IPA Action Group Rock glacier inventories and kinematics

Towards standard guidelines for inventorying rock glaciers

Practical concepts

(Version 1.0)

https://www3.unifr.ch/geo/geomorphology/en/research/ipa-action-group-rock-glacier (Action Group website)

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Authors and contributions

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

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Acronym:

RGI_PCv1.0

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). Its content is in particular 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 allowing a better understanding and visualization of the rules and concepts. 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 illustrations are welcome (using the dedicated boxes inserted at the end of each section).

Provisional timeline

- Version 1.0 is open to comment until 15.09.2021 using exclusively the dedicated boxes inserted at the end of each section.
- Version 2.0 is intended to be released by 15.11.2021
- If necessary, a virtual workshop will be organized in November 2021 or later to debate and decide about unsolved points.
- Version 3.0 (final version) is intended to be released for approbation by 31.01.2022.

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Comment box 0

The present document is extending RGI_BC chap. 3-4 with practical concepts. It follows the structure of the inventorying strategy briefly presented in RGI_BC chap. 4. It should serve as a baseline for the practical establishment 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 discriminant geomorphological criteria of a rock glacier unit are described hereafter focusing on details, which will have implications at later stages for the inventorying process (e.g. outlining rules).

Front (mandatory criterion):

The front is the terminal steep 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 (down to the shear horizon). 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 are deposited toward the bottom of the front and progressively overridden by the rock glacier advance itself. (**55**)

There are however different typologies of the front profile (**40**):

- *Talus-like:* the debris mobilized from the uppermost steeper section (>35-40° for active rock glaciers) are building 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 smoothed for relict ones.
- *Exaggerated talus:* if the rock glacier terminates in steep terrain, the reworking processes may create a frontal talus which is significantly much larger than the expected thickness of the moving section of the rock glacier. (**42**, **81**)
- *Bulgy*: a less common but distinct morphology that is characterized by a smoothed and sometimes complex frontal topography, even for active rock glaciers. (**43**)

The front line of rock glacier unit draws generally a curved (*lobate*) convex morphology perpendicular to the principal rock glacier flow direction. In some cases, the front appears as *truncated,* showing a non-lobate morphology: its position is constrained by the topography (e.g. connection to steep torrential gully or rock cliff overriding) and tends to stay almost invariant over time, the front edge is usually sharp and the front profile develops as an exaggerated talus. (**44**, **82**)

Lateral margins (mandatory criterion):

Lateral margins are the continuation of the front on the side of the rock glacier. Three different types of margins typically occur, talus-margins, levees and shear-margins, or a combination of them (**45**). Well-developed lateral margins may be morphologically absent in particular in the upper part of the landform.

A *talus-margin* designates a morphology similar to a talus-like front, which can even form an exaggerated talus and exceptionally can be truncated. A *levee* is a former talus-margin not building up anymore due to the lowering of the rock glacier surface. It could be sometimes confused with glacier lateral moraines, especially in the case of relict rock glaciers, and disentangling the two is sometimes not possible. A *shear-margin* is an elongated, superficial furrow developing alongside the rock glacier moving part consecutively to shearing. It develops mostly at the inner bottom side of levees and in the uppermost part of rock glaciers.

Ridges and furrows (optional criterion):

Ridges and furrows are pronounced convex downslope 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 are reflecting either some flow convergence or shearing and deformation occurring between areas moving at different rates. (**46**, **45**)

These linear features should not be confused neither with transversal cracks (**37**) and scarps (**36**), which display a downward concavity associated to extensive flow and high longitudinal velocity gradient, nor with crevasses which are rare on rock glaciers (**76**).

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Comment box 5a

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 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 locating the rock glacier unit/system and discriminating it unambiguously from neighboring ones. The positioning does not require to follow 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 above yet not far from the rock glacier front and within the identified rock glacier unit/system extent.

Each primary marker is identified by a unique code (primary ID) distinguishing between morphological unit (RGU) and system (RGS) followed by its WGS84 coordinates in decimal degrees with 4 digits. The primary ID code will necessarily be 18 characters. For example, a rock glacier unit locating at 46.9435°N, 12.3693°E (decimal degrees) will be coded RGU46935N0123693E. (**47**)

Each RGU must imperatively be associated to one single RGS.

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.

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Comment box 5b

5c) Characterizing rock glaciers

Rock glacier characteristics (e.g. connection to upslope unit, activity) can be attributed to any rock glacier unit defined by a primary marker. Some of them can also be attributed to rock glacier systems by aggregation of their composing units.

Tables 1 and 2 list the essential attributes to integrate into a rock glacier inventory as a minimal standard. Beside the mandatory primary attributes, all others are optional but recommended. The values "n.a." (not available) is used for any attribute, which has not been assessed.

