier unit: an outline should be drawn only if sufficient geomorphological evidence is available.

In order to minimize the subjectivity associated with the compilation of inventories, due to either the motivation (*cf.* Section 2.1), the operator's experience, the quality of the available data or the characteristics of the landforms, outlining rock glaciers requires specific rules to be followed, which are described in the following section. Note that these rules are not comprehensive and cannot solve all issues related to the drawing of rock glacier outlines.

5.4.1. Front

The front (*cf*. Sections 3.1 and 5.1) can be recognized by surface characteristics, which may include: a steep slope angle, erosional features and distinct scars, a contrast in material (grain-size constitution and freshness of surface exposure implying changes in texture and color), shadowing (in hillshade and orthophoto data) and vegetation cover compared to the rock glacier surface [66, 67, 68]. In some cases, the delineation can be aided by ephemeral snow cover present at the base of the front [69].

The **restricted outline** excludes the front talus of the rock glacier. It must be drawn following the upper front edge (or front line), where the topographic slope angle changes abruptly [70]. In case of smooth and subdued topography at the front edge (bulgy front, relict landforms), the outline should be placed approximately where the convexity along a profile perpendicular to the front slope is the largest [71].

The **extended outline** includes the entire rock glacier front. It follows its lower edge, which is the base of the frontal talus [70, 72], except in cases of an exaggerated talus front where the front line is truncated or not. In the latter cases, it is recommended that at the rock glacier front the horizontal distance between the restricted and the extended outlines does not exceed 50 m (plan view). If a change of front slope angle is visible due to differential displacements between the rock glacier above the shear horizon and the material below, the outline is drawn at this limit or a little further below [73]. If not, the extended outline must be drawn by maintaining an almost constant distance from the restricted outline and/or as a continuation of visible extended lateral margins [74, 75]. Note that the suggested 50 m threshold is intended to minimize inter-operator variability when mapping an exaggerated talus front.

5.4.2. Lateral margins

Lateral margins are outlined based on indicative surface characteristics, which depend on the relevant typology (*cf*. Section 5.1).

For **talus margins***,* the outlining procedure follows the same approach as specified for the rock glacier front. The restricted outline excludes the talus margins. The extended outline includes the margins, with the due limitations for exaggerated talus and truncated margins. In some cases, extended or restricted outlines of lateral margins merge in the upper part of the rock glacier [76].

For **levees**, the outline is mainly indicated by topographic differences. The restricted outline follows the inner side of the levee, where a shear margin can typically be found. The extended outline is drawn along the outer side of the levee at a limited distance up to 50 m, but a shorter distance is recommended [77, 58].

For **shear margins**, outlining is based primarily on detecting the margin itself, which typically forms a visible line indicating differential movement on either side. There is generally no significant associated change in topography. Where the shear margin is not associated with a levee, the extended and the restricted outlines are equivalent [77].

In a rock glacier system, coalescent units are sometimes imbricated and exhibit discontinuous and/or ill-defined lateral margins. In such cases, unit-specific margins have to be drawn arbitrarily and the relevant boundaries have to be labelled "uncertain". In addition, the outline is the same for both units, and there is no distinction between the restricted and extended ones [78].

5.4.3. Upslope boundary

The boundary of the upper limit of a rock glacier unit connected to an upslope unit, as defined in Section 3.3, is probably where the largest differences between operators can occur. This upper boundary of a rock glacier unit must be outlined based on indicative surface characteristics, which depend on the type of the upslope connection itself. The defined rules are set in order to minimize subjectivity in mapping strategies. They do not exclude the manifestation of permafrost creep to appear further upslope.

The extended and restricted outlines tend to coincide/overlap towards the rock glacier upslope boundary. For a rock glacier unit that is overridden by another one, its upper limit is shared with the extended footprint of the upper unit [65]. The same rule is applicable when the rock glacier unit is partly covered by another landform (e.g., morainic system, talus slope [79, 80]). For the other cases, the uppermost evidence of lateral margins gives a first indication of the minimum upper extent. The following rules on outlining the upper rock glacier boundary must then be followed as closely as possible.

