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IPA Action Group Rock glacier inventories and kinematics

Towards standard guidelines for inventorying rock glaciers

(Responses to version 1.0)

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

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Box 1 – Preamble

It would be useful to include examples of landforms outside of the Alps and Andes Mountains (e.g. North America, Australasia).

What about rock glacier inventories in other planetary bodies (e.g. Mars; Brough et al., 2019)? maybe more work for us...

Brough, S., Hubbard, B., Hubbard, A., 2019. Area and volume of mid-latitude glacier-like forms on Mars. Earth Planet. Sci. Lett. 507, 10–20. doi:10.1016/j.epsl.2018.11.031

"global assemblage and completion not feasible", I suggest to add that comparisons between rock glaciers can also hardly be done.

Replace "many" with "selected". Compared to the number of rock glaciers, and considering the limitations of remote sensing (topographic shadows, snow, etc.) and the number of rock glaciers that exist on the planet, I wouldn't call it many.

I haven't reviewed all examples provided in the kmz, but we have to be very careful what we are showing.

For example, is the El Sombrero RG really a rock glacier? See:

https://earthengine.google.com/timelapse#v=-33.6035,-69.63766,11.621,latLng&t=0.25&ps=50&bt=19840101&et=20181231&startDwell=0&endDwell=0

Although it is not definitive for the rocky glaciers inventory, as a complement and for their classification, when it is possible, suitable complementary field techniques could be included, not only manual (vision) actions, such as temperature of water in the front, geophysics, soil temperatures or geomatics.

You should mention here that there is no global inventory existing and for many regions there is no information available.

Box 2a – Purpose of standardized guidelines

By far, inventorying rock glaciers cannot be automatized. However, with an increasing number of manually identified rock glaciers based on the widely accepted standard, it is possible to adopt automatic techniques (e.g., deep learning) to compile rock glacier

There is a lack of knowledge to the World Glacier Monitoring Service and previous efforts to include rock glaciers into inventories of perennial ice masses. Although rock glacier does not receive the same attention as other perennial ice masses, they have been, for more than 70 years, a category to be included in perennial ice masses inventories.

Also, there are more examples of rock glaciers inventories, like Zalazar and others (2017) or Barcaza and others (2017) for the Southern Andes. However, a better citation for this paragraph could be the review of Jones and others (2019).

Barcaza G, Nussbaumer SU, Tapia G, Valdés J, García J-L, Videla Y, Albornoz A and Arias V (2017) Glacier inventory and recent glacier variations in the Andes of Chile, South America. Ann. Glaciol. 58(75pt2), 166–180 (doi:10.1017/aog.2017.28)

Jones DB, Harrison S, Anderson K and Whalley WB (2019) Rock glaciers and mountain hydrology: A review. Earth-Sci. Rev. 193, 66–90 (doi:10.1016/j.earscirev.2019.04.001)

Zalazar L, Ferri L, Castro M, Gargantini H, Giménez M, Pitte P, Ruiz L and Villalba R (2017) Glaciares de Argentina: Resultados Preliminares del Inventario Nacional de Glaciares Glaciers of Argentina: Preliminary Results of the National Inventory of Glaciers. Rev. Glaciares Ecosistemas Mont. 2, 13–22

In the context of cryospheric inventories (mostly glaciers), we should indicated why initiatives like the World Glacier Inventory (WGI; Müller et al., 1977) and Global Land Ice Measurements from Space (GLIMS; Bishop et al., 2004) have failed to properly include rock glacier inventories, even though that both initiatives indicate a rock glacier category.

Bishop, M.P., Olsenholler, J.A., Shroder, J.F., Barry, R.G., Raup, B.H., Bush, A.B.G., Copland, L., Dwyer, J.L., Fountain, A.G., Haeberli, W., Kääb, A., Paul, F., Hall, D.K., Kargel, J.S., Molnia, B.F., Trabant, D.C., Wessels, R., 2004. Global Land Ice Measurements from Space (GLIMS): Remote Sensing and GIS Investigations of the Earth's Cryosphere. Geocarto Int. 19, 57–84. doi:10.1080/10106040408542307

Müller, F., Caflisch, T., Müller, G., 1977. Instructions for compilation and assemblage of data for a world glacier inventory. Department of Geography, Swiss Federal Institute of Technology (ETH), Zürich, Switzerland.

I would add that the objectives of the inventories are also different, i.e. often an inventory is created for a specific scope and as such, different inventories may not be compared. Also the scale at which an inventory is generated depends on its scope.

I suggest to add that rock glaciers are transitional landforms and therefore one can see various evolutionary stages. The scientific community has not yet created a guideline for the various forms of rock glaciers that exist that is widely accepted.

I think it is important to focus on the detection of limit elements for monitoring change, so marginal environments are also of great interest.

In other words, also consider those rock glaciers that may undergo dynamic changes in the short term, or morphological transformations indicating changes in high mountain dynamics or permafrost environments.

Could be included the change control by indicators as scientific motivations to the rock glacier inventory.

