IPA Action Group Rock glacier inventories and kinematics

Kinematics as an optional attribute in standardized rock glacier inventories

(Version 2.1)

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

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Authors and contributions

The document has been edited by the scientific committee of the Action Group Workshop II held in Fribourg (Switzerland) on 11-13 February 2020, namely and in alphabetical order Chloé Barboux (University of Fribourg, Switzerland), Aldo Bertone (University of Fribourg, Switzerland), Xavier Bodin (CNRS, France), Reynald Delaloye (University of Fribourg, Switzerland), Line Rouyet (NORCE, Norway) and Tazio Strozzi (Gamma Remote Sensing, Switzerland).

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The purpose of this document is to serve as a baseline for the establishment of practical guidelines permitting the integration of kinematics as an optional attribute in standardized rock glacier inventories.

Contents

Preamble

Task 1 of the IPA (International Permafrost Association) Action Group *Rock glacier inventories and kinematics* (2018-2022) aims at exploring the feasibility of developing widely accepted standard guidelines for inventorying rock glaciers on a global scale, including information on their kinematics. *Baseline concepts* (Sub-Task 1.1) have been elaborated in a common contribution of the Action Group members. *Practical guidelines* and a *technical (operational) manual* for inventorying rock glaciers (Sub-Tasks 1.2 and 1.3) will be prepared in accordance in a later stage.

The *baseline concepts* specify that **kinematics could be included as an optional attribute in standardized rock glacier inventories**. However, the way this integration could be performed requires further investigation.

The present document intends to set the **necessary concepts** for including kinematics as an optional attribute in standardized rock glacier inventories. The document content results from preparatory work performed by the scientific committee of the Action Group Workshop II (version 1.0), comments received on it until 2 February 2020 and the following discussions with the participants to the workshop held in Fribourg (Switzerland) on 11-13 February 2020 (version 2.0).

Provisional timeline

Feedbacks on version 2.1 by the Action Group members are expected until **31 May 2020**, using exclusively the dedicated boxes inserted at the end of each section.

The final version (3.0) is intended to be submitted for approbation in June 2020.

The practical issues regarding the implementation of a rock glacier kinematic attribute will be included in the *practical guidelines* for inventorying rock glaciers.

If you have any comment about the previous section, please use this box.

Comment box 0

1. Purpose of integrating kinematics in rock glacier inventories

Today, although many (published and unpublished) regional rock glacier inventories exist, they are not exhaustive worldwide. Existing rock glacier inventories have various ages and have been compiled for different purposes and using different methodologies. For these reasons, merging all inventories in a fully coherent way is presently not possible. The IPA Action Group *Rock glacier inventories and kinematics* (2018-2022) has thus agreed to work on the establishment of standard guidelines permitting the coherent development, homogenization, comparison and fusion of new and existing inventories.

The increasing emergence of open-access and high-resolution remote sensing imagery (e.g. optical, SAR) facilitates the development of new regional inventories and/or the update of existing ones. The growing availability of remotely sensed data (e.g. Sentinel-1 SAR images) makes the systematical capturing of rock glacier surface motion and consecutively the integration of a kinematic information in standardized rock glacier inventories potentially feasible.

In the *Baseline concepts towards standard guidelines for inventorying rock glaciers*, the Action Group has defined that the attribution of an activity category (namely active, transitional, relict) to a rock glacier unit is primarily based on geomorphological indicators, but, if available, can also depend on any measured and adequate kinematic data. It has therefore been specified that an **optional kinematic attribute** could be included in standardized rock glacier inventories, the way this integration could be performed however requiring further investigation.

The *Baseline concepts* also describe the two approaches in use for inventorying rock glaciers, namely:

- **Geomorphological approach**: rock glaciers are recognized by a systematic visual inspection of the (imaged) landscape and DEM-derived products. To this purpose, surface texture and morphometric analysis could also be used. This is the classical approach, locally complemented by field visits. It allows the production of exhaustive inventories of presumed moving and non-moving landforms, whose discrimination (activity classes) is primarily based on geomorphological characteristics. Photogrammetry and LiDAR DEM surveys, when available, facilitate the identification of rock glaciers in forested areas.

