Integration of morphological characteristics into rock glacier inventories



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Abstract

Rock glacier inventories are based on various methodologies and research objectives and are investigated in regard of discontinuous permafrost and its evolution in time. Providing inter-regional and global conclusions on permafrost conditions implies comparable rock glacier inventories. Current research proposes standard guidelines for rock glacier inventories based on the widespread and numerous existing data of rock glaciers in order to create a standardised data basis. The variability of existing rock glacier inventories entails the evaluation of which morphological characteristics optimally acquire a rock glacier in its context.

An online survey amongst rock glacier experts combined with a literature review identifies the following morphological characteristics essential to be integrated into standardised rock glacier inventories: the shape, the area, the activity status, the velocity, the altitude (max, min), the aspect, the slope, the upslope boundary and a commentary. A list of parameters describing these characteristics is discussed. A standardised rock glacier inventory may consider a limited number of morphological details, however, it allows the introduction of a certain homogeneity and a global use of the data even if there are several independent projects and contexts included. In-depth information on single rock glaciers may be derived from individual observations.

Keywords: rock glacier inventory, rock glacier morphology, permafrost monitoring

Front page: Réchy, Becs-de-Bosson (Valais, Switzerland), rock glacier, photo : Delaloye, R., 2011.

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1. Introduction

Rock glacier inventories are potent research tools in order to explore the spatial and temporal distribution of permafrost in alpine environments (e.g. Delaloye and Morand, 1998; Azócar et al.,2017). Since May 2018 the IPA (International Permafrost Association) Action Group *Rock glacier inventories and kinematics* aims to propose standard guidelines of rock glacier inventory designs and its content. The project furthermore strives to develop open access to existing rock glacier data including the aspect of kinematics as well as the use of a regional rock glacier kinematics indices in the course of for example the Global Terrestrial Network on Permafrost (GTN-P) (Delaloye et al. 2018).

Rock glacier inventories are established based on various methodological approaches as for example geomorphological cartography (e.g. Lillehoern and Etzelmueller, 2011), interpretation of aerial photographs (Delaloye and Morand, 1998) or DInSAR (Barboux et al., 2014). Morphological characteristics of rock glaciers are integrated in the process of the establishment or validation of a rock glacier inventory. In order to enable the scientific comparability and usability of rock glacier inventories it is therefore important to analyse which morphological characteristics of rock glacier provide the essential informations on the morphology of a rock glacier in regard of standardised rock glacier inventories.

Based on the research question *which morphological characteristics enable general rock glacier inventories to optimally acquire the morphology of the periglacial landform «rock glacier»?*,
the objective of this Bachelor thesis is to propose a catalogue of morphological characteristics and information considered important to be integrated into a standardised rock glacier inventory. The chosen morphological characteristics of rock glaciers consider the various types of rock glacier characteristics in different geographical regions as well as the use of Geographical Information Systems (GIS).

The present Bachelor thesis is divided into two parts. An introduction to rock glacier inventories (abbreviated RGI in the following) and a literature review exploring the previous integration of morphological characteristics into RGI is given. Furthermore, an online survey introduces the experience of rock glacier (referred to as RG in the following) experts. The methodological explication of the literature review process is given in chapter 3. In the second part of the Bachelor thesis the results gained from online survey and the literature research are discussed and synthesised in chapter 5 and 6.

Part 1: rock glacier inventories and morphological characteristics: a literature review

2. State of Research

In order to situate the analysed RGI in the scientific context of RG research, the following chapters present a short explanation of permafrost and a definition of RG, an overview on RGI as also an introduction on the integration of morphological features into RGI.