Among new tools to be mentioned are Lidar DEM's: they give a detailed view of the topography and tend to replace the classical stereoscopic veiw of aerial photographs. If well filtered, a Lidar DEM allows even a good representation for the topography under dense forest cover. This facilitates the recognition and inventory of forest covered fossil rock glaciers, often difficult to assess even on the field (mentioned in notes under 2.b, but should be already mentioned here).

A fundamental aspect of modern inventories is the database. A database typically has a set of morphometrical fields (coordinates, slope, area, etc) and a set of classification fields (morphology, activity and metadata). An important objective of the guidelines should be to suggest the number of fields and give the corresponding description.

Geomorphological mapping (i) – Rock glaciers also play an important role in sediment transport. We suggest adding this to the objective “geomorphological mapping”. Currently this is implied, but it would be good to include it explicitly.

Paleo-climate studies – Intact rock glaciers should also be included in this motivation as cores obtained can be used to study climate variability. Glaciogenic rock glaciers may also provide an indication of where debris-free glaciers existed in the past.

Climate relevant variable – We suggest adding air temperature to this motivation as this may impact rock glacier temperature and therefore movement.

Hydrological significance – In addition to being important ice storage features, rock glaciers can play an important hydrological role by changing water transit times, and changing water chemistry. Understanding the degradation of rock glaciers is also important for water resources since rock glaciers act as both storage features and supply water to the hydrological cycle, especially under conditions of degradation.

Add an objective: Mapping landforms that may contain ice - Rock glaciers and other ice-debris landforms (e.g. permafrost landforms, ice cored moraines) are considered potential water resources. Mapping the geographical extent of these features provides baseline information required to make decisions regarding land use and conservation measures.

“Mountain periglacial (permafrost) landscape.” As it is stated, periglacial and permafrost could be seen as synonyms. Although some authors used like this, others will prefer the more generalist definitions of periglacial related to frost action and not restricted to the presence of permafrost.

Mountain periglacial landscape, depending on the criteria used to define it, could be more extensive than the mountain permafrost area. In this case, mountain periglacial features like solifluxion lobes or terraces could be more widely developed or representative of the periglacial landscape than rock glaciers. It will be more beneficial to the guideline if it uses clear definitions.

Relic rock glaciers should be treated totally different as they lack current permafrost. They are the expression of past permafrost creep and therefore only useful for paleo-permafrost reconstructions (equivalent to moraines for true glaciers, but we don’t include moraines in glacier inventories).

The motivation defines which information is necessary (or not) to provide in (or in complement to) the inventories. For example, for "Climate relevant variable" and "Geohazards", the temporal variations of the velocity is important to document, while this may not be a priority for the 3 first listed motivations. By classifying the rock glacier activity as described in 3d, we may "lose" useful information. Considering this, in addition to the definition of a minimal set of information to include in all inventories, the guidelines should also discuss how to deal with additional data potentially available but not directly highlighted in the final simplified version ("level 1 products" such as kinematics from remote sensing before any classification, displacement time series, etc.).

2 details :

- "climate warming" is not scientifically correct --> prefer "climate change"
- "anthropogenic environment" seems a bit weird --> prefer simply " human infrastructures"

I have some suggestions regarding several wording in this section. For example:

- replace "most common" with "characteristic". I would argue that solifluction slopes are more common
- "essential periglacial". If you talk about rock glaciers in general you would include relict rock glaciers that may not be part of the periglacial environment anymore. But it is geomorphicaly important to map those as rock glaciers (see your point on paleo climate)
- alpine sediments, replace with sediments in mountainous regions
- I encourage to not use terms such as continuous or discontinuous permafrost in mountain regions (hence the term mountain permafrost). Just talk about spatial probabilities.
- Even active rock glaciers can provide information on paleo climatic conditions as their ice can be 10,000 years old
- "are considered" is not proper wording for such a document. I suggest to say "may act as ice storage".
- "threaten" is also not a proper term in this context. it is a hazard to infrastructure and other environments, e.g. also agriculture.

Finally , and most critical in this section, I disagree with how the climate relevant variable is described. In particular the link to its kinematics. This is a point that needs significant discussions.

First paragraph: if considering periglacial in its broad sense, solifluxion is at least as common as rock glaciers, but not related to permafrost.

Box 2b - Inventories achievement

It is important to acknowledge that the geomorphological approach can be done with the full resolution of the remote sensing data (satellite image or aerial photo), while the kinematical approach reduces the data spatial resolution (typically 4-20 times). This has implications for the minimum size of detectable units.

We agree that it is important to use a combined geomorphological and kinematic approach. However, this section does not specify if an inventory should include a) landforms that have both a geomorphological expression and are moving or b) landforms that have either a geomorphological expression or are moving.

We strongly suggest that an inventory should include landforms that show only one criteria (option b) as there are landforms that are not moving but contain significant amounts of ice (e.g. parts of Llano de las Liebres, Chile). Likewise, there are very active rock glaciers that show almost no geomorphological expression that are known to contain significant amounts of ice (e.g. Dérochoir rock glacier).

In general, we do not know enough about the relationship between ice motion and ice volume for rock glaciers around the world to assume that low or undetectable motion is mainly associated with little to no ice.

