IPA Action Group Rock glacier inventories and kinematics

Towards standard guidelines for inventorying rock glaciers

(Version 2.0)

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

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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 not feasible. In the meantime, quantitative information about kinematics has been made available for numerous rock glaciers, particularly with the development of remote sensing techniques. The aim of the Action Group task 1 is to **explore the feasibility of developing widely accepted standard guidelines for inventorying rock glaciers, including information on their kinematics** and the following document is intending to fix the **baseline concepts**.

Task 1 has to be divided in two sub-tasks:

- 1.1: agreement on the main concepts and principles (present document, which will be discussed during Workshop I),
- 1.2: establishment of a guidebook, which will provide the principles of application (including worldwide examples).

The sub-task 1.2 as well as the two other main tasks of the Action Group, namely task 2 (rock glacier kinematics as an associated parameter of the ECV permafrost) and task 3 (operational development of a database / web platform), will not be addressed here.

The content of the present document is the result of a preparatory workshop held in Chambéry (France) on 23 March 2019, comments received about the workshop wrap-up, further informal meetings and discussions between participants of the Chambéry meeting and comments received on version 1.0 until 15 August 2019. It still aims to be a provisory document (working document) synthetizing **baseline concepts**, which has to be finalized during the Workshop I of the Action Group on 23-27 September 2019. Any important feedback on the content of this document from non-participants to Workshop I may be sent to rockglacier-ipa@unifr.ch until the beginning of the latter.

Additional comments by the authors are inserted in grey between paragraphs. They are intending to serve for any discussion at the current stage, but will have to be either integrated in the final version of the document or transferred toward a technical guidebook or simply deleted.

Various examples are provided as illustration. Many of them have been taken from the region where the Workshop I will be held, in particular from sites that are foreseen to be visited during the related excursions. A call for "best illustrating" rock glaciers will be launched at a later stage, depending on the results of the workshop.

On many illustrating links, you will be redirected on GIS visualization platforms. Various maps to be displayed have already been selected in advance. Use the related boxes or screw icon to display or not the map, vary the transparency, etc. On the Swiss platform, for running the Swissimage Journey though time, click first on the clock icon appearing on the right of the screen.

All the examples provided in this document are grouped in a .kml file. Imagery is not always good on Google Earth, do not hesitate to use the "historical imagery" option to find a correct one.

Provisional timeline

- *Version 1.0 was made available to the 92 subscribers of the Action Group mailing list as well as publicly on the Action Group website on 24 June 2019. It was open to comment in an anonymous way until 15 August 2019.*

The authors warmly thanks all those who sent their feedback. It has been very constructive and useful for the compilation of version 2.0 and also to define the main points to be worked on during Workshop I.

- The current document (**version 2.0**) is intended to be discussed during Workshop I. Some modifications have been applied to version 1.0 without any fundamental change so far. A section dedicated to the inventorying strategy has been added.
- A post-workshop version (3.0) will be submitted as short as possible after the workshop and opened to comments until 15 November 2019.
- The final version (4.0) is intended to be made available in December 2019.

Workshop I will be the opportunity to discuss/decide about the realization of a **technical guidebook** for inventorying rock glaciers (sub-task 1.2) on the basis of version 4.0 of the baseline concepts. ICOP 2020 would be an ideal, but for sure ambitious deadline for its achievement.

1. Purpose of standardized guidelines

Today, a large amount of rock glacier inventories exists worldwide (e.g. Jones et al., 2019), published or not, but are not exhaustive at the global scale. Rock glacier inventories are of different ages. They have been set up on different methodologies, which mainly depend on the unequal availability of source data (e.g. satellite imagery) and varying objectives (motivations). Merging all inventories in a fully coherent way is not possible today due to the variability of the methodologies used for their creation.

The increasing emergence of open-access satellite imagery (e.g. optical, SAR) facilitates the set-up of new inventories (and some overlapping) and/or the update of former ones. Current increasing availability of remotely sensed data (e.g. Sentinel SAR) makes an almost systematic integration of kinematic attributes in a rock glacier inventory potentially feasible.

Inventorying rock glaciers is a manual (visual) action, which cannot be automatized yet and requires expert geomorphological know-how by the operator(s). Identifying and characterizing rock glaciers has often led to various and sometimes controversial opinions due to the complexity of morphologies (*e.g.* multiple generations, coalescent landforms, heterogeneous dynamics, interaction with glacier) and the variety of environments in which rock glaciers have developed. It must be accepted that subjectivity is part of the action of recognizing rock glaciers, and will continue to be so. Establishing standard guidelines aims at minimizing its impact. It could even be envisaged that an increasing number of manually identified rock glaciers based on a widely accepted standard would support the development of automatic techniques (*e.g.* deep learning) as a complementary tool to compile inventories.

