IPA Action Group Rock glacier inventories and kinematics

Towards standard guidelines for inventorying rock glaciers

Practical concepts

(Version 2.0)

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Authors and contributions

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

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If major changes are required, a thorough document revision must be undertaken, and the Action Group 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* (RGI_BC),
- 1.2: establishment of *practical inventorying guidelines*,
- 1.3: establishment of a *technical (operational) manual*, on how to compile a rock glacier inventory in an open-access database.

The present document is an extension of the **baseline concepts** for inventorying rock glaciers defined in Sub-Task 1.1 with **practical concepts** (Sub-Task 1.2). It is particularly the result of two workshops held in Evolène (Switzerland) on 23-27 September 2019 (Workshop I) and in Fribourg (Switzerland) on 11-13 February 2020 (Workshop II).

The main text is complemented with illustrations, which allow to better apprehend the rules and concepts described in this document. Numbers in brackets (e.g. (**4**)) are active links to these illustrations, which will be compiled in an accompanying atlas at a later stage. Suggestions for further or better illustrations are always welcome (please write to rockglacier-ipa@unifr.ch).

Provisional timeline

The integration of the present document (RGI_PCv2.0) with the baseline concepts for inventorying rock glaciers (RGI_BCv4.2.2) as one single document is foreseen at a later stage before the completion of the current Action Group phase in June 2023.

The present document extends RGI_BC sections 3-4 with practical concepts. It follows the structure of the inventorying strategy briefly presented in RGI_BC section 4. It should serve as a baseline for the practical implementation of standardized rock glacier inventories on a global scale.

5. Practical concepts

5a) Detecting rock glaciers

Detecting rock glaciers consists **primarily of recognizing rock glaciers** according to the technical definition proposed in RGI_BC section 3a and the system/units classification presented in RGI_BC section 3b. This could be performed on the basis of optical imagery as well as DEM-derived products, but also with the help of deep-learning techniques and kinematic data (e.g. InSAR) as complementary approaches.

The geomorphological criteria for identifying a rock glacier unit are described hereafter. They focus on details that will have implications at later stages for the inventorying process (e.g. outlining rules).

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 (**55**).

Rock glacier fronts may display a variety of vertical profile typologies, including (**40**):

- *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 (**41**), but smooth for relict ones.
- *Exaggerated talus*: if the rock glacier terminates in steep terrain, the reworking processes may create a frontal talus that is significantly taller than the expected thickness of the moving section of the rock glacier.[1] (**42**, **81**).
- *Bulgy*: a less common but distinct morphology characterized by a smooth and sometimes complex frontal topography, even for active rock glaciers (**43**).
- *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 (**44**, **82**).

In the three first typologies, the front line of the rock glacier unit generally draws a curved upward, concave (*lobate*) morphology perpendicular to the principal rock glacier flow direction. In the truncated case, the front line has a non-lobate morphology.

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 (**45**). Well-developed lateral margins may not always occur, particularly in the upper part of the landform.

[1] An arbitrary value is given in section 5d in order to standardise the process of outlining exaggerated rock glacier fronts.

- *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, developing alongside the rock glacier moving part associated 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 (**46**). These linear features should not be confused with transversal cracks and scarps, which display a downward concavity associated with extensive flow and a high longitudinal velocity gradient usually associated with destabilization (**36**, **37**).

5b) Locating rock glaciers

Any rock glacier unit and system (cf. RGI_BC Section 3b) must be identified by a **primary marker** (primary ID). The primary marker is a mandatory requirement in any rock glacier inventory. Any other characteristics (attributes) related to a rock glacier unit/system are subsequently linked to the primary marker.

The marker is a **point** whose associated **primary attributes** allow to:

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

The positioning of the primary marker on the rock glacier unit/system should avoid, as far as possible, any temporal variation and updating. It must not refer to anything else other than to 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 primary marker 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 (**47**).

Each RGU must imperatively be associated with one single RGS.

5c) Characterizing rock glaciers

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

Specific tables list the essential attributes to include in an inventory as a minimal requirement for rock glacier units and systems (**74**, **75**). Besides the mandatory primary attributes, all others are optional but recommended. The value "n.a." (not available) is used for any attribute that has not been assessed.

The optional attributes are summarized as follows:

Rock Glacier Morphology (RGU only)

Describes the complexity of the morphology of a rock glacier unit according to RGI_BC Section 3b.

Rock Glacier Composition (RGS only)

Describes the composition of a rock glacier system according to RGI_BC Section 3b.

Rock Glacier Completeness (RGU only)

Describes if the delineable area of a rock glacier unit corresponds to the entire landform (yes) or only to part of it (no), meaning: "does the rock glacier unit comprise the entire sequence of a rock glacier landform from its rooting zone to its front?". The masking is typically caused by the overriding of a rock glacier unit by another one (**77**) or by any other landform that has developed at a later stage (e.g. talus slope, large rock fall deposit) (**83**).