The document needs to specify which option (a or b) is acceptable. If left to individual interpretation, inventories will likely differ substantially as some may choose option (a) while others may choose option (b).

I strongly agree with the last sentence, it is crucial to integrate the two approaches. For the first time, we have now the possibility to assess the activity of rock glaciers on large (regional) scale, by using airborne LIDARs and satellite SAR data. However, in my opinion these latter methods should be used in a second stage, for example to improve an inventory compiled with a geomorphological approach. This is because the expertise of the scientist that do the visual inspection remain essential and because the SAR approach has still strong limitations in identifying the landforms, for example due to layover and shadowing issues.

Furthermore, an exclusively kinematic approach does not allow to detect not only relict rock glaciers, but also inactive ones.

I of course agree that both approaches are complementary and must be combined, but I don't think the sentence «this [kinematical] approach is limited to the identification of moving areas» is totally right. Kinematics information may also indicate where it is not moving. Relict rock glaciers can indeed not be «detected», but measurements can provide an additional clue that some landforms already mapped by the morphological approach are relict (or inactive).

For the kinematic approach it is also important to state significant limitations due to topography as well as other factors that affect coherence. Also, deformation are LOS and not absolute, which makes it difficult for comparison, some active rock glacier may be considered inactive because of that.

I have also noted that because of the SAR approach, some researchers called a rock glacier that is deforming "active". However, from a traditional perspective, only a rock glacier that is advancing, i.e. the front is moving, is an active rock glacier. A rock glacier where the permafrost is degrading will also move, but should likely be considered an inactive rock glacier.

Concerning InSAR: an important point is that InSAR datasets cannot be totally comprehensive, because of 1) shadow zones not visible on images, and 2) N and S oriented movements, which can only partly be assessed by the method.

Box 3a - Technical definition of rock glaciers

I agree it is very useful to set a minimum threshold of 0.01 km2 for the area and 10 m for thickness.

I also agree with the rooting or contributing zone comment. It is fundamental for a rock glacier but is hard to define and has not been adequately deled within available studies.

Main definition: the motion comes in the first place from deformation of ice-rich debris. I would highlight this point.

Thickness: the thickness alone ~10 meters cannot determine permafrost creep. It is the driving stress, given by the combination of density, slope and thickness, that matters.

The suggested minimal extent makes sense, especially when applying the kinematical inventorying approach, due to the limited resolution of remote sensing products.

In the rock glacier definition the terms "inherited or functional" are used. These terms are not intuitive to understand and may cause confusion or misinterpretation. We suggest rewriting this definition using language that is more explicit and easier to understand.

This rock glacier definition defines these landforms as "creeping". However, landforms may contain a significant amount of interstitial ice and may not creep, so the definition excludes this type of landform. Please consider rewriting the definition to include such landforms.

The rock glacier definition does not specify if one or a combination of the geomorphological criteria are required to classify a landform as a rock glacier. This needs to be clearly defined as inventories would vary significantly if left up to individual interpretation. We suggest that only one criterion be required to include a landform in the inventory. This would ensure that most if not all landforms that may contain ice are included by default, at least for the inventory that has an "extended morphological footprint."

The rock glacier definition should also be clarified to allow for differentiation between rock glaciers and landforms with similar characteristics that are not considered to be rock glaciers.

Examples outside of the Alps should be provided in this section.

Front – It is not clear from this definition if rock glaciers with eroded fronts are included or excluded from the inventory.

Lateral margins – If lateral margins are a requirement for all landforms included in the inventory, this would exclude permafrost landforms (e.g. cryogenic rock glaciers) that may not contain well defined lateral margins but may contain significant amounts of ice. We suggest one of these four criteria should be required to include a landform in the inventory, but not all four.

Ridge-and-furrow-topography – Perhaps add that if there are measurements that indicate motion that this criterion is met, even in the absence surface topography indicating motion.

Thickness – This criteria might be useful if measurements are available, but in many regions (e.g. Andes mountains) measurements of rock glacier thickness are scarce making this criteria inapplicable in the vast majority of cases. Why was 10 m chosen? Is this the total thickness of the landform or the thickness of the active layer? Does it make sense to require a particular thickness? Is the minimum thickness of about 10 m meant to relate to a particular amount of ice motion? If that is the case, the slope of the terrain surface would also be important since the velocity of a glacier may vary due to a change in slope even if the thickness remains constant.

Fixing a minimum extent – we agree that it makes sense to fix a minimum extent for rock glacier inventories.

In addition to describing the characteristics that define rock glaciers, we think it is also important to clearly define the difference between rock glaciers and debris-covered glaciers in this section. A possible description of the difference could be:

Debris-covered glaciers are characterized by exposed ice due to the discontinuity of debris cover or thermokarst collapse, among other features, that create a rough surface. In contrast, almost no ice is visible on the surface of rock glaciers and they are comparably smooth and convex (Janke et al. 2015; Monnier and Kinnard 2017).