Talus-connected – The upper extent of the rock glacier should be outlined in correspondence with the depression located at the base of the talus slope. The definition of the outline can be aided by the topography itself (change from a steep to gentler slope angle), a change in texture and color between the talus slope and the rock glacier beneath, and in some cases by the presence of snow patches in correspondence with the change in slope angle [81, 82]. The same applies to protalus ramparts.

Where the rock glacier unit has been occupied by a small glacier or ice patch in recent colder times (e.g., Little Ice Age) but has presently almost or completely disappeared, the rock glacier upper boundary should be placed where the first visual indication of creep can be discerned. This boundary is usually not at the immediate foot of the talus slope but somewhat further downslope [83, 84]. The occurrence of small back-creeping push-moraines (creeping features directed towards the former area covered by the glacier/ice patch) or terminal moraines may indicate the former glacier extent. Permafrost is often lacking where glacier/ice patches develop, which prevents creep from occurring.

Debris-mantled slope-connected – The upper extent of the rock glacier should be outlined based on geomorphological evidence of permafrost creep (e.g., lateral margins and surface topography) observed at its highest altitude or, similarly to talus-connected, where a change in slope may occur. Embedding the debris-mantled slope (source zone) into the rock glacier footprint must be avoided [85, 86, 87].

Landslide-connected – If the rock glacier is located directly downslope of a landslide, the upper extent of the rock glacier should be outlined in correspondence with the lowermost deposition area of the landslide, independent of the type of landslide. Embedding the landslide area into the rock glacier footprint must be avoided [88 right].

If the rock glacier lies on a large deep-seated gravitational slope deformation, the same rule defined for talus-connected rock glaciers applies. If the talus slope unit is lacking, the upper extent of the rock glacier should be drawn at the elevation where geomorphological evidence of permafrost creep ends (e.g., lateral margins and surface topography), observed at its highest altitude [88 left].

Glacier-connected – As landforms resulting from permafrost creep processes, rock glaciers should not be confused with debris-covered glaciers, which are glaciers partially or completely covered by supraglacial debris. The latter are often, but not necessarily, characterized by exposed ice due to the discontinuity of the debris cover or the development of thermokarst ponds that create a rough surface. In contrast, ice is usually not visible on the surface of rock glaciers, except if the latter is embedding debris-covered glacier ice as a superimposed layer. In this case, their surface is comparably smooth and convex. The development of a ridge-and-furrow topography is characteristic of permafrost creep, which should not be confused with morphologies resulting from the accretion of morainic ridges (i.e., glaciotectonic structures).

The downslope transition from debris-covered glacier to rock glacier is extremely challenging to identify (*cf.* Section 3.3, glacier-connected). In these cases, the upper extent of the rock glacier unit, meaning the area affected by permafrost creep, should be outlined in correspondence with the transition between the debris-covered glacier and the rock glacier system/unit, according to the geomorphological and textural characteristics summarized in Table 3 [89, 90]. Outlining is arbitrary and particularly uncertain [91]; a more precise determination is in principle only possible by means of direct geophysical analysis. In case of high uncertainty, an alternative is to draw a straight line between the two sides of the landform approximately where the transition occurs.

Table 3. Indicative features [92, 93] to distinguish between rock glaciers and debris-covered glaciers [100].

Geomorphological/ Kinematic feature	Rock glacier	Debris-covered glacier
Transverse ridges and furrows	Frequent	Non-frequent
Talus-like front	Frequent	Non-frequent
Crevasses with exposed ice	Non-frequent	Frequent
Abundant thermokarst	Non-frequent	Frequent
Abundant supraglacial lakes	Non-frequent	Frequent
Ice cliffs	Non-frequent	Frequent
Supraglacial streams/channels	Non-frequent	Frequent
Subsidence rate	~cm/yr	~m/yr
Flow field coherence	Good	Reduced, due to differential melt

Glacier forefield-connected – The upper extent of the rock glacier unit should be outlined in correspondence with any geomorphological (i.e., ridge and furrow topography) or kinematic evidence of motion [94, 95, 96]. The formerly glaciated area may be characterized by well-developed lateral moraines and a transverse concave topography, evidence of previous glacier flow-like fluted moraines (if the glacier was temperate-based) or the presence of surface streams with corresponding alluvial deposits and ponds. Dead ice bodies, meaning almost non-moving volumes of debris-covered glacier ice, can be widespread and should not be embedded into the rock glacier area.