2.1 Permafrost

In accordance with Haeberli et al. (2006) *permafrost* (permanent frost) implies ground temperatures of 0°C or less for one or more years regardless of the present ice content. Ground penetrated by permafrost includes an active layer thawing in summer season and a perennially frozen (≤ 0°C) layer. While the active layer is highly sensitive to changes in e.g. the solar radiation, the deeper layers react time-delayed. The thickness of permafrost varies in depth and space (SSGm, 2009). Permafrost cannot be seen by eye but through landforms resulting from the deformation of permafrost penetrated ground or by its exposure (e.g. through rock falls). In mountainous terrain permafrost may manifest itself in mass movement processes such as solifluction or rock glaciers, depending on the context, the material, thickness and volume affected by the process; whereas e.g. in the frozen tundra landforms such as pingos or ice wedges emerge (Ahnert 2015, 115–17; SSGm, 2009).

2.2 Rock glacier definition

Traditional approaches of RG definitions treat the three domains process, material and form. Rock glacier definitions originally are generated by the attempt to explain the origin of the form and its activity. The genetics range from debris covered glaciers to landslides, however, were synthesised by Barsch (1996) into glacier- and talus-derived rock glaciers (Hulum, 1998: 376). The degree of activity usually is classified to *active, inactive and relict* or *intact and relict* (Barsch, 1996: 11). Barsch (1996: 4) proposes a complete and in general well-fitting definition, considering "*active rock glaciers as lobate or tongue-shaped bodies of perennially frozen unconsolidated material, supersaturated with interstitial ice and ice lenses that move downslope or down valley by creep as a consequence of the deformation of ice contained in them and which are, thus, features of cohesive flow"*. Non-active RG therefore are either inactive (not moving but still containing ice) and relict (or fossil) RG (no more ice present).

Barsch (1996) is often cited and further definitions are based on this publication. However, the RG form and process description are misleading. The following Table 1 shows its discussion and reformulation. Certain aspects are further discussed in chapter 6.

Table 1 – Reformulation and explanation of the reformulation of the rock glacier definition from Barsch (1996).

	Barsch (1996: 4)	***Argumentation***	***reformulation***
Rock glacier activity	Active rock glaciers…	Independent of the rock glacier's (RG) activity status the landform resulting from material and process takes (or has taken) place. The definition therefore starts independent of the activity status, which is then introduced in a second sentence.	Rock glaciers… According to the functionality…
Form	…lobate or tongue-shaped bodies…	RG often build distinctive forms as Barsch (1996) describes, though in mountainous regions RG often end in steep debris slopes. It is therefore proposed include all forms resulting from the characteristic cohesive flux process (Delaloye, 2004: 29).	…distinctive landforms resulting from…
Material	…perennially frozen unconsolidated material, supersaturated with interstitial ice and ice lenses…	RG material is not homogenous throughout the landform. Introducing the term permafrost automatically implies a certain active layer, ventilation processes at the surface, characteristic ice features as interstitial ice or ice lenses, etc.	… super-saturated, unconsolidated, permafrost penetrated material.
Process	…move downslope or down valley by creep as a consequence of the deformation of ice contained in them and which are, thus, features of cohesive flow.	The physical conditions of mass movements (induced by gravity) imply a downward motion if no other forces are acting. The process of internal deformation of the ice and its propagation in a cohesive flux are important to mention in order to derive the resulting landforms.	…the gravity induced deformation (cohesive flux) …

<u>The resulting definition of rock glaciers therefore is:</u>

Rock glaciers are the visible landforms resulting from the gravity induced deformation (cohesive flux) of supersaturated, unconsolidated, permafrost penetrated material. According to the functionality of the debris accumulation and deformation process, rock glaciers may be distinguished into active (fully functional process), inactive (partially functional process) and relict rock glaciers (process inexistent, no more permafrost present).

In contrary to other definitions the empirical versatility and complexity of rock glaciers is considered, however, the essentials of the definitions remain the same. Due to the global variety of RG dimensions the metrical notions of for example the size is neglected in this definition. The indication of time is renounced as the full expression of the geomorphological process of a RG is depending on its environmental conditions.