"generated by an inherited or functional permafrost creep process" this implies that a rock glacier must be generated as a periglacial form. However, several rock glaciers are of glaciogenic origin and started as glaciers, i.e. glacial forms, and only due to the cover and changes in environmental conditions / sediment transport etc. they turned into a rock glacier.

What is steep? Please provide a technical definition, for example reference the angle of friction of the material. However, if a rock glacier becomes inactive, the front slope may flatten. Would that landform no longer qualify as a rock glacier? I suggest that we say, it must show signes of current or past frontal slope equal or close to the angle of friction of the material.

How do you define the bottom of a rock glacier? Is it the base of the permafrost, or the original valley, or where, after being potentially compressed and pushed, the original surface material is located? How can the depth of a rock glacier be determined? Geophysics has its limitations and cannot be done for large study areas.

Do we include protalus ramparts? Where does a rock glacier start? I've seen very large protalus ramparts.

The minimum thickness of 10 meters is rather arbitrary and should be expressed as it, unless litterature exists about it.

• In 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.

I think this section is important to be clarified to differentiate different forms such as debris-covered glaciers, block streams or protalus lobes. The first is vital to differentiate transversal ridges from transversal cracks or crevasses, where the context, the passage from glacier to debris-covered glacier and possibly rock glacier, allows a reliable approximation, but criteria should be established. In the second, the blocks streams and rock glaciers without transversal ridge can be confusing, but they have clear differentiating features, such as frontal steep talus, lateral margins and size. All of them, combined, can be the main criteria to differentiate between blocks stream and rock glacier. The third one, criteria most clear can be the size, slope position and absence of surface features.

• Thickness: a minimum of about 10 meters (for an active landform) that allows for permafrost creep to (have) occur(red).

A minimum thickness (10 m thickness) is a problematic criteria. In mountains with marginal periglacial environments during the Holocene or at present day there are small active rock glaciers that may not be 10 meters thick, but they have the characteristic features, such as furrows, transversal ridges, steep talus in the fronts and lateral margins.

An example in the Pyrenees is La Paúl rock glacier, where it does not have 10 meters thick, but it is attested to be an active rock glacier.

In my opinion, a precise altimetric criteria should not be established as a limiting factor for the existence of a rock glacier. The combination of size, thickness and surface features could be better to define the rock glacier, but morphological criteria over size and thickness are predominant.

Landslide: this a confusing generic term for mass movements, and dosn't mean "glissement de terrain". It should be avoided. Use mass movement if generic term, or the appropriate process if refering to a given process (slide, rockfall, ...)

Thickness and area: why limiting the size ? from a hazard point of view, small features may be important. They should be surveyed. Filtering a dataset by size for intercomparison purpose is an easy task on a GIS.

Any example or counter-example?

http://www.glaciaresargentinos.gob.ar/wp-content/uploads/legales/manual_ING_2014.pdf.

Larsbreen, Svalbard 78.193968°, 15.598948°
Tapado, Chile -30.159662°, -69.921806°

https://www.sciencedirect.com/science/article/pii/S0034425716305053

Below is a list of examples that may be used for further discussions as in most cases there are many uncertainties:

Landform 01	69° 32' 36" W 28° 26' 48" S
Landform 02	70° 15' 35" W 32° 01' 15" S
Landform 03	70° 26' 56" W 31° 44' 27" S
Landform 04	70° 10' 11" W 31° 52' 40" S

Landform 05	70° 12' 10" W 31° 56' 04" S
Landform 06	70° 28' 59" W 31° 47' 02" S
Landform 07	70° 27' 47" W 31° 48' 53" S
Landform 08	70° 14' 36" W 33° 12' 50" S
Landform 09	69° 43' 31" W 33° 11' 01" S
Landform 10	69° 44' 56" W 33° 10' 43" S
Landform 11	69° 45' 15" W 33° 10' 21" S
Landform 12	69° 54' 11" W 29° 58' 48" S
Landform 13	69° 51' 51" W 30° 00' 12" S
Landform 14	69° 51' 48" W 30° 01' 42" S
Landform 15	69° 52' 28" W 30° 01' 29" S
Landform 16	69° 53' 07" W 30° 02' 06" S
Landform 17	69° 50' 12" W 30° 03' 14" S

La Paúl rock glacier (Posets massif, The Pyrenes)
42º 38´ 39´´N   0º 26´ 34´´E

Box 3b – Rock glacier morphological units

The differentiation of units is characteristics of rock glaciers that must be included as a parameter to be recorded. In the National Glacier Inventory of Argentina, we use single and multi-units. For more information, please see http://www.glaciaresargentinos.gob.ar/wp-content/uploads/legales/manual_ING_2014.pdf.

Something unclear to me about the minimal size of the rock glaciers / units (100x100 m / 45x45 m). The values are written twice at pages 6 and 7 but with different terminologies. Does it mean: rock glacier (the whole landform potentially including several units)

instead of "different ages" I suggest to use "different generations". The age in a rock glacier can vary with depth of severel 10s of thousands of years.