Poly-connected – The upslope boundary should be spatially outlined in correspondence with the specific upslope connection (e.g., talus- and glacier-connected) as described above.

5.4.4. Associated uncertainty and dating

If there is enough geomorphological evidence to unambiguously draw outlines with an accuracy of 20 m, the outline segment is labeled as **certain**. If an outline segment cannot be unambiguously drawn within the set accuracy and presents a larger uncertainty, it should be labelled as **uncertain**. The uncertainty derives from the absence of clear geomorphological evidence (i.e., due to neither the complexity nor the size of the rock glacier) or insufficient quality of the available images (e.g., snow, cloud, shadows, or poor georeferencing [97]). The sources of uncertainty should be specified (e.g., rock glacier morphology and/or data quality). Additionally, the date (dd/mm/yyyy) of data acquisition used for rock glacier delineation should be specified, particularly the imagery used to outline the front of active rock glaciers.

If a rock glacier unit can be detected and located, yet large parts of its front, lateral margins and/or upslope connection cannot be outlined within reasonable reliability (i.e., the range of uncertainty in outlining alters the rock glacier area by more than approximately 10%), no outline should be drawn. In this case, the PM remains as the only georeferenced information associated with the landform.

6. Kinematic attribute

The following chapter introduces the baseline concepts that enable the integration of specified kinematic information as an optional attribute in RoGIs.

6.1. Basic concepts, limitations, and requirements

Due to the mechanism of rock glacier movement (permafrost creep) occurring primarily at great depths, the associated surface displacements build up consistent flow fields. Consequently, rock glacier units present rather gradual surface movement patterns that can be documented by means of moving areas (Section 6.2.1). These moving areas can be detected, characterized, and used to assign a kinematic attribute to the rock glacier unit.

Although adopting a kinematic approach has its advantages, such as validating qualitative interpretation of morphological evidence, it is important to recognize several limitations, including:

- Surface velocity is expected to be principally dependent on the rock glacier downslope movement, but various processes can alter this relationship and even dominate the measured surface displacement (e.g., melt-induced subsidence).
- Surface velocity is generally faster than the effective mean motion rate occurring within the rock glacier body down to the main shear horizon (by a factor of up to approximately 1.5), but in the absence of borehole deformation measurements the difference is not known.
- Surface velocity usually displays a certain degree of spatial heterogeneity over a rock glacier unit, in relation to the landform (e.g., internal structure) and terrain (e.g., slope) characteristics. For instance, the terminal area (front), lateral margins, and rooting zone are often slower than the central section.
- Temporal variations of the surface velocity can occur, for example:
    - The velocity may change significantly from year to year (inter-annual to decennial variations) as a response to changing environmental factors.
    - The velocity often oscillates within a year. It is usually faster during or after the warm season, due to higher ground temperature and increased water inputs from snowmelt and liquid precipitation. A large amplitude is possible within a year. Thus, when observing rock glacier velocity during summertime only, generally faster values are noted than when considering a time period of one year [**98**].
    - The velocity may vary within a season. There is usually a decreasing trend during the colder season and an accelerating trend during the warmer season, and thus a large amplitude is possible. Ground temperature and water content appear to be the main drivers of these velocity variations.
    - Other changes over various time scales could occur (e.g., destabilization, short-term peaks).

Hence, the kinematic attribute has to be, as far as possible, representative of the **multi-annual movement rate of the rock glacier unit at the time of an inventory**. It should provide a generic velocity information about the inventoried rock glaciers, that allows comparisons within and between RoGIs at regional and global scales. The kinematic attribute should be derivable from in situ or remote sensing measurements. Contrary to the velocity time series (see "Rock Glacier Velocity as an associated parameter of ECV Permafrost"), it has no monitoring purpose.

6.2. Determination of the kinematic attribute

Rock glacier kinematics are defined as the surface movement rate related to the downslope creep. The kinematic attribute is a semi-quantitative (order of magnitude) velocity information.

A two-step procedure, possibly iterative, is proposed to assign a kinematic attribute to inventoried rock glacier units. It consists of:

a) identifying **moving areas** on rock glaciers (6.2.1) and assigning a **velocity class** based on adequate kinematic data (6.2.2);

b) categorizing the inventoried **rock glacier units** with a **kinematic attribute** based on the previously identified moving area(s) (6.2.3).