The availability of high-resolution remote sensing technologies, such as LIDAR or DInSAR, allows the determination of kinematics specifying the characteristic behaviour of a RG (every RG has for example its characteristic mean annual velocity rates) (e.g. Barboux et al., 2014).

Formerly dominating elements of RG definition as the morphological properties of RG are still important though not the only defining elements. The various expressions of RG in any part of the world (artic to mountainous regions), the RG front, ridges, crevasses, are included in *distinctive landforms resulting from … deformation*. The use of the word *distinctive*, however, could be critically questioned, as they demand a certain back ground knowledge on RG.

The activity status of a RG is depending on the functionality of the geomorphological process. It must not to be confused with the velocity of a RG. However, kinematic informations, along with morphological characteristics as mentioned above, are helpful indicators on the functionality of the process. The activity status and its definition are further discussed in chapter 6.1.6.

Detailed aspects of RG definitions in relation with their integration into RGI, as e.g. how to define the maximal elevation, are discussed in chapter 6.

2.3 Rock glacier inventories

The compilation of rock glacier inventories all over the world has been intensified for the last thirty years and also reflects the increase of scientific interest in these landforms resulting from periglacial mass movement processes (Haeberli et al. 2006: 189). Jones et al. (2018: 124) presents a broad overview on the existing RGI in central and western Europe, Northern Europe (Greenland, Scandinavia and Iceland), North and South America as well as New Zealand. Especially in central Europa, for example in the Alpes, RGI of multiple generations and methods are known. Recently developed RGI often are validated by existing inventories or currently investigated rock glaciers (Barboux et al., 2014: 6; Krainer and Ribis 2012: 24). As a consequence of the advancement of remote sensing technologies, larger inventories all over the world as for example in the Himalaya (China, Nepal) or parts of the Andes in South America are created (Jones et al. 2018; Brenning et al., 2007).

RGI prove to be effective data to model the local and regional permafrost distribution as well as for an estimation of the content of stored water in RG, done so in for example in the Nepalese Himalaya (Jones et al. 2018) or San Juan region (Andes, Argentina; Angillieri 2017). The understanding and monitoring of climate change through rock glaciers as indicators of past (relict RG) and present (intact RG) permafrost distribution is another explanation for the increasing number of inventoried rock glaciers.

In order to increase the significance of the resulting data it is essential to develop standard guidelines of how RGI contents and structures should look like, enabling worldwide scientific progress without implementing predetermined outputs. Present attempts aim to establish standard guidelines (Delaloye et al., 2018) for RGI describing the structure and defining its content. Standard definitions enable scientists to effectively compare and use the inventoried data as it is mentioned above. Moreover, new scientific knowledge such as kinematic informations may be integrated effectively. The standard guidelines should include the characteristics of rock glaciers independent of the method used to establish the RGI. The requirements to such standardised RGI as for example their applicability, however, demand efficiency and usability in reasonable effort and time (Cremonese et al., 2011: 652). One objective therefore is the application of Geographical Informations Systems (GIS).

So far, most RGI were established individually and according to the scientific requirements of the research objective. In Cremonese et al. (2011) the compilation of a permafrost evidence network (PermaNET) is justified and explained, however, the project is not actively continued until today. It implies that, due to the cost and time intensity of such projects, their continuous actualisation is difficult to realise and to maintain on global scales despite their scientific importance.

The proposal of standard guidelines for a RGI may introduce a certain homogeneity into RGI enabling a global use of the data even if there are various independent projects, contexts and efforts included.

2.4 Morphology in rock glacier inventories

The integration of rock glacier morphologies into rock glacier inventories encloses some aspects of vagueness. This work aims to summarize if and how RGI include morphological characteristics, and moreover, to investigate which characteristics are considered to be important by RG experts.