Box 3c – Connection of the rock glacier to the upslope unit(s)

talus connected

debris mantle connected

Another example of debris mantle connected rock glacier in East Kunlun Mountains of China: 35°41'55.32"N, 94° 2'32.46"E. The coordinates record the central location of one landform which has been identified as a rock glacier based on remote sensing observations (optical and InSAR imagery) and field visits as well in our recent study. The nearby lobes show similar kinematical behaviors in our study but lack field validation due to their inaccessibility.

This category certainly exists, but should possibly be sub-divided into two distinct types. As defined in the document, the process means that surficial debris produced by weathering suply debirs downwards to a rock glacier. Solifluxion is a shallow process, which thickness doesn't exceed the depth of the active layer. It cannot therefore evolve per se into a rock glacier.

I think that there exist cases where in-situ frost shattered bedrock evovles directly into a rock glacier, through developpement of ice between rock layers/debris. This concerns fine layered rocks like shales or shists. An example is the Berard rock glacier, which starts on the crest without any heawall. Another possible case is the Col du Lou, based on observations in the slide scar in 2015. I will come with some examples on the workshop.

landslide connected

I don't like this category because a rock glacier is in essence also a landslide. In addition, there are different types of landslides (e.g. Cruden and Varnes, 1996; Hungr, et al., 2001)

Lanslide is a confusing generic term (see comment on 3.a). This category should be reowrked, possibly distinguishing mass movement processes. For instance, rock glaciers developing from a rock fall deposit, or activated by a rock fall onto the rock glacier. Nota at all the same as a rock glcier developing potentially from a slide mass (this category being ptentially difficult to dstinguish from the "debris-mantle derived" category. In any case, the specific process term should be used instead of the generic term.

glacier connected

The glacier-connected rock glaciers should be considered as one unit (one ID) with different parts. The different part should have a morphological category assigned, using a mixt category when necessary.

A glacier connected rock glacier sometimes can be differentiated from the upslope debris-covered glacier based on their different kinematical behaviors due to their contrasting dynamic mechanisms (permafrost creep vs. basal sliding of ice patches). For instance, the upslope glacier part frequently appears to be decorrelated in the interferogram while the downslope rock glacier part with moderate displacement can be well recorded in the same InSAR image, although this criterion does not always work when the rock glacier part is extremely active.

It is true that it is not easy and sometimes feasible. But it is important to differentiate the elements of the glacier/debris-covered glacier/rock glacier system if we search for to inventory and classify rock glaciers.

In my opinion we must look for morphological and textural criteria to separate the debris-covered glacier and rock glacier. In this case the existence of furrows is not a good indicator, as they can be transversal cracks or crevasses, but the combination of clear-cut elements can serve as criteria:

- Presence of a steep front with continuity in the margins. When the steep talus ends on the lateral margins, it can be the end of the rock glacier.
- Transversal ridges, crossing from one side of the glacier to the other, without discontinuities or ruptures (which can imply the existence of crevasses in the underlying ice).
- Textural changes, from more homogeneous in the debris-covered glacier to greater heterogeneity where transversal ridges appear. There may also be other types of textural changes.

A single criteria is not definitive, but the combination of all of them may allow greater precision in the delimitation between debris-covered glacier and rock glacier within the glacier-rock glacier system.

This type may lead to confusing discussions on the origin of ice ... Even if obvious cases exist. The core question is whether to consider theses as debris-covered glaciers or even dead ice bodies, or as rock glaciers. I will show the example of the Fontenil debris-covered/rock glacier.

glacier forefield connected

A good example: the Marinet rock glacier in the Haute Ubaye. Retreat fo the glacier leaves a deep depression occupied by a moraine/rock glacier dammed lake, with total deconnection between the glacier and the creeping debris covered boy. See also the paper by Ribolini et al.

General comment regarding upslope unit(s) connection

The rooting zone of rock glaciers must be included as a parameter of any rock glaciers inventory. The descriptive category suggested looks practical to analysis the origin of the ice content of the different rock glaciers. In the National Glacier Inventory of Argentina, we use single and multi rooting zones. For more information, please see http://www.glaciaresargentinos.gob.ar/wp-content/uploads/legales/manual_ING_2014.pdf.
However, it must be taken into account that the “Glacier connected” type could contain more area of the debris-covered glacier than rock glacier. In the National Glacier Inventory of Argentina, we use the category debris-covered glaciers with rock glacier to emphasis that it is more a debris-covered glacier that “ends” as rock glacier.

To some extent we need to be able to define the upper boundary if one wants to draw a polygon around the rock glacier. A criterion must be defined.

I do not like the term "connected", and prefer the tem "derived". Of course, we have to avoid any consideration on the origin of ice. But the origin of debris is, in most cases, clearly identifiable. The term "derived" shoud therefore refer exclusively to the debris

Box 3d – Rock glacier activity

I think the activity category (active, inactive, relict) should be noted in one field of the database. When available velocity and measurement technique should be reported in additional fields.

The difference between active, very active and extremely active should not be made only based on velocity. The velocity depends on the stresses, which depend on internal structure and (in first approximation only) on the slope. A very steep rock glacier with a velocity of 3 m/a could be less "active" than a more gentle rock glacier with the same (or even lower) velocity.