The identification and characterization of moving areas (a) is an initial step, after which it is recommended to subsequently assign a kinematic attribute to a rock glacier unit (b). An example based on InSAR is shown on Fig. 4.

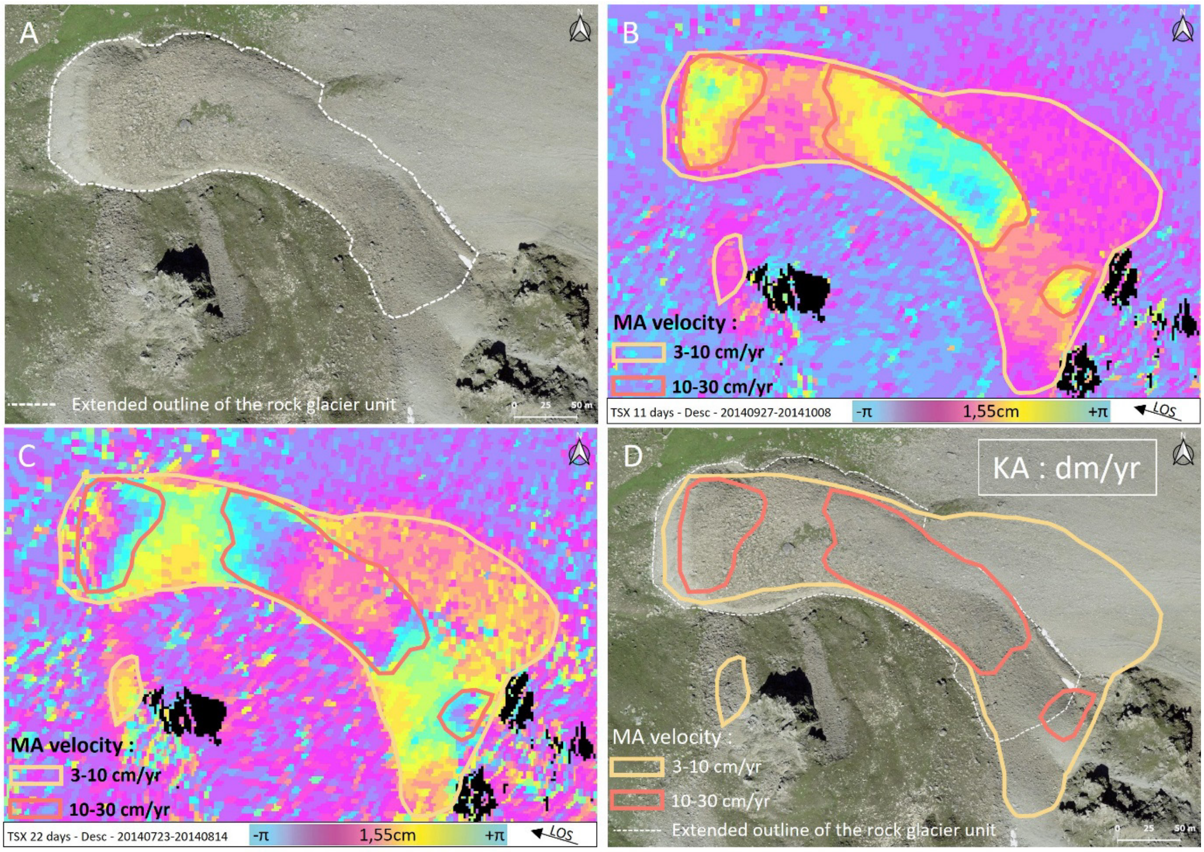

Fig. 4. Example of MA characterization and KA assignment based on InSAR data. A: Extended geomorphological footprint of the rock glacier unit (cf. Section 5.4). B: MA detected on a TerraSAR-X 11-day interferogram (cf. Section 6.2.1) C: MA detected on a TerraSAR-X 22-day interferogram (cf. Section 6.2.3) D: KA of the rock glacier unit, meaning that it was active and moving at a rate of ≈ 0.1 m/yr at the time of the inventory (2014). Les Cliosses (Switzerland), 46.1441°N, 7.5028°E 2400-2600 m a.s.l. For more information, refer to the following document "InSAR-based kinematic attribute in rock glacier inventories: practical InSAR guidelines" [99].