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 in particular complicated to properly include rock glaciers due to the difficulty of detecting them automatically by remote sensing (GLIMS methodology).

Inventorying rock glaciers requires the latter to be specifically defined in this purpose: what is a rock glacier inventory effectively inventorying and why? Therefore, the motivation for producing a rock glacier inventory and later the way of exploiting it (by a third user) within the framework of another study may (have) strongly differ(ed).

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

2. Rock glacier inventory

a) Motivations for inventorying rock glaciers

Rock glaciers are characteristic landforms associated to the mountain periglacial landscape. They are prevalent periglacial items of the Earth geomorphological heritage. However, their identification can be challenging, especially for people lacking experience and knowledge in the field of mountain geomorphology. Therefore, **inventorying rock glaciers allows their visibility**.

Scientific motivations for producing and/or for exploiting an exhaustive rock glacier inventory (at various scales) can be summarized as follows:

- *Geomorphological mapping*: rock glaciers are identified and mapped as functional or inherited landforms (items) of the geomorphological landscape (i): 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 realize a rock glacier inventory (ii).

  e.g. (i) Swiss geological maps, (ii) Swiss national park, Vanoise National Park.

- *Proxy for permafrost occurrence*: active and inactive (or intact) rock glaciers are geomorphological indicators of the occurrence of permafrost conditions. Even if it is accepted that active rock glaciers may export perennially frozen ground outside of a permafrost prone area, active (or intact) rock glaciers can be used for defining the regional lower limit of the mountain "discontinuous" permafrost belt and to validate spatial models of permafrost extent. Relict rock glaciers are discriminative items for current non-permafrost areas.

  Active rock glaciers attest the occurrence of permafrost at depth, but with regards to the ongoing climate change, they may gradually no longer attest that the surface conditions are still favorable for permafrost to potentially occur.

- *Paleo-climate studies*: relict rock glaciers in particular can be used as proxies for various paleo-permafrost extents.

  Relict rock glaciers are inventoried as inactive or active ones are, as it is a rock glacier state. Moreover, the distinction between a relict state or not is often difficult to assess, particularly in case of coalescent landforms, making a strict delimitation between what should be inventoried or not very difficult and thus the inventorying of relict landforms indispensable.

- *Climate relevant variable*: rock glacier kinematics is sensitive particularly to changing permafrost temperature. Repeating (updating) inventories of active rock glaciers which include a temporally well-defined kinematical information can be used to regionally assess the impact of ongoing climate change on the mountain periglacial environment.

  Several studies have shown the potential of using a selected set of rock glaciers for characterizing the evolution of mountain permafrost at the regional scale (e.g. PERMOS 2019). The scope extends here to the monitoring of rock glacier kinematics (instead of the production or use of a rock glacier inventory) and will be addressed in the task 2 of the Action Group.

- *Hydrological significance*: intact rock glaciers may act as ice storage features, which may play a significant role on the hydrological regime of river/stream catchments of concern, especially in dry areas. Rock glacier inventories have been set up and/or used in particular for estimating their regional water-equivalent significance. In addition to being important ice storage features, rock glaciers can play a significant hydrological role by affecting water transit time and water chemistry in a catchment.

- *Geohazards*: intact rock glaciers may be the source of direct or indirect hazard phenomena (e.g. destabilization, conveying of loose debris into a debris flow prone gully) that may threaten an anthropogenic environment (e.g. transport infrastructures, buildings, livelihoods). Rock glacier inventories and related kinematic data can be used to locate and assess some potential geohazards at local to regional scales.

It is very important to note that the **motivation for producing and later for exploiting an inventory by a third user may strongly differ**. Standardized guidelines should help to avoid or at least to minimize potential discrepancies.

This has already been mentioned in an earlier paragraph in the preamble section. Maybe not necessary to repeat.

In a later stage (guidebook), compiled by regional experts, it would be useful to include a section that describes the context for each region and specifically how the geomorphological expression and motion would differ between these regions for rock glaciers with similar ice content.

b) Inventories achievement

Two main approaches have been commonly used for inventorying rock glaciers:

- **(geo)morphological approach**: rock glacier features are recognized by visual inspection of the (imaged) landscape and DEM-derived products; surface texture and morphometric analysis could also be used;

  This is the classical approach. Also locally based on field visits. Allows the production of exhaustive inventories of moving and non-moving landforms. Discrimination of moving and non-moving landform (activity classes) primarily based on morphological characteristics. LIDAR-DEM surveys, upon availability, have facilitated the identification of rock glaciers in forested areas.