The time scale of observation is an important issue for measuring surface movement and identify the level of activity of a rock glacier with InSAR because the period between two SAR measurements is normally shorter than several tens of days for the sake of good coherence. When the observed rock glacier has strong seasonal kinematic variations, the InSAR results may vary with the period of the measurement.

The definitions of rock glaciers at the beginning of this section indicate a gradation of ice volume from no ice (relict) to some ice (inactive) to a significant amount of ice (active). Likewise, the terms listed as bullets below are placed in an order that also implies a gradation of ice volume from no ice (relict) to some ice (transitional) to more ice (active). While there is no mention of the amount of ice for "transitional" rock glaciers, the name could imply that it is between relict (approximately no ice) and active (generally assumed to contain a significant amount of ice).

While this direct relationship between velocity and ice content may be true for some regions of the world, we think it is important to consider the activity definitions in terms of different climate settings. For example, rock glaciers in the semiarid Andes exist in a relatively cold climate and there are examples of rock glaciers in this region that have little to no detectable motion, but are very likely to have a significant amount of ice (e.g. portions of Llano de las Liebres). In this region and other regions in the world we simply do not have enough information (both velocities and ice volume) to be able to assume that slow moving or stagnant glaciers have a smaller ice volume than those that are active. We propose that the amount of ice is not only related to the motion, but also to temperature and the internal structure (massive ice versus interstitial ice; sediment configuration; presence of water; etc).

We strongly suggest separating the definitions of ice content from ice motion. We envision two subsections: 1) rock glacier ice content and 2) rock glacier activity. In section 1 the terms intact and relict would be defined as these directly relate to ice content. Below are suggested definitions for each term. Given that in many parts of the world there is simply insufficient information to quantify the ice content (e.g. GPR measurements) or the ice motion, we suggest that these definitions provide specific geomorphological descriptions and do not solely rely on criteria that must be measured.

Relict – Rock glaciers that have lost all of their ice content and stopped moving often several hundred years ago or more. Where there are no measurements to verify the lack of ice, the landform is considered to be relict if it agrees with the following geomorphological description. There is subsidence on the surface (e.g. due to water movement, gravitational settling), the surface has an erratic, chaotic appearance of superficial debris characterized by irregular small hills and boulders, and the front slope of the rock glacier has been removed. The rock glacier may also exhibit coarser surface debris that has not moved in a significant amount of time, weathering processes may have altered the exposed surfaces of boulders, fine material may have been removed by snowmelt, and there may be vegetation cover (Janke et al., 2015). Given that there are no measurements of rock glacier motion from > 100 years ago, the second part of the definition cannot be verified. However, if a rock glacier has remained stagnant throughout its measurement period, this can support the geomorphological interpretation that the rock glacier is relict.

Intact - Rock glaciers that contain ice (e.g. Azocar et al., 2017; Brenning et al. 2007)

In section 2 terms related rock glacier motion (activity) would be defined. As mentioned above, we think that the term "transitional" can be misleading as it may relate to both ice content and motion. Instead, we suggest using a term that specifically relates to motion such as "semi-active." Given that the term relict is associated most directly with the ice content, we also suggest removing this term and instead using "inactive" to describe rock glaciers that have no detectable motion. The terms relict and intact would not appear in this section as they primarily relate to ice content. It should be mentioned in this section that in some regions glaciers may not have detectable motion or may be moving slowly and still contain a significant amount of ice. We suggest the following definitions.

Inactive – rock glaciers that are immobile or almost immobile. This category may include relict and intact rock glaciers.

Semi-active – rock glaciers that move slowly without obvious geomorphology that suggests motion (e.g. steep fronts, ridges and furrows). Depending on the topographic / climatic context, they can either evolve toward inactive or active landforms.

Active- rock glaciers that move downslope across most of their surface at an annual averaged rate ranging from about 0.1 – 2 m per year. These rock glaciers may have steep fronts (mostly steeper than the angle of repose) and eventually may have lateral margins with freshly exposed material on top.

….we have emphasized “may” have steep fronts since we know of at least one rock glacier without a steep front that would be considered active (Dérochoir rock glacier).

Very active – rock glaciers moving mostly faster than about 2 m/a (annual mean).

Extremely active - unusually high motion rate, i.e. (arbitrarily) > 10 m/a (annual mean).

Additional comments:

Do we want to define the activity status based on velocity measurements (e.g. in situ, satellite based) only? Would it make sense to define geomorphological criteria which could be used in the absence of velocity measurements to determine if a rock glacier is likely to be active? For example, one could consider a form to be “likely active” if the landform shows coordinated movement over much of its surface (e.g. ridges and furrows) and a steep front. Requiring that lateral margins exist would largely exclude cryogenic landforms from the inventory. Do we want to include all landforms that may contain a significant amount of ice or just those that have an approximate glacier form (e.g. defined frontal slope and lateral margins)?

The proposed terminology highly improves the definition of this essential kinematic characteristic of rock glacier and would motivate future studies of rock glacier dynamics and ice content.