In publications, scientists working on RGI define accurately which morphological characteristics are collected as scientific data. Some authors as Angillieri (2017: 44) ask their readers to derive these informations from the results presented. For example, the overall surface covered by RG implies the integration of the RG surface into the inventory. On the downside most authors of the analysed sources partially describe the integrated morphology in the methodological part of their publication, done in Onaca et al. (2017: 393), Uxa and Mida (2017:848), Sattler et al. (2016: 4) and other authors. Eventually there are no exactly identical RGI existing and mixed approaches are possible, such as Lillehoern and Etzelmueller (2011). In the following chapters the focus changes from how to which morphological characteristics are integrated how.

3. Methods

3.1 Analysis of morphological characteristics into rock glacier inventories

An online survey assessing the general importance of morphological characteristics by an online survey and an analysis of actually into RGI integrated characteristics based on a literature review allow a versatile approach on the research question.

Aiming to combine the online survey with the literature review it is important to point out the difference between the unspecific notion of the importance of a RG characteristic and a scientist specifically responding to a question on RGI aiming to answer a research question as e.g. permafrost modelling. Both approaches may neglect certain aspects, however, they are indispensable for usability of a standardised RGI as the contextualisation but also the characterisation of a RG must be derivable.

3.2 Online survey

As mentioned above, the online survey aims to investigate the general importance of RG characteristics based on the experience of RG experts. It is asked whether or not a certain characteristic should be integrated. The “how” is dependant on their specific research objectives and backgrounds. In this thesis this aspect is evaluated by the literature review (compare below).

The online survey is conducted amongst the 16 members of the IPA Action Group on Rock Glaciers and Kinematics (Delaloye et al. 2018) and developed on the online survey provider findmind.ch (Keller, 2018). The form and content of the survey is based on the objective to gain further information about the implementation of morphological characteristics in standardised RGI. Additional practical informations such as question types are taken from findmind.ch and Ertl and Gruber (2006).

Four questions based on the research question are asked (the detailed contents are presented in chapter 4.1). Three out of four questions are open questions which can be answered accordingly. The first question has 17 answering characteristics whose significance must be rated. For each characteristic four classes from 1 (very important) to 4 (unnecessary) are available. This question has to be answered while the other questions (remarks and inputs, see chapter 4.1) are optional. This strategy is chosen in order to increase the number of useful responses.

3.2.1 Choice of analysed publications in literature review

The literature review aims to evaluate how RG characteristics are integrated into RGI. It is primarily consisting of a systematic literature research completed by associative research approaches (Niedermair 2010: 136) based on the concept of forward and backward research (Webster and Watson 2002: 16). As explained below, the number of search results is reduced. A selection of scientific articles is analysed with regard to the research question (see below and chapter 1) including two approaches: a) the assessment of the importance of RG morphologies through rock glacier experts and b) the analysis of the morphological characteristics inventoried in RGI.

The terms “rock glacier”, “morphology” and “inventory” (as their equivalent in French and German) are entered into online research engines (sciencedirect.com, etc.) in order to explore the subject and to gain a broad list of scientific contributions. This first step includes a total of 3800 articles containing the mentioned terms. All publication sources are saved in the automatic citation manger Zotero (Zotero, 2018).

To specify the results according to the research question a) any duplicates resulting from the search in different search engines are removed and b) the Zotero data base is filtered on the following two keywords “rock glacier inventory” “permafrost modelling” in the headings. Permafrost models often are based on RGI which is why this term is integrated here. The elimination of multiples reduced the number of publications to about 2200. The application on the keyword filter in title and abstract lead to 105 publications. These were then rated on their relevance for the research question by scanning their abstract. Finally, twenty-five publications are actually considered in this work. The associative (backward) search of cited sources (Webster and Watson 2002: 16) is accepted as a complementary approach to systematic literature researches though often identifies subject relevant contributions (Niedermair 2010: 136). Applying this approach five more publications were introduced.

3.2.2 Analysis of the chosen publications

The thorough analysis of these chosen publications is based on the binary indexing of all morphological characteristics inventoried into those RGI.