- **kinematical approach** (more recent): detection of surface motion using multi-temporal spatial data (e.g. SAR-derived products, multi-temporal airborne LIDAR, high resolution optical satellite and aerial images).

  This approach is limited to the identification (and delimitation) of moving areas (e.g. InSAR-derived polygons, Barboux et al., 2014). Relict rock glaciers, for instance, cannot be detected with this method. Provides quantified data for the motion rate, which is however far from being homogeneous on most rock glaciers. Allows also the identification of moving areas, which cannot be morphologically identified as rock glaciers (but which can also be driven – or not – by a permafrost creep process).

While these two approaches yield different resulting inventories, both are complementary and the proposed guidelines have to make them as far as possible compatible.

3. Rock glaciers

a) Technical definition of rock glaciers

Inventorying rock glaciers requires the latter to be specifically defined in this purpose (technical definition). What has to be inventoried?

The definition (also called working definition) is exclusively addressed to frame the objects of concern by a rock glacier inventory, beyond any controversy about rock glacier genesis, origin of ice, etc.

The present technical definition is process-oriented and relies on the most common geomorphological evidences allowing the identification of rock glaciers in the landscape.

Rock glaciers are debris landforms generated by an inherited or functional permafrost creep process, detectable in the landscape due to the occurrence of the following morphological evidences:

A rock glacier is considered exclusively as being (or having been) a sediment conveyor integrated in a broader mountain sediment transfer system, the latter including other elements outside of the rock glacier (e.g. glacier, debris slopes, other periglacial landforms, hydrological system).

Using the term "landform" implies that the perimeter of a rock glacier can mostly be outlined.

Using the terms "inherited" and "functional" comes from the French terminologies classically used in geomorphology to distinguish between what is "acting" (functional) and what is no more "acting" (inherited).

The permafrost creep process may have to be described additionally in a few words (deformation of an ice-debris mixture, shear horizon at depth, etc).

Permafrost creeping areas (e.g. landslides) that can be detected as moving (kinematic approach) but not expressing a rock glacier morphology are excluded. The same for many push-moraines. Therefore a rock glacier inventory is an inventory of rock glacier landforms and neither of any ground ice occurrences, nor of any mountain permafrost-related landforms.

The debris grain size is not specified and can be various.

- **Front:** a steep talus delimiting the terminal part of a (former) moving area overriding a non- or less-moving terrain and, when non-eroded, drawing an arcuate convex linear morphology perpendicular to the flow direction.

Commonly set around 35° and over for intact rock glaciers and between 30°-35° for relict ones but this is a rule of thumb. A clearer rule seems difficult to define.

For a rock glacier developing in a steep slope, its front may be very difficult to be recognized.

Laurichard rock glacier (45°01'05.34"N, 6°23'59.29"E), non-eroded frontal part, French Alps.

Tsarmine rock glacier (46°02'47.177"N, 7°30'24.850"E), eroded frontline, Western Swiss Alps (read more).

Aget back-creeping push-moraine (46°00'32.408"N, 7°14'24.125"E), and its well-developed front, Western Swiss Alps (more) (read more).

- **Lateral margins**: generally well defined morphological structures in the lower part of the landform, in side continuation of the front, often presenting also a front-like morphology, lateral margins may be absent in particular in the upper part of the rock glacier.

Tsarmine rock glacier (46°02'47.177"N, 7°30'24.850"E), lateral margins well delineable in the lower two thirds of the rock glacier, but not in the rooting zone, Western Swiss Alps (read more).

Gugla-Bielzug rock glacier (46°08'19.627"N, 7°49'09.949"E) is a very good example of an active rock glacier where effective lateral margins are very difficult to delineate, or even falsely apparent (the apparent southern margin is attested by GNSS measurement as moving at the same speed as the rock glacier main body).

- **Ridge-and-furrow topography:** linear features associated to a (former) cohesive flow such as transversal or longitudinal ridges and furrows are typically, but not necessarily occurring.

Tsarmine rock glacier (46°02'47.177"N, 7°30'24.850"E) is a very good example where ridges and furrows are lacking, Western Swiss Alps (read more).

Becs-de-Bosson rock glacier (46°10'24.430"N, 7°30'38.528"E), ridges and furrows, Western Swiss Alps (read more).