One thing we should think about when dealing with surface displacements measured from remote sensing: as we are measuring the surface dynamics, we cannot be sure it is directly related to the rock glacier creep. For ex, in the case you have only one SAR geometry available and you detect 1D displacements along the LOS using InSAR, you cannot be sure about the movement orientation and the involved mechanism. F.ex: small displacements on a rock glacier could potentially be related to subsidence due to ice melting on an inactive rock glacier, or to a slowly moving active rock glacier. Couldn’t it even be related to superficial displacements on a relict rock glacier even if there is no ice anymore?

About the sentence «any activity assessment must be dated»: Not only the time period has to be documented, but also the temporal and spatial resolutions, as well as the detection capability of the measurement technique. I think it would be important to add a chapter related to the metadata in the guidelines.

In my view, there are too many categories. IN addition I have the following comments, that I think should be discussed during the meeting:

1. I do not support the term "intact" as it means there is an not intact or damaged rock glacier.

2. I see challenges in defining the surface moving rate as a single value, because it may not be clear what exactly is the outline (see comments regarding the top, or are you looking at individual generations, or the whole complex?) and I have hardly seen inSAR from a rock glacier where every point on the rock glacier has a good deformation point. Often we just have a couple of points and with inSAR you may also have many coherence challenges.

3. rock glacier deformation rate is not directly linked to ice content as the deformation typically depends on the characteristics of a discrete shear zone and not the constitution of the whole rock glacier.

4. Are the values taken annually, or measured over several years, or what is the criteria for the deformation rate?

5. The term active rock glacier as defined here is significantly different from what has been used in the past where activity was referring to the advancement of the rock glacier, not its velocity per se. I think that the original concept should also be recognized.

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.

I understand that "transitional" replaces "relict" in the new dynamic classification. I think that it is not necessary to change the names even if the attributes are changed when knowledge advances, because it complicates the conceptualization of the elements to study and take into account the contributions of the past. In this case it is defined as a dynamic state, transition to relic or active, presuming that it cannot remain as a frozen body without movement for thousands of years. In the other hand, historically, we considerate the inactive as a transition from active to relict, never in the opposite sense, and it is necessary to think about if it is possible changes from relict or inactive to active in present day climatic context. Is there any current example or for the last 12000 years? I think it must be discussed in the workshop.

I think it is very difficult to establish changes or movements in inactive-transitional rock glaciers. It is necessary to differentiate between horizontal displacements and vertical or horizontal movements derived from like-cryokarstic processes that generate subsidence, and displacements according to the slope and readjustments. We have found that there are small horizontal displacements derived from the melting of the ice of the rock glacier, with short displacements in different directions (uphill, transverse and downhill) in the rock glacier of Maladeta, linked to subsidence depressions.

A difficult criteria to establish the inactive-transitional or active ones, but interesting when we have data, would be:

- A minimum displacement (I do not know how much is it, but the minimum displacement could be the minimum pointed in the proposal, <10 cm/a), and a homogeneity (of direction and gradual increase or decrease of the speed of movement) in the entire body of the rock glacier to be classified as active rock glacier. The minimum displacement must be discussed and established with a small rank, because active rock glaciers have areas with displacement lesser than 10 cm/a.

-Displacements on individual points and scattered throughout the body of the rock glacier, with variables displacements speeds, vertical movements (sinking), together with subsidence depressions on the surface, would indicate a greater probability of being an inactive-transitional rock glacier. In any case it is a transition to relict rock glacier.

Transitional: an "inactive" rock glacier still contains ice, which means that at least movements due to the melting of this ice can still occur. The question therefore is to define what is meant by movements. According to the definition, lateral creep movements should no more occur, but vertical subsidence movements are not only likely, but must occur with permafrsot degradation, and possibly thermokarst features. The problem with InSAR is that lateral and vertical movements cannot be easily distinguished, especially if the movements are very slow.

Box 3e – Rock glacier destabilization

Destabilization could also be a special case of a very active rock glacier. Although not always the case, when rock glacier or a unit of a rock glacier speed up could produce a destabilization of the rock glacier (unit).

Maybe a naive question: what does abnormal mean and how to know it based on the classification described in 3d? Or more generally: how to integrate information related to the temporal variations of the velocity in the inventories?

I very much caution from using this category and strongly suggest to delete it as it will result in misleading interpretations. The stability of a rock glacier, or any slope for that matter, must be assessed using proper stability assessment methods. And it would not be practical to collect the information required for such an assessment for every rock glacier inventoried.

Box 3f – Rock glacier outlines

We think that these "footprint" definitions are very useful and should be included. If the inventory is not defined in this way, there could be drastic differences between inventories as mentioned in the first paragraph. The term "geomorphological footprint" would likely be more appropriate than "morphological footprint". Please consider changing this term in the document.

Extended morphological footprint – We agree with this definition.

Restricted morphological footprint – The description here only talks about including creeping morphologies such as ridges and furrows. We think that this footprint should also include steep frontal slopes. The extent of the frontal slope to be included should also be defined (up to the external portion of the talus apron, or mid-way where there is often a change in colour due to talus movement). Some landforms may not exhibit creeping morphology, but may have an abnormally steep slope indicative of ice within. Should these landforms be included within this footprint?