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 Integrality (RGU only)

Describes if the delineable area of a rock glacier unit corresponds to the entire landform (yes) or only a part of it (no), meaning "is the rock glacier unit comprising the entire sequence of a rock glacier landform from its rooting zone (source area) 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 which 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 "Unknown" is used when a rock glacier unit has been overridden by another one and the former connection to upslope unit cannot be assessed with confidence anymore.

Activity Assessment

Describes if the activity assessment is performed on the basis on geomorphological criteria only or with the support of kinematic data. 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 "Uncertain activity" is attesting that the rock glacier unit is not in a relict state, but there is not sufficient data or geomorphological evidence to distinguish between an "active" and "transitional" state. "Uncertain relictivity" 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 "n.a." 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 geomorphological evidences and/or kinematic data attest an ongoing phase of destabilization. “Completed” means that geomorphological evidences and/or kinematic data attest that a phase of destabilization has occurred but is now completed. The latter statement could also apply for relict rock glacier units. In both cases of current or recent destabilization, the data used for the assessment must be dated.

Delineation (RGS only)

Describes if the delineating of a rock glacier system is completed or not.

“Yes” means that all constituting units are delineated, whereas “Partial” means that only some of the constituting units are outlined.

Delineation type

Describes if and how the delineating of a rock glacier unit or system has been performed according to Section 5d and RGI_BC Section 3f. If delineation has been performed, type and date of the source date 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 has strictly been followed. “Various” means that different rules have been used depending on the constituting units (RGS only).

Table 1 : Essential attributes – Rock glacier unit (RGU).

Attribute	Values/Units	Description
Primary (mandatory)		
Primary ID	RGU + 15 digits	(*cf.* Section 5b)
Associated RGS	RGS + 15 digits	(*cf.* Section 5b)
Optional		
Rock Glacier Morphology	Simple Complex n.a.	(*cf.* RGI_BC Section 3b)
Rock Glacier Integrality	Yes No n.a.	
Upslope Connection	Talus Debris-mantled slope Landslide Glacier Glacier-forefield Other Poly-connected Uncertain Unknown n.a.	(*cf.* RGI_BC Section 3c)
Activity Assessment	Geomorphological Kinematic n.a.	(*cf.* RGI_BC Section 3d)
Kinematic Attribute		(cf. Kinematics as an optional attribute in standardized rock glacier inventories)
Activity Class	Active Transitional Relict Uncertain activity Uncertain relictivity n.a.	(*cf.* RGI_BC Section 3d)

Destabilization	Yes, ongoing Yes, completed No n.a.	(*cf.* RGI_BC Section 3e)
Delineation	Restricted Extended Restricted and extended Other n.a	(*cf.* Section 5d and RGI_BC Section 3f)

Table 2 : Essential attributes – Rock glacier system (RGS).

Attribute	**Values/Units**	**Description**
Primary (mandatory)		
Primary ID	RGS + 15 digits	(*cf.* Section 5b)
Associated RGU(s)	RGS + 15 digits	(*cf.* Section 5b)
Optional		
Rock Glacier Composition	Mono-unit Composite	(*cf.* RGI_BC Section 3b)
Delineation	Yes Partial n.a.	
Delineation type	Restricted Extended Other Various n.a.	(*cf.* Section 5d and RGI_BC Section 3f)

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Comment box 5c

5d) Delineating rock glaciers

Two ways of delineating rock glacier boundaries are recommended to be included as standards: the **extended** and the **restricted** geomorphological footprints (*cf.* RGI_BC Section 3f). Outlines can be attributed to each rock glacier unit identified by a primary marker, but remain optional. The outline of a rock glacier system is defined by the merged perimeter of its composing units.

A rock glacier footprint is a closed 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 require specific rules to be followed, which are described farther in this section. Note that these rules are not comprehensive and cannot solve all peculiar 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 identified within a region of 20 m in width, the outline segment is referred to as **certain**. If an outline segment cannot be unambiguously identified within the set accuracy and presents a larger uncertainty, it should be referred to as **uncertain**. The uncertainty derives from the absence of clear geomorphological evidence, possibly also due to the insufficient quality of the available images (e.g. obstructed vision, such as in shadowed areas, or georeferencing imprecision (78). The source of the uncertainty should be specified (e.g. rock glacier morphology or data quality). Additionally, used data must be dated, in particular 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 a reasonable reliability (i.e. the range of uncertainty in drawing the outline alters the rock glacier area by more than approximately 10%), no outline should be drawn. The primary marker remains in this case as the only georeferenced information associated with the landform.

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Comment box 5d_1

Front

The front of a rock glacier is the steeper section terminating the landform downslope, which marks the boundary between the main rock glacier body and the subjacent terrain (cf. section 5a). It is recognizable to surface characteristics which may include steeper slope angle, erosional features and distinct scars, and 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). Remnant of snow accumulation at the bottom of the front can also help the delineation in some cases (50).