Transversal ridges and furrows have mostly a concavity facing upslope expressing a compressive flow and must not be confused with transversal cracks, scarps and crevasses, which often have a downward concavity and express an extensive flow.

Rock glaciers should not be confused with debris-covered glaciers that are "glaciers where part of the ablation zone has a continuous cover of supraglacial debris across its full width." In some cases, the transition from glacier to debris-covered glacier and possibly rock glacier is continuous and challenging to define (*cf.* section 3c).

- **Thickness:** a minimum of about 10 meters (for an active landform, estimated using the front) that allows for permafrost creep to (have) occur(red).

The idea of adding a minimal thickness criterion is to avoid other "tongue-shaped" periglacial landforms like solifluction lobes to be inventoried.

Fixing arbitrarily a minimal extent would be important as well, for instance that rock glaciers smaller than 0.01 km^2 (100x100 m) are not necessarily considered in an inventory and single landforms smaller than 0.002 km^2 (45x45 m) should be excluded.

In a functional geomorphological slope sequence, rock glaciers are (or were) landforms conveying debris from an upslope unit (source area or rooting zone) towards their front.

b) Rock glacier morphological units

A rock glacier morphological unit is a part of the rock glacier which can be identified according to the geomorphological evidences described in section a).

A rock glacier landform can be constituted of a single morphological unit or be multiunit (polymorphic). In the case of multiunit rock glacier, the units must be differentiated according to the following non-cumulative (adapted from Brardinoni et al., 2019):

- they are characterized by morphological and land cover attributes that clearly suggest different generations of formation (e.g. overlapping lobes),

- the connection(s) to the upper slope unit can be discriminated (see section c),
- their dynamics are or were differing.

The identification of units is also a question of scale. According the minimal size of identification proposed in the section a), a rock glacier unit smaller than 0.01 km^2 (100x100 m) is not necessarily considered in an inventory and units smaller than 0.002 km^2 (45x45 m) should be excluded.

From this point, the distinction between a rock glacier and a rock glacier morphological unit is not done and only the terminology "rock glacier" is used. All concepts are nevertheless applicable to any rock glacier morphological unit.

c) Connection of the rock glacier to the upslope unit(s)

Rock glacier identification and characterization (e.g. internal structure and composition, ice origin, ice content), as well as assignation of attributes (e.g. landform outlining, definition of the rooting zone) may strongly differ depending on the connection to the upslope unit.

The term "derived" is commonly used in the literature and often leads to never-ending debates on the ice origin. This is why the term "connected" has been preferred in order to strictly refer to the geomorphological slope sequence in which the rock glacier is located.

- **Talus *connected*** - Continuous sequence headwall – scree slope – rock glacier (or headwall – rock glacier): the rock glacier unit is subjacent and connected to a scree slope (talus slope) unit which is dominantly fed by rock fall activity but also by surface runoff, debris flow and/or avalanche events from the headwall unit. The connection area between the scree and the rock glacier is often characterized by a concave morphology, where the episodic to frequent occurrence of long lasting snow/ice patches or avalanche cones as well as their embedding under debris are possible during the lifetime of the rock glacier. The sediment transfer throughout the scree slope unit can be caused by various and imbricated processes.

Talus connected rock glacier (42°49′55.00″N, 43°53′57.62″E), Caucasus mountain range, Russia.

Barmé rock glacier (46°07′01.821″N, 7°39′25.81″E), talus connected rock glacier (ensemble), Swiss Alps.

Laurichard rock glacier (45°01′05.34″N, 6°23′59.29″E), talus connected rock glacier where the scree slope unit is almost lacking, French Alps.

The absence of perennial snow patch in the rooting zone, under current warmer climatic conditions, does not mean that they were not existing during the lifetime of the rock glacier.

Open questions: 1) Integration of protalus lobes/ramparts to the talus connected category? Or to a specific sub-category?

2) Quid of very small (formerly) glacierized area in the rooting zone of much larger rock glaciers? Does it imply that the rock glacier is excluded from this category? Many rock glaciers are of concern. e.g. Becs-de-Bosson rock glacier, Western Swiss Alps (read more).

- **Debris mantle *connected*** - Absence of any (significant) headwall, the debris are dominantly produced by in-situ bedrock weathering (debris mantle) and gradually put into motion by shallow mass movement processes (e.g. solifluction) before developing into a rock glacier feature.

Debris mantle connected rock glaciers (35°45’26.18”N, 80°42’23.21”E), western Kunlun Shan, China.

Gugla-Grüengarten rock glacier (46°07’37.203”N, 7°49’18.019”E), debris mantle connected rock glacier? Swiss Alps.