Upslope Connection

Describes the connection of the rock glacier unit to its geomorphological upslope unit according to RGI_BC Section 3c.

The value "n.a." is used when the data quality is insufficient to determine any upslope connection with confidence. 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 (**105**).

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 be provided in addition.

Kinematic Attribute

Under development (cf. Kinematics as an optional attribute in standardized rock glacier inventories)

Activity

Describes the activity rate of the rock glacier unit according to RGI_BC Section 3d.

The value "active uncertain" attests 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 according to RGI_BC Section 3e.

"Ongoing" means that the geomorphological evidence and/or kinematic data attest to an ongoing phase of destabilization. "Completed" means that the geomorphological evidence and/or kinematic data attest to a phase of destabilization that has occurred but is now completed. The latter statement could also apply to relict rock glacier units. In both ongoing and completed destabilization cases, 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.

"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 according to Section 5d and RGI_BC Section 3f. If delineation has been performed, the type and date of the source data must be provided in addition.

"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 standards.

5d) Delineating rock glaciers

Delineating rock glaciers consists in drawing a polygon around the rock glacier unit/system. Two ways of delineating rock glacier boundaries are recommended as standards: the **extended** and the **restricted** geomorphological footprints (*cf.* RGI_BC Section 3f). Outlines, which remain optional, may be drawn for each rock glacier unit identified by a primary marker. 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.* RGI_BC Section 2a), the operator's skills, 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.

Associated uncertainty and dating

If the geomorphological evidence is such that the outline can be unambiguously drawn within an accuracy of 20 m, the outline segment is labelled 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 (due neither to the complexity nor the size of the rock glacier), possibly also due to the insufficient quality of the available images (e.g. snow, cloud, shadows, or poor georeferencing information (**78**)). 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 employed 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 primary marker remains as the only georeferenced information associated with the landform.

Front

The front of a rock glacier is the steeper section terminating the landform downslope, marking the boundary between the main rock glacier body and the subjacent terrain (cf. section 5a). It is recognizable on the basis of 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 (**48**, **49**, **93**). In some cases, ephemeral snow cover at the bottom of the front can also help the delineation (**50**).

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 (**51**). 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 (**85**).

The **extended outline** includes the entire rock glacier front. It follows its lower edge, which is the base of the frontal talus (**51**, **80**), except in cases of an exaggerated talus front with the front line being truncated or not. In the latter cases, the horizontal distance (plan view) between the restricted (front edge) and the extended rock glacier outlines should not exceed 50 m. 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 down (**52**). 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 (**79**, **94**).

Lateral margins

Lateral margins are outlined based on indicative surface characteristics, which depend on the relevant typology (*cf*. Section 5a).

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 (**53**).

For **levees**, the outline is mainly indicated by differences in the topography. 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 from it (up to 50 m, but a shorter distance is recommended) (**54**, **45**).

For **shear margins**, the 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 (**54**).

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". Moreover, the outline is the same for both units, and there is no distinction between the restricted and extended ones (**86**).

Upslope boundary

The boundary of the upper limit of a rock glacier unit connected to an upslope unit, as defined in RGI_BC Section 3c, is probably where the largest differences between operators would 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 (105). The same rule is applicable when the rock glacier unit is partly covered by another landform (e.g. morainic system, talus slope) (95, 96). For the other cases, the uppermost evidence of lateral margins gives a first indication of the minimum upper extent. The specific 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 (87, 64). 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 evidenced. This boundary is usually not at the immediate foot of the talus slope but somewhat further downslope (56, 68). 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 be hints of the former glacier extent. Permafrost is often lacking where the glacier/ice patch was developing, preventing any 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 occurs, if any. Embedding the debris-mantled slope (source zone) into the rock glacier footprint must be avoided (57, 88, 89).

Landslide-connected – If the rock glacier is located directly downslope of a landslide (i.e. rock or debris slide), 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 (58 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 (58 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 frequently - yet not necessarily - characterized by exposed ice due to the discontinuity of debris cover or the development of thermokarst ponds, among other features, 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).

When occurring, the downslope transition from debris-covered glacier to rock glacier is extremely challenging to determine (*cf.* Section 3c, glacier-connected). In those 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 1 (38, 100). The outlining is arbitrary and particularly uncertain (59); a more precise determination is in principle only possible by means of direct geophysical prospection. In case of high uncertainty and if most of the rock glacier unit can be outlined, an alternative is to draw a straight line between the two sides of the landform approximately where the transition occurs.

Table 1: Indicative features to distinguish between rock glaciers and debris-covered glaciers (104, 106).

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/y^{-1}	~m/y^{-1}
Flow field coherence	Good (unless too fast)	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 (60, 61, 62). 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.