The **restricted outline** excludes the rock glacier front. It must be drawn following the front edge (or front line), that is where the topographical slope angle is abruptly changing (51). In case of smoothed topography of 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 delineation is *uncertain* in many of such situations.

The **extended outline** includes the entire rock glacier front. It follows its bottom, that is the base of the frontal talus (51, 80), except in the cases of exaggerated talus front, the front line being truncated or not. In the latter cases, the distance between the front edge (restricted outline) and the extended rock glacier outlines should not exceed 50 m horizontally. If a change of slope angle is visible in the front slope 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 few downslope (52). If not, the extended outline must be drawn by maintaining an almost constant distance to the restricted outline and/or as a continuation of visible extended lateral margins (79, 94). The delineation is *uncertain* in many of such situations.

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Comment box 5d_2

Lateral margins

Lateral margins are outlined based on indicative surface characteristics, which depend on the type of the lateral margin itself (*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. (**53**)

For **levees**, the outline is mainly indicated by 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, but at a limited distance of it (maximally 50 m, but a smaller distance is recommended). (**54**)

For **shear margins**, the outlining is based primarily on the detection of 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 to a levee, the extended and the restricted outlines are equivalent. (**54**)

In a rock glacier system, coalescent units are sometimes imbricated without that the occurrence of any obvious geomorphological margin is permitting to separate them unambiguously. In such cases, the divide has to be set arbitrarily and considered as an *uncertain* boundary. The outline section is the same for both units and there is no distinction between the restricted and extended ones (**86**).

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Comment box 5d_3

Upslope boundary

Bounding the uppermost limit of a rock glacier unit effectively connected to a geomorphological upslope unit as defined in RGI_BC Section 3c is probably where the largest differences between operators would potentially occur. This uppermost 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 these subjective discrepancies. They do not exclude the occurrence of permafrost creep to occur further upslope.

Toward the rock glacier upslope boundary, the extended and the restricted outlines are equivalent. The outline is in any case qualified as *uncertain*. For a rock glacier unit which is overridden by another one, its uppermost limit is the extended footprint of the upper unit. 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 ones, a first indication of the minimum upper extent is given by the uppermost evidence of lateral margins. The specific rules on outlining the rock glacier unit upper boundary related to its upslope connection must then be followed as closely as possible.

Talus-connected – The upper extent of the rock glacier should be outlined in correspondence with the concave topography at the bottom 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 for protalus ramparts.

In case of the rock glacier unit has been occupied by a small glacier or ice patch in recent colder times (e.g. Little Ice Age) and has nowadays almost or completely disappeared, the rock glacier uppermost boundary should be placed where the first creep evidences can be evidenced, which are usually not a the immediate foot of the talus slope but somewhat further downslope. The occurrence of small back-creeping push-moraines (creeping features directed towards the former area covered by the glacier/ice patch) may be hints of the former glacier extent, as well as some kind of terminal moraines. Permafrost is often lacking where the glacier/ice patch was developing, preventing any creep to occur. (**56**, **68**)

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Comment box 5d_4

Debris-mantled slope-connected – The upper extent of the rock glacier should be outlined based on geomorphological evidence of permafrost creep features (e.g. lateral margins, surface topography) observed at its highest altitude or, similarly to talus-connected, where a change of the slope inclination is occurring, if any. Embedding of the source debris-mantled slope of into the rock glacier footprint must be avoided. (**57**, **88**, **89**)

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Comment box 5d_5

Landslide-connected – If the rock glacier is located in direct downslope spatial connection to 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 of 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 as for the talus-connected rock glacier applies. If the talus slope unit is lacking, the upper extent of the rock glacier should be outlined based on geomorphological evidence of permafrost creep features (e.g. lateral margins, surface topography) observed at its highest altitude. (**58** left)

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Comment box 5d_6

Glacier-connected – Rock glaciers, as landforms resulting from a permafrost creep process, 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 pounds, 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, and 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.

Where 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 3 (38). The outlining is arbitrary and particularly uncertain; a more precise determination is in principle only possible by means of direct geophysical prospection (59). 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 is taking place.

Table 3 : Indicative features to distinguish between rock glaciers and debris-covered glaciers.

Geomorphological/ Kinematic Feature	Rock glacier	Debris-Covered Glacier
Transverse ridges and furrows	typical	non-frequent
Talus-like front	typical	non-frequent
Crevasses with exposed ice	non-frequent	typical
Abundant thermokarst	non-frequent	typical
Abundant supraglacial lakes	non-frequent	typical
Ice cliffs	non-frequent	typical
Supraglacial streams/channels	non-frequent	typical
Outflow breaches	non-frequent	typical
Subsidence rate	~cm/y^{-1}	~m/y^{-1}
Coherence (InSAR - summer)	good (unless too fast)	reduced, due to differential melt

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Comment box 5d_7

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. The former glaciated area may be characterized by well-developed lateral moraines and a transverse concave topography, evidences 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. (60, 61, 62)

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.

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Comment box 5d_8