May (some) frozen debris lobes be part of this category? e.g. FDL-A (67°48'44.33"N, 149°48'27.25"O) (read more).

- **Landslide *connected*** – Mass movement (landslide) is dominantly occurring (or has occurred) in direct connection upslope of the rock glacier or subjacent to it. The scree slope unit is usually lacking where the landslide is developing upslope of the rock glacier, whereas situations where the “landslide” is significantly influencing the rock glacier development have to be considered for the latter.

Landslide connected rock glacier (30°10’08.28”S, 69°54’59.49”W), Tapado, dry central Andes, Chile.

La Cassorte rock glacier (46°02’04.944”N, 7°26’25.067”E) landslide connected rock glacier, upslope connection, Swiss Alps.

Pramousse rock glacier (46°02’14.594”N, 7°30’11.535”E), landslide connected rock glacier, subjacent connection, Swiss Alps.

- **Glacier *connected*** - Continuity from a (debris-covered) glacier or ice patch to a rock glacier feature (debris-covered glacier-to-rock glacier transition). Delimitation between the glacier or the ice patch section and the rock glacier section is not feasible. Embedding of glacier ice within the rock glacier is likely to occur. Morphological indices evidencing the presence of a debris-covered glacier upslope of the apparent rock glacier feature can be observed (crevasses, thermokarst, etc.).

Glacier connected rock glacier (30°09’28.45”S, 69°55’03.16”W), Tapado, dry central Andes, Chile.

Glacier connected rock glacier (30°19’24.52”S, 69°51’47.19”W), dry central Andes, Argentina.

Glacier connected rock glacier (42°01’19.40”N, 78°56’52.23”E), Tian Shan, Kyrgyzstan.

Glacier connected rock glacier (69°45’20.55”N, 52°11’23.88”W), Disko Island, Greenland (Denmark).

To which extent is such a continuum-landform to be inventoried as a (glacier connected) rock glacier or a debris-covered glacier? Or which ones have to be inventoried as rock glaciers (on which criteria) and which ones as debris-covered glaciers (on which criteria)?

- **Glacier forefield *connected*** – 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); embedding of glacier ice within the rock glacier is possible; when retreating (e.g. a common pattern nowadays), the glacier disconnected from the rock glacier or may have completely disappeared. This category includes moraine-derived rock glaciers (flowing towards the outside of a morainic system) and back-creeping push-moraines (flowing towards the inside of a former glacierized area).

Glacier forefield means here the area covered by a glacier, where - by glacier retreat - some geomorphological evidences of previous glacier flow (e.g. fluted moraines) or the absence of frozen debris (e.g. surface running water (stream), absence of motion caused by permafrost creep) can be observed. The delimitation of the glacier unit, even if debris-covered, is mostly feasible.

La Réchasse rock glacier (45°22’54.75”N, 6°47’42.74”E), glacier forefield connected rock glacier, French Alps.

Hohchrüt (46°07’57.50”N, 7°58’38.52”E) and Wysse Bodu (46°08’32.12”N 8°02’13.94”E) rock glaciers, glacier forefield connected rock glaciers, Swiss Alps.

Aget back-creeping push-moraine (46°00’32.408”N, 7°14’24.125”E) and its well-developed front, Western Swiss Alps (more) (read more).

Glacier forefield connected rock glacier (42°33’58.59”N, 44°19’59.49”E), Caucasus mountain range, Georgia.

- **Other** – other type of geomorphological sequence related to a rock glacier landform.

For practical issues, at least three other categories could be added:

- **Poly-connected** – Two or more upslope connection (e.g. talus and glacier connected),
- **Unidentified** – The upslope connection cannot be identified with the used dataset (e.g. imagery limitation (resolution/clouds, etc.)).
- **Unknown** – This is in particular the case for distal units of multi-unit landforms and relict features whose (former) upslope connection is difficult, when not impossible to define.

d) Rock glacier activity

The activity of rock glaciers was conceptually and classically categorized regarding the presumed flow behavior and in consequence the ice occurrence (e.g. Wahrhaftig and Cox, 1959; Haeberli, 1985; Barsch, 1996; Brardinoni et al., 2019). Primarily based on the visual observation of morphological and vegetation-related indicators (that differ locally to regionally due to lithological and climatic settings) rock glaciers have been commonly classified into the following categories of activity:

- Intact:
  - Active : rock glaciers (with excessive ice) which are in effective motion
  - Inactive: rock glaciers that remain (almost) immobile (but 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 content

“Fossil” has also been used to refer to the “relict” definition given above, and “relict” has been used in the sense of “inactive” according to the definition above. “Inactive” has also been used as a synonym of the above given definition of “relict”. Kinematics data show that most apparently “inactive” rock glaciers are effectively moving up to several cm/a and would be “active”.