6.2.1. Moving areas

The identification of **moving areas (MAs)** can be performed using a single technique or a combination of techniques providing surface velocity maps over entire mountain slopes or ranges. The MAs may document processes other than rock glacier creep. To focus on rock glaciers in the absence of any already existing inventory, a simultaneous thorough analysis of aerial images is necessary, and a sufficient knowledge of geomorphology is therefore required.

When related to an inventoried rock glacier, a **MA** is defined as an **area at the surface of the rock glacier in which the observed direction and velocity of the flow field are spatially consistent and homogeneous during a documented timeframe**. It must represent its downslope motion rate (permafrost creep), where confusion with movement related to other processes (e.g., melt-induced subsidence or subjacent deep-seated landslide) should be avoided.

Identification and delineation of MAs must be performed **in accordance with the following requirements**:

- The delineation of a MA is strictly dependent on the mapped surface velocity. It is not constrained by any geomorphological feature and does not have to be adjusted to the rock glacier margins.
- Any MA can override the geomorphological limits of a rock glacier unit (e.g., when two overlying/adjacent rock glacier units are moving at rates that are not significantly different, or if the rock glacier is spatially connected with another moving landform).

- The velocity range within a MA should not exceed a min/max ratio of 1:5 (i.e., half an order of magnitude). Otherwise, the MA must be split into two or more MAs with variable velocities. Thereby, several MAs can be superimposed, with a slower MA always embedding a faster one.

In addition, it should be acknowledged that:

- The minimum extent of a MA depends on the spatial resolution of the data input, but also on the size of the considered landforms. It is based on the operator's judgment.
- The delineation of a MA is often difficult to obtain with precision, depending for instance on the detection capability of the applied technique but also on the time during which the observation is performed. Therefore, the use of kinematic datasets spanning several seasons/years is recommended.
- A single point measurement is basically not a MA, but the information it provides could be taken into consideration if it can be spatially related to any MA.
- Areas outside of any delineated MA refer without distinction either to a lack of movement, to a movement that may be under the detection limit, to unreliable data or to the absence of any analysis.

Any MA is always **stamped by time characteristics**, which are mostly related to the technique in use. These characteristics include:

- **Observation time window**: the period during which the detection and characterization is computed/measured (e.g., multi-annual, annual, intra-annual). When the technique does not allow for an annual or multi-annual observation time window, the minimal required duration is one month (which can also be obtained by aggregating observations of several shorter time windows).
- **Validity time frame**: the duration during which the periodic measurements/computations are repeated and aggregated to define the MA (i.e., during which year(s)). In particular, if the observation time window is shorter than a year, it is recommended to repeat the measurements over several years to obtain multi-annual velocity information.

The **reliability** (or the degree of confidence) of the MA detection/delineation must be qualitatively documented (e.g., low, medium, high).

6.2.2. Velocity of a moving area

Assigning accurate velocity values (e.g., mean, median, amplitude, min/max) to a MA is a very challenging task, which strongly depends on the data quality, the measurement technique, and consecutively, the extent of the MA. In order to facilitate the assignment of homogeneous and simplified velocity information to MAs, the use of **velocity classes** is therefore proposed.

The velocity class documents the overall movement rate observed in a MA during a considered time frame and according to a specific observation time window. It must, as far as possible, refer to a **multi-annual surface velocity representative of the creep rate**. However, the measured/computed velocity is partly dependent on the applied technique and the conditions of observation. Some methodologies only allow for observations during summertime, meaning that the velocity cannot be measured over an annual time interval. The dimensionality (one- to three-dimensional displacement observation) also varies depending on the technique.

Therefore, various ways of classifying could be applied (e.g., range, number and limits of classes, dimensionality). The definition of the velocity classes as well as the rules for subsequently assigning the kinematic attribute to a rock glacier unit are dependent on the used technique and it is up to the operator to set them. See Section 6.3 for an example.

The specific dataset, the applied method, the observation time window and the validity time frame must always be documented. The reliability (or the degree of confidence) of the velocity class assignment must be assessed (e.g., low, medium, high) in combination with the reliability of the MA detection/delineation (*cf.* 6.2.1).