- **Kinematic approach**: moving areas, which may be temporally and spatially heterogeneous, are detected using multi-temporal remotely sensed data (e.g. SAR-derived products, multi-temporal airborne LiDAR, high resolution optical satellite and aerial images). The association of a moving area to a rock glacier is then mainly performed by the geomorphological assessment of optical images (geomorphological approach). This approach is limited to the non-exhaustive identification and delimitation of moving areas on rock glaciers, whereas non-moving rock glaciers, for instance, are missed. It provides quantitative data for evaluating the motion rate of rock glaciers. It also allows the identification of moving areas, which cannot be geomorphologically related to rock glaciers

Whereas the two approaches are complementary and can be used in an integrated and iterative process, a rock glacier inventory is by definition a geomorphological inventory.

The overall purpose of the present document is thereby to define the **baseline concepts permitting the integration of specified kinematic information as an optional attribute in standardized** (geomorphological) **rock glacier inventories**.

If you have any comment about the previous section, please use this box.

Comment box 1

2. Kinematics as an optional attribute in standardized rock glacier inventories

2.1. Background and limitations

Within the framework of rock glacier inventories, only **surface velocity measurements** can be taken into consideration due to the considered regional-global scale of concern. Because the motion mechanism is primarily taking place at large depth, surface displacements related to rock glacier (permafrost) creep are building up consistent flow fields. Areas presenting a rather homogeneous surface movement rate behavior both in space and time on a moving rock glacier unit can be identified using different techniques (kinematic approach). They are called *moving areas* and are defined further in this document.

Several limitations have nevertheless to be acknowledged and taken into consideration:

- Surface displacements are principally dependent on the downslope movement of the rock glacier (permafrost creep), but various processes (e.g. thaw subsidence) can alter this relationship.
- Surface velocities can be considered as being generally faster than the effective mean motion rate occurring within the rock glacier body down to the main shear horizon (by a factor of approximately up to 1.5), but in the absence of borehole deformation measurements the difference is not known.
- Spatial variations of the surface velocity:
    - The velocity can often display a certain degree of spatially heterogeneity over a rock glacier unit, in relation to the landform (e.g. internal structure) and terrain (e.g. slope) characteristics. This is reflected within the distribution of some typical geomorphological features on a rock glacier: for instance, the terminal part (front), lateral margins and rooting zone are often slower than the central part.
- Temporal variations of the surface velocity:
    - The velocity may change significantly from year to year (inter-annual to decennial variations) as a response to changing environmental factors.
    - The velocity may change within a year. A large amplitude is possible between the seasons, with usually higher velocities during or after the warm season due to higher ground temperature and increased water inputs from snowmelt and liquid precipitation[1].
    - The velocity may change within a season. A large amplitude is possible within a season, with usually but not necessarily a decreasing trend during the colder season and an accelerating trend during the warmer season; velocity variations in relation to

[1] The comparison of 260 pairs of seasonal (3 months) and annual 2D surface velocities determined on the basis of terrestrial geodetic (GNSS) measurements performed on various rock glaciers moving faster than 14 cm/year in the Swiss Alps between 2006 (for the longest time series) and 2017 shows that the summer velocity is in average 24% faster (median: +18%) than the annual velocity, with a standard deviation of 24% (see Figure). No value has exceeded 100%, which would represent a doubling of the velocity in summertime. A pair is constituted by the averaged velocity values for a set of 1 to more than 20 measurement points.

temperature and water can be rapid or progressive and delayed depending on each rock glacier geometry and context.

- Other changes over various time scales could occur (e.g. destabilization).

If you have any comment about the previous section, please use this box.