Intact would mean that there are also “damaged” rock glaciers…?

Regional inventories of rock glaciers have been historically achieved using a *geomorphological approach*. Measurements (in-situ or remotely sensed) as well as valuable field visits have remained almost occasional. With this approach, the activity attribution has always been a highly subjective task depending on the "operators' skills". Thanks to the development of operational procedures to the rock glacier surface motion from remote sensing technics in particular (e.g. photogrammetry, satellite-borne InSAR), precise kinematical information can be obtained for a large majority of rock glaciers, allowing finer categorizations of rock glacier activity to be developed.

Whereas the classical categorization was considering the activity rate of rock glaciers as almost constant over the long-term (decades to centuries), the recent observations on the rock glacier kinematical behavior in particular in the European Alps have shown for instance that an acceleration by a factor 2 to 10 of the surface velocities since the 1980s is a common feature, probably in response to increased permafrost temperature resulting from warmer air temperatures. Whereas a significant majority of the rock glaciers follows this regional trend, some single features experience singular behaviors (e.g. reactivation, rapid acceleration, destabilization or decrease in velocity). In cold permafrost regions (e.g. Arctic) heavily frozen rock glaciers, which are almost not moving or only very slowly, may be expected to accelerate significantly if a warming occurs.

These advances suggest to extend the categorization of rock glacier activity to more classes than in earlier time. The following renewed conceptual categorization is still based on a mass transfer approach (efficiency of the sediment conveying) but not on ice content/volume. It also includes the availability of (some) kinematic information:

The proposed classification and terminology is very open to debate and discussion (and adaptation) to be led during Workshop I.

The original activity concept should also be recognized and somehow be compatible with the new one proposed below.

Morphological and vegetation-related characteristics have to be defined according to the environmental context (guidebook).

Values for motion rate are so far indicative. Surface displacement should also be representative of the permafrost creep and not of another movement like subsidence.

- ***Relict****:* rock glaciers, which have stopped moving for a long time, i.e. at least for several hundreds to thousands of years and in which pore-saturating ice is considered to have fully or largely disappeared.

  Ongoing and expected future climate evolution may do that some currently still moving rock glaciers are becoming or will become relict. Maybe a category to add. But for sure difficult to identify without kinematic data.

- ***Transitional***: rock glaciers with low movements only detectable by measurement and/or restricted to limited area(s). According to the topographic and/or climatic context, they can either evolve towards the relict features or toward active features.

  Inactive means basically no motion. The onset of in situ or remote sensing measurement techniques show that many apparently inactive rock glaciers are moving, slowly, but moving. The terminology is abandoned.

  Cold rock glaciers, which are almost not moving, may (dramatically) accelerate in response to any permafrost warming.

- ***Active***: rock glaciers that move downslope in most of their surface at rates ranging from about 0.1 to 2 m/a in an annual mean. They show steep fronts (mostly steeper than the angle of repose) and eventually lateral margins with freshly exposed material on top.

2 m/a is approximately the uppermost range of motion rate given for active rock glaciers in former textbooks.

- ***Very active:*** rock glaciers moving mostly faster than about 2 m/a in an annual mean.

… that is faster than the velocities mentioned in former textbooks.

- ***Extremely active***: unusually high motion rate, i.e. (arbitrarily) > 10 m/a in an annual mean.
- ***Undefined relictivity:*** inadequate data for discriminating between a relict and a transitional (or active) stage.
- ***Undefined activity***: inadequate data for discriminating between transitional and/or any activity stage.
- ***Unknown***

The recent study by Brardinoni et al. 2019 shows a heterogeneity for activity classification, with least inter-operator agreement for transitional bodies (inactive in the paper). Precise kinematics information allows the proper categorization of rock glacier activity especially for the distinction in between transitional and active classes.

Any activity assessment must be dated, defined and well documented in the metadata.

It might be important to evaluate also the question of time scale of observation. Our ability to discriminate between moving and immobile rock glaciers might increase with increasing interval of observation (i.e. 1 month vs 1 year vs 5 years).

e) Rock glacier destabilization

Rock glaciers characterized by a significant acceleration that can bring the landform, or a part of it, to abnormally high velocities. During this phase of acceleration, morphological features typical of sliding processes, such as crevasses and scarps, could appear and develop on the rock glacier surface. Different stages of destabilizations could be observed: a) a significant acceleration of (a part of) the rock glacier body (suspicion of destabilization), b) the appearance and growing of recognizable surface disturbances (cracks, crevasses or scarps) evolving in time (potential destabilization), c) the dislocation or exceptionally the collapse of the lower part of the rock glacier (consequence of the destabilization). Destabilization generally occurs in a steep and/or convex topography.