6.2.3. Rock glacier kinematic attribute

The **kinematic attribute (KA)** is the category assigned to a rock glacier unit based on the MA characteristics (extent, velocity class, time specificities), which have been detected at the surface (Table 4). It must reflect the overall kinematic state of the rock glacier unit **at the time of the inventory** (validity time frame, *cf.* 6.2.1). In order to minimize the potentially large inter-annual variations of rock glacier velocity, the validity time frame must be set **to a minimum of two years**, but a longer range is recommended. The KA consists of **semi-quantitative categories expressing the multi-annual downslope velocity** of an entire rock glacier unit.

Table 4. Description of the KA categories to be assigned to the RGU.

Category	Label	Comment	Related activity
0	Undefined	Default category	Undefined
1	< cm/yr	No up to very little movement	Relict
2	cm/yr	Order of magnitude ≈ 0.01 m/yr	Transitional
3	cm/yr to dm/yr	Order of magnitude ≈ 0.05 m/yr	Transitional
4	dm/yr	Order of magnitude ≈ 0.1 m/yr	Active
5	dm/yr to m/yr	Order of magnitude ≈ 0.5 m/yr	Active
6	m/yr	Order of magnitude ≈ 1 m/yr	Active
7	>m/yr	More than ≈ 3 m/yr	Active

A KA is assigned to a rock glacier unit only when the latter is documented by **consistent kinematic information on a significant part of its surface**. There is only one kinematic category per rock glacier unit, generally defined as the dominant MA. However, as a dominant MA rarely covers an entire rock glacier unit and may not reflect a multi-annual displacement rate, a systematical translation of the velocity class of a MA to KA of a rock glacier unit is not always straightforward and has to be performed carefully. In addition to the characteristics of the MAs, the KA is highly dependent on the technique and the operator's judgment. It must also be taken into consideration that the documented surface velocities may be faster than the effective rock glacier displacement rate at depth and that intra-annual (usually summer) velocities may be faster than annual velocities (*cf*. 6.2.1).

The default category is **0/Undefined**. The rock glacier unit falls into this category when:

- no (reliable) kinematic information is available,
- the kinematic information is derived from a single point survey which cannot be related to any MA (as defined in Section 6.2.1),
- the rock glacier unit is mainly characterized by an identified MA of undefined or unreliable velocity,
- the kinematic information is too heterogeneous.

If two equally dominant, but directly adjoining KA categories (e.g., 5–6) occur on a rock glacier unit, the category of the area closer to the front is favored for the attribution. In case of a larger spread of equally dominant categories on the same rock glacier unit (e.g., 4–6), the median category (e.g., 5) should be retained, with an additional indication of the heterogeneity and the low reliability of the attribution. A large heterogeneity can also indicate the need to refine/redefine the delineation of the initial geomorphological units (iterative process combining geomorphological and kinematic approaches).

For each rock glacier unit with an assigned KA, the following additional information must be documented, depending on the supporting kinematic data (e.g., identified MAs):

- *observation time window* (e.g., multi-annual, annual, intra-annual) and multi-year *validity time frame* of the attributed category,
- *datasets utilized, applied technique(s) and their properties,* e.g., dimensionality of the resulting kinematic data (velocity values),
- *approximated spatial representativeness*: percentage of the rock glacier area that is documented by supporting kinematic data (e.g., < 50%, 50–75%, > 75%),
- *reliability of the* KA assignment (low, medium, high).

The KA is a generic parameter that can be retrieved from various measurement techniques. Conversely, the determination of velocity classes related to MAs as well as the rules for subsequently using this information to assign a KA to a rock glacier unit are dependent on the technique used to measure/compute the velocity and should be specified for each.

6.3. Example of application: kinematic attribute based on InSAR-derived moving areas

Within the framework of the European Space Agency Climate Change Initiative (ESA CCI+) Permafrost project and in accordance with the present document, recommendations have been stated for a systematic procedure based on the accurate interpretation of **InSAR data**. The practical guidelines describe standards to locate and estimate the displacement rate of MAs related to rock glaciers and the translation rules to subsequently assign a KA to the rock glacier units. These detailed rules are provided as an example. They are described in the document "*InSAR-based kinematic attribute in rock glacier inventories: practical InSAR guidelines*"