It could be useful to define a "geomorphological footprint" for calculating the amount of stored ice to ensure consistency when calculating water reserves stored in rock glaciers around the world. We would like to suggest that this be a combination of 1) the extended morphological footprint excluding all areas that are defined as "relict" based on geomorphology and possibly part of the rooting zone if there is no geomorphological evidence for the presence of ice and 2) includes the moving area outlines if available (in addition to 1). In this footprint we start by assuming that all landforms or parts of landforms that may possibly contain ice now or may have contained ice in the past (based on geomorphology or measured motion) should be included, then parts of landforms or entire landforms identified as very unlikely to contain a significant amount of ice are removed (e.g. those areas that are defined as relict).

Additional comments:

Given that the geomorphological expression and motion of rock glaciers having a similar ice volume can vary significantly in different parts of the world, it would be very useful to include a section that describes the context for each region and specifically describes how the geomorphological expression and motion would differ between these regions for rock glaciers with similar ice content. A sentence or two could be added to highlight the most pressing motivation for studying rock glaciers in each region (e.g. water resources, rock glaciers as hazards in populated areas).

We have noticed that most if not all of the examples are ones that "fit" the guidelines described. It would also be good to provide examples that are difficult to define and exceptions to the rules to help others interpret these types of exceptions and ensure consistency among those completing inventories around the world.

Thanks for your effort in putting together a first draft and being open and receptive to receiving feedback!

This is a crucial point that was not tackled by previously perennial ice masses inventory guidelines. If there is an intention to include the rooting zone, it must be done as a separate category or polygon. If not, any intention to derive the potential as water storage of rock glacier from an inventory will be inhibited. The same is valid if we want to include the foot of the frontal slope.

The mapping of rock glacier as the area where there are surface characteristics of creeping permafrost will be more comparable with the "moving area" defined by surface displacement studies.

We need to recognize that subjectivity will always be present, particularly to delimit the boundary between the rock glacier body and it nourish area or rooting zone. Nevertheless, some degree of freedom is better than the inclusion of high slopes or bedrock slopes, where the presence of ice is extremely low.

Pratically, does it mean that you consider two categories of polygons, one based on the morphology, one on the kinematics? Just wondering how to inventory landforms with large spatial variability of velocity? Or two neighbouring/imbricated landforms with similar velocity class but different mechanisms/morphologies?

1. I actually question why do we need to outline rock glaciers. Wouldn't it be more reasonable to describe rock glacier as it is suggested and in maps only map the outline that is possible, i.e. often just the sides and the front? Other than for the benefit of putting them in a box, what is the actual benefit of knowing where on a slope the rock glacier starts? Wouldn't it be more valuable to talk about potential ground ice volume, thereby completely understanding the range will be huge?

2. If a outline is defined, the group should propose a single method. There can't be different methodologies.

3. My suggested outlines depend on the type of a rock glacier. For the traditional rock glacier, the upper limit would be where there is a clear break in the slope where the source zone (talus slope) ends. For glacier / rock glacier transitional forms, the rock glacier would start where signs of permafrost occur, i.e. active layer and creep movements, v.s more thermokarst type deformations that are more likely signs of a debris covered glacier.

4. As per other comments regarding significant limitations of InSAR, the moving area outline is not a practical approach. We have to be careful to not choose an approach that works on ideal cases, but is globally not practical.

I agree with the details of section f. I think the different outlines must be discussed and established.

As general criteria I think that the body of the rock glacier should be separated from the external parts and considered a restricted morphological footprint. External parts may include other forms and processes (protalus lobes, gelifluxion lobes, on debris talus connecting with rock glaciers) that need to be differentiated from the rock glacier.

In each outline type can be taken into account:

- Geomorphological changes: as you expose. The existence of furrows, transversal ridges, and so on.

- Changes in roughness and texture. Mainly to differentiate different areas of the rock glacier and the rock glacier itself from the elements connected to it (talus, clast-covered glacier, protalus lobes...).

- Detection of ice bodies, crevasses, cracks.

- Differentiate the debris slope and associated landforms (debris lobes, gelifliuction lobes or sheets, rockfall) and glaciers, as clast supplies, from rock glaciers and their feeding areas (roots), transition or front.

I think we should consider the rock glaciers as an individual part of the alpine cascade system, integrated in a broader system that includes other elements outside the rock glacier (glacier ice, debris slopes, periglacial landforms, proglacial water, and so on), but in the case of inventory, works only on the rock glacier body.

In the initial French rock glacier inventory, the frontal/lateral slope was digitized separately. This allows to combine surface and front polygons into an "extended" footprint (the question of rooting zone being an additionnal question). The mapingoof the frontal/lateral slpe can be interesting for mapping representation purpose too.

Relict rock glaciers: the "rooting zone" may have be subjected to various processes after inactivation of the rock glacier (e.g. development of a large scree cone over the rooting zone, glacieret, etc.). In these cases, the "rooing zone" should not be included in the footprint. There shoould be therefore an "extended footprint without rooting zone", which corresponds to what a geomorphologist would noramlly map on a geomorphological map.