A high displacement rate may not be a necessary feature, as some apparently destabilized rock glaciers have moved at a “normal” rate of around 2 m/a or less (Marcer et al., 2019). Inversely, a severe acceleration of a rock glacier showing a singular behavior regarding regional trend without obviously recognizable surface disturbance can also suggest a destabilization (e.g. Tsarmine rock glacier is suspected to be destabilized and has become extremely active (> 10 m/a) since early June 2019) (read more).

El Sombrero (33°36’24.50”S, 69°38’01.80”W), ID: G696332O336058S in the National Inventory of Argentinean Glaciers, glaciers (animation based on Google Earth© and Bing Map© data) destabilized and extremely active rock glacier, dry Andes, Argentina.

Pierre Brune (45°22′49.50″N, 6°50′57.83″E) and Tête du Longet (44°39′39.08″N, 6°54′33.17″E) rock glaciers (animation based on IGN© data), well-defined crevasses and scarps due to phase acceleration, French Alps.

f) Rock glacier outlines

Technically defining a rock glacier as a landform implies an outlining task and for various practical issues (e.g. area calculation) an outline has to be a closed polygon. The operation retains some degree of subjectivity, i.e. is dependent of the "operator". Brardinoni et al. (2019) have shown that the "operators' mapping styles" may highly differ, which consequently impact significantly the exploitation of rock glacier inventory data as for instance the basin-wide rock glacier density, rock glacier specific area as well as maximum and minimum rock glacier elevation, which therefore interfere directly, for example, with altitudinal thresholds for modelling past (e.g., Lateglacial) and present occurrence of mountain permafrost and with first-order assessment of inherent water content.

The study of Brardinoni et al. 2019 identify three main mapping styles to delineate single creeping bodies in the rooting zone (the exclusion, partial inclusion or complete inclusion of the rooting zones), whereas frontal and lateral margins are generally similar through different operators. Outlining a rock glacier in its rooting zone must depend on rules, which could be specific to each type of rock glacier activity and related connection to the upper slope unit(s). The combined use of ortho-imagery, DEM-derived products and remote sensing data is an interesting tool to spatially delineate rock glaciers.

"Outlining" a given rock glacier will always retain some degree of subjectivity…

The following outlines could be conceptually defined:

- ***Extended geomorphological footprint***: the outline embeds the entire rock glacier body up to the rooting zone and includes the external parts (talus apron) of the frontal and (when existing) lateral margins. Rules for determining an outline in the rock glacier rooting zone have to be defined specifically for each category of upslope connection.

Or "total footprint".

Particular issues will rise to outline the frontal area (and the lateral margins), when, i) because of the local topography the talus apron is extending far away from the active front edge, ii) the front is actively eroded, iii) the rock glacier is developing between formerly built lateral levees (moraines) which may be of glacier or rock glacier origin.

Olivares Theta rock glacier (30°16′49.23″S, 69°55′46.03″O) with front toe difficult to be outlined due to steep local topography (i), dry central Andes, Chile.

Undefined-active rock glacier (42°59′20.02″N, 43°32′24.11″E) with front toe difficult to be outlined due to an active erosion (ii), Caucasus mountain range.

Hohchrüt rock glacier (46°07′57.54″N, 7°58′37.74″E) Swiss Alps, as an example to rise up the question about an outline including or not lateral levees (moraines) (iii).

Except where the front is eroded, the extended footprint necessarily includes rock glacier areas which may not be underlain by permafrost and which may be, at least in most external parts, of much thinner than the rock glacier main body (down to the subjacent unit, e.g. bedrock) or the rock glacier moving mass (down to the lowermost shear horizon) (e.g. frontal and lateral talus).

- ***Restricted geomorphological footprint***: the outline includes the main rock glacier body that displays evidence of cumulative creep deformation only. The areas bearing creeping or formerly creeping morphologies (i.e., rock glacier body marked by ridge-and-furrow topography and convex lobes) are included in the outline, starting from upper parts of the front and lateral margins up to the lower end of the rooting zone. Rules for determining an outline in the rock glacier rooting zone have to be defined specifically for each category of upslope connection.

Extended and restricted outlines may be the same where lateral margins (levees, talus) are lacking and in the rock glacier rooting zone.