Comment box 2a

2.2. Specific motivations and requirements

There are basically two sets of techniques for measuring surface movements on rock glaciers: terrestrial surveys (e.g. repeated GNSS field campaigns, permanent GNSS stations) and remote sensing methods (e.g. InSAR, photogrammetry). Whereas some of these allow only for the measurement at single location(s) on a rock glacier, others permit to upscale the analysis and provide rock glacier kinematic information in a uniform way at the regional scale. In the framework of rock glacier inventories, the exploitation of such data offers the possibility to **refine the activity categorization** by adding a semi-quantitative (i.e. giving an order of magnitude) **kinematic attribute,** whose baseline rules must be applicable globally.

The kinematic attribute has to be, as far as possible, representative of the multiannual movement rate of the rock glacier unit at the time of an inventory (snapshot). It should be derivable from in situ measurements as well as from remotely sensed based approaches. It needs to be technology independent. Its assignment to a rock glacier unit should be based on the characteristics of recognized related *moving area(s)*.

The kinematic attribute should allow comparisons to be feasible in and between rock glacier inventories at regional and global scales. Contrary to kinematic time series (see "Rock glacier kinematics as an associated parameter of ECV Permafrost"), however, it has no monitoring purpose.

The way a kinematic attribute could be integrated in rock glacier inventories must also be standardized, as it may refer to different types of values (e.g. the maximum velocity observed on the fastest area of a rock glacier unit, the mean velocity computed on a moving area, or a range of values, such as min, max, mean, standard deviation) obtained with different techniques over different time spans.

If you have any comment about the previous section, please use this box.

Comment box 2b

2.3. Basic concepts and proposed standards

Kinematics is defined here as the surface movement rate related to downslope rock glacier creep. Surface velocity measurements of any type constitute the **kinematic data**.

The **kinematic attribute** associated to rock glacier inventories is a refinement of the activity categorization and may be derived from the integration of different sources of information (e.g. for landforms that are documented by multiples devices/methods).

A two-step procedure, possibly iterative, is proposed to determine the kinematic attribute. Hence, the following sections provide the basic concepts to:

- identify **moving areas** on rock glaciers, including the assignment of a related **velocity class** on the basis of adequate kinematic data (2.3.1-2.3.2);

- assign a **kinematic attribute** to a **rock glacier unit** on the basis of the characteristics of recognized related **moving area(s)** (2.3.3-2.3.4).

If you have any comment about the previous section, please use this box.

Comment box 3a

2.3.1 Moving areas

The identification of moving areas is an initial step, which is recommended to assign subsequently a kinematic attribute to a rock glacier unit. In the framework of a rock glacier inventory, a moving area is defined as an **area at the surface of a rock glacier in which the observed flow field (direction and velocity) is uniform (spatially consistent/homogeneous)** during a documented time. It has to represent the downslope movement rate of the rock glacier (permafrost creep) in the area of concern. Confusion with movement related to other processes (e.g. thaw subsidence or deep-seated landslide) has to be avoided. The identification of moving areas could be performed on the basis of any technique or combination of techniques providing areal (surface) displacement information. A simultaneous thorough analysis of aerial images may be useful, and a strong background in geomorphology interpretation is required.

Moving areas are identified in accordance with the following requirements:

- The velocity range within a moving area should not exceed a min/max ratio of 1:5.
- Several moving areas can be superimposed, a slower moving area always embedding a faster one.
- A moving area can override the geomorphological limits of a rock glacier unit (e.g. when two overlying rock glacier units are moving at rates that are not significantly different).
- The minimum extent of a moving area depends on the spatial resolution of the data input, but also on the size of the landform to which it refers, based on the operator’s judgment.
- Isolated movements, unreliable areas and unrepresentative parts have to be avoided.

In addition, it should be noted that:

- The border of a moving area is often non-sharp, depending also on the detection capability of the used technique, making a precise delineation difficult to obtain.
- A single point measurement is basically not a moving area, but the information it provides could be taken into consideration if it can be spatially attached to any moving area.
- Areas outside of any delineated moving area refer without distinction either to the absence of movement, to a movement which may be under the detection limit, or to unreliable data.