Tsarmine rock glacier (46°02'47.177"N, 7°30'24.850"E) is an excellent illustrative case to discuss about the use of extend and or restricted outlines (see animation 1968-2016 based on Swisstopo© data) (read more).

One can note that defining the upper edge of a front may be difficult… A very good example is given by Gemmi/Furggentälti rock glacier (46°24'23.59"N, 7°37'52.52"E) where the front is pushed down (away) by the rock glacier moving mass (read more).

- ***Undefined morphological footprint:*** the outline is not strictly following the extended or restricted footprint rules.

- ***Moving area outline(s):*** delimited area(s) with an almost homogeneous motion rate, which may not necessarily be morphologically recognizable. InSAR is a useful tool to spatially outline moving areas.

Specific guidelines are in preparation within the framework of ESA CCI+ Permafrost – Options Mountain Permafrost (2019-2020). Will be discussed at Workshop I.

4. Inventorying strategy

Proceeding to an inventory implies several steps to be followed:

- Recognition of landforms (units and sub-units) to inventory (detecting rock glaciers)
- Identification (ID attribution) and georeferencing
- Attribution of characteristics (attributes), including kinematical information
- Outlining

a) Detecting rock glaciers

Detecting rock glaciers is **primarily recognizing landforms** (rock glacier unit(s)) according to the technical definition proposed in section 3a. It could be basically performed on ortho-imagery as well as DEM-derived products, but also with the help of kinematical data (e.g. InSAR) as a complementary kinematical approach.

How many rock glacier units? Tellers Davains, (46°32'18''N, 9°40'36"E)Swiss Alps (SwissAlti3D, Swissimage © Swisstopo).

How to deal with coalescent rock glaciers? Barmé rock glacier(s) (46°07'01.821"N, 7°39'25.81"E), Swiss Alps.

b) Identification (ID attribution) and georeferencing

A rock glacier (unit) 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) (georeferencing),
- discriminate it unambiguously from other units,
- and associate it to a multi-unit landform, if occurring.

Any other information related to the rock glacier (unit) can then be linked to the primary marker.

The positioning of the point on the rock glacier should avoid, as far as possible, any (frequent) temporal updating. It should not refer to anything else than the three identifying aspects listed above.

The primary marker point is arbitrarily located on the terminal lobe at some distance of (but not on) the front edge.

A proposal is to use a point on the rock glacier front edge as a marker. Choosing the "center" of the front edge seems to be a simple and intuitive way to reduce the uncertainty regarding the point positioning. However, as any active rock glacier is moving and, except where the front is eroded (e.g. Tsarmine), the marker position is quickly out of date.

The option of choosing the geometric centroid cannot be retained because it must be computed on the basis of a rock glacier outline and, depending on the geometry of the rock glacier, could be located outside of the rock glacier.

In case of complex features (multi-unit rock glaciers), the scale of discrimination between units depends of the study motivation(s), the operator, the available data and the complexity of the landform (in particular for relict rock glaciers for which interpretation is complicated by vegetation and/or time/erosion), a **multi-level (tiered) system of marking** has to be adopted.

It is expected that 3 or 4 levels will be enough for the trickiest cases, but it is basically not restricted.

Basic scheme of multi-level concept.

Ribon valley rock glaciers (45°15’50.54”N, 7°03’03.4”E). Depending on purpose, data and operator experience, several interpretations can be done.

c) Attribution of characteristics (attributes), including kinematical information

Rock glacier characteristics are attributed to each unit defined by a primary marker (e.g. connection to upslope unit, activity), regardless the level.

"Unknown" or "undefined" should be used more frequently than today in case of obvious uncertainty in characterizing rock glaciers (attributes).

It is likely also important to mention if the landform is fully visible from the rooting zone to the front or only partly visible (for instance, if overridden by younger units.

Inclusion of kinematical information must be explored during Workshop I. Specific guidelines are in preparation within the framework of ESA CCI+ Permafrost – Options Mountain Permafrost (2019-2021).

d) Outlining

Outlining rules for drawing the extended and restricted footprints have to be defined specifically for each category of *connection to the upslope units* and to be followed as strictly as possible.

Outlining rules are to be worked on during Workshop I.

Rock glacier outlining requires the consideration and the definition of several parameters (e.g. rooting zone, latero-frontal talus) and several options can be used depending on the objective of the inventory.

Any outline which is not following theses specifically defined rules must be characterized as "undefined".

5. References

References in this document have been deliberately limited. An exhaustive bibliography will be compiled at a later stage.

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