A moving area is always **strictly stamped by time characteristics**, which are mostly related to the technique in use:

- The *observation time window*, i.e. the period during which the detection and characterization is computed/measured (e.g. multi-annual, annual, intra-annual). When the technique does not allow for an annual or multi-annual observation time window, the minimal required duration is 1 month (which can also be obtained by aggregating observations of several shorter time windows).
- The *temporal frame*, i.e. the duration during which the periodic measurements/computations are repeated and aggregated for defining the moving area (i.e. during which year(s)).

In addition to the detection capacity of the used technique, the extent of a moving area could also vary depending on the observation time window and the temporal variability of the velocity, making its delineation possibly difficult to obtain with precision. The *reliability* (or the degree of confidence) *of the detection* has to be qualitatively documented (low, medium, high) accordingly.

If you have any comment about the previous section, please use this box.

Comment box 3b

2.3.2 Velocity class of a moving area

A velocity-dependent classification of moving areas is also recommended to be able to determine subsequently the kinematic attribute of a rock glacier unit. Assigning velocity values (e.g. mean, amplitude, spread) to a moving area presents a potentially challenging task, which may strongly depend on the data quality and the measurement technique, and consecutively, the delineated extent of the moving area. The use of velocity classes intends to facilitate the assignment of a more homogeneous and simplified velocity information to moving areas.

A velocity class has to document as good as possible the spatio-temporal mean movement rate observed within a moving area during a considered *temporal frame* and according to a specific *observation time window*. The class label must refer as far as possible to a 2D (horizontal) displacement rate representative of a downslope creep movement. Various ways of classifying could, however, be applied (e.g. range, number of classes, dimensionality). One has also to be aware that the class assignment is difficult when the obtained value is close to a category border, regardless of the applied classification.

A velocity class assigned to a moving area is partly dependent on the technology and the conditions of observation. The exploited data, the applied method and the observation time window must imperatively be documented. Some methodologies only allow for the observation of displacement during summertime, meaning that the velocity value cannot be measured over an annual time interval. Others only allow for the measurement of annual velocity or multi-annual velocity. The dimensionality (one- to three-dimensional displacement measurements) also varies depending on the technology. Therefore, the definition of the velocity classes as well as the rules for subsequently using this information to assign a kinematic attribute to a rock glacier unit are dependent on the technology and should be specified for each (cf. 2.4).

The *reliability* (or the degree of confidence) *of the velocity* class assignment has to be qualitatively documented (low, medium, high) in combination with the detection reliability (cf. 2.3.1). When the reliability in classifying velocity is low due to specific technical limitations, the velocity class has to be set as “undefined”.

If you have any comment about the previous section, please use this box.

Comment box 3c

2.3.3 Rock glacier kinematic attribute

The kinematic attribute is a **semi-quantitative[2] (order of magnitude) optional information, which must be representative of the overall multi-annual downslope movement rate of a rock glacier unit at the time of an inventory**. The time of an inventory is called the *validity time frame.* In order to minimize the potentially large inter-annual variations of rock glacier movement rate, the validity time

[2] Contrary to the quantitative velocity class attribute, the kinematic attribute is intended exclusively to assess and/or refine the activity attribute with the purpose to describe, explain, explore or interpret rock glaciers using inductive analysis. Thus, it is defined as a semi-quantitative (or qualitative ordinal) variable.

frame must be at least 2 years, but a longer range is recommended. Being a refinement of the activity categorization, the kinematic attribute must reflect the mean kinematic behavior of a rock glacier unit during the inventory validity time frame. It is basically determined by the characteristics (extent, velocity class, time specificities) of the moving area(s) (as defined in 2.3.1), which have been identified at the surface of the rock glacier unit. The attribute must be spatially representative of the rock glacier unit. The exploited data, the applied method and their related time characteristics (observation time window and time frame) of all the supporting kinematic data must imperatively be documented.

A kinematic attribute can be assigned to a rock glacier unit only when the latter is documented by consistent kinematic information on a significant part of its surface. However, as dominant moving area(s) only rarely cover a rock glacier unit in its whole and may not reflect a multi-annual displacement rate, a systematical translation of a (moving area) velocity class to a (rock glacier unit) kinematic attribute is not always straightforward and has to be performed carefully. It is highly dependent on the technique and the operator's judgment (cf. 2.4). It must also be taken into consideration that the documented surface velocities may be faster than the effective rock glacier displacement rate at depth and that intra-annual (usually summer) velocities may be faster than annual velocities (cf. 2.1).

According to the results of the User Survey provided during the Action Group Workshop I in September 2019, the standard for a kinematic attribute should be representative of an order of magnitude (e.g. cm/yr, dm/yr, m/yr and higher), rather than absolute velocity values.

If you have any comment about the previous section, please use this box.

Comment box 3d

2.3.4 Categorization of the kinematic attribute

The categorization of the kinematic attribute consists of semi-quantitative classes of the **multi-annual downslope displacement rate** of the entire rock glacier body. There is only one assigned category per rock glacier unit. Detailed rules for assignment will be defined in related *practical guidelines* (cf. 2.4).

Category	Label	Comment	Related activity
0.	Undefined	default category	
1.	< cm/yr	no up to very few movement	relict
2.	cm/yr	order of magnitude ≈ 0.01 m/yr	transitional
3.	cm/yr to dm/yr	order of magnitude ≈ 0.05 m/yr	transitional
4.	dm/yr	order of magnitude ≈ 0.1 m/yr	active
5.	dm/yr to m/yr	order of magnitude ≈ 0.5 m/yr	active
6.	m/yr	order of magnitude ≈ 1 m/yr	active
7.	> m/yr	more than ≈ 3 m/yr per year	active

If two equally dominant, but directly adjoining categories (e.g. 5-6) occur on a rock glacier unit, the category of the area closer to the front is favored for the attribution. In case of a larger spread of equally dominant categories on the same rock glacier unit (e.g. 4, 6), the median category (e.g. 5) should be retained, with a specific additional indication of heterogeneity. A large heterogeneity can also indicate the need to refine/redefine the delineation of the initial geomorphological units (iterative process combining geomorphological and kinematic approaches, cf. 1).

The default category is *0. Undefined*. The rock glacier unit falls into this category when no (reliable) kinematic information is available, the kinematic information is derived from a single point survey which cannot be related to any moving area (as defined in 2.3.1), or the rock glacier unit is mainly characterized by a moving area of undefined velocity.

For each rock glacier unit with an assigned kinematic attribute, the following additional information has to be documented, according to the supporting kinematic data (e.g. recognized moving areas):

- Multi-year *validity time frame* of the attributed category,
- Data/technique(s) used, observation time window (e.g. multi-annual, annual, intra-annual), temporal frame and dimensionality of the supporting kinematic data (velocity values),
- *Approximated spatial representativeness*: percentage of the rock glacier surface that is documented by supporting kinematic data (e.g. < 50%, 50-75%, > 75%),
- *Reliability of the assignment* of the kinematic attribute (low, medium, high).

If you have any comment about the previous section, please use this box.

Comment box 3e

2.4. Example of application: assigning a rock glacier kinematic attribute on the basis of the characteristics of recognized InSAR-derived moving areas

The determination of velocity classes related to moving areas as well as the rules for subsequently using this information to assign a kinematic attribute to a rock glacier unit are dependent on the technology used to measure/compute the velocity and should be specified for each.

Within the framework of the European Space Agency Climate Change Initiative (ESA CCI+) Permafrost project (2018-2022) and in accordance with the present document, recommendations have been stated for a systematic procedure based on the accurate interpretation of **wrapped interferometric signals from a large InSAR dataset** in order to locate and estimate the displacement rate of moving areas related to rock glaciers and subsequently to assign a kinematic attribute to rock glacier units. These detailed rules are provided as an example. They are described in the specific *Practical guidelines: rock glacier inventory using InSAR (kinematic approach)*. These recommendations could be applied to other InSAR methods (unwrapped interferograms, multiple stacking, PS, IPTA, etc.) but they require an initial evaluation regarding the need for any specific adaptations.

If you have any comment about the previous section, please use this box.

Comment box 4