Webster and Watson (2002: 16ff) propose the use of binary matrix tables structuring the various concepts (here: morphological characteristics). The results of these results are presented in chapter 4, the interpretation in chapter 5 and 6.

3.3 Establishment of a catalogue of RG characteristics for a standardised inventory

The catalogue of morphological characteristics being considered essential to be integrated into a standardised RGI is based on the online survey and the results of the literature review. The final choice and detailed definition, as for example where the maximal altitude is measured, are discussed and defined in chapter 6, however, the definition of a RG implies the guiding principles. Finally, the list is sorted according to their practicability by Geographical Information Systems, in this case QGIS.

3.3.1 Reflexion on the methods

The online survey was answered by eleven out of sixteen persons. They are suggested being members of the IPA Action Group though at least three participants are other scientists to whom the online survey was forwarded to. The online survey was launched before the literature review had been conducted. Conducting the online survey after interpreting the results of the literature review might have to be considered for similar projects, however, in this case is legitimate as the survey records the general importance of a morphological property (compare above). The survey's goal is not to know where exactly for example the minimal altitude it is measured, but if it is considered important. The literature review explores the specific way of integrating a morphological characteristic into a RG. Both approaches are important for this thesis.

The literature review may have led to interesting results though could have been performed more efficiently using more specific search terms and most importantly more specific search configurations.

The number of finally analysed publications shows the variety of RGI analysed (different research objectives, purposes and contexts and regional settings) allows an overview and a versatile approach on the research question. The final listing is sorted by its practicability by GIS (QGIS) which may not be essential for this thesis, however, is an important factor for the establishment of a standardised RGI.

Part 2: the integration of morphological characteristics into general rock glacier inventories

4. Results

4.1 Online survey

4.1.1 Summary of the importance of morphological RG characteristics

The following Table 2 shows a list of the summarised and sorted RG characteristics considered as both very and rather important in the online survey. As mentioned in chapter 3, the online survey aims to identify which aspects of a RG morphology experienced scientists consider to be essential to integrate into a RGI. In this thesis, the question of how such characteristics are integrated, is looked at by the literature review.

Table 2 – Online Survey Results, hierarchic listing of morphological characteristics considered very important or important. Total number of participants:11.

Question1: Which morphological properties do you consider important to be assessed in general rock glacier inventories?	Number of answers	Percentage per answer
Shape 1 (in general)	11	100.0
altitude (max, min)	10	90.9
aspect	10	90.9
Shape 3 (multiroot, - lobe)	9	81.8
front slope	9	81.8
Shape 2 (tongue-, lobate-shaped, complex)	8	72.7
Surface area 1 (with side ridges, front slope)	8	72.7
length and width (averaged)	8	72.7
thickness (if availiable)	8	72.7
slope (in general)	8	72.7
origin (p.ex. glacier, talus slope)	8	72.7
length and width (max, min)	7	63.6
adjoining morphologies (p.ex. moraines)	7	63.6
morphologies on RG	7	63.6
altitude (mean, median)	6	54.5
length and width (median)	4	36.4
Surface area 2 (sans side ridges, front slope)	3	27.3

4.1.2 Question 1: detailed results

As mentioned above the online survey was transmitted to 16 members of the IPA Action Group "Rock glacier and Kinematics" (Delaloye et al. 2018). Due to result table automatically generated

by findmind.ch (Keller 2018) 16 persons participated in the online survey of which eleven completed the survey.

The first question is: *which morphological characteristics do you consider important to be assessed in general rock glacier inventories?* Each of 17 answering fields have to be rated into one of four classes: very important, rather important, rather unnecessary and unnecessary. The following figures show the number of answers per category but also the resulting percentages.

The 17 answering fields ask for opinions on e.g. the minimal and maximal altitude, however, the exact measurement position of e.g. the minimal altitude of a RG is not defined. The survey's goal is not to know where exactly it is measured, but if it is considered important.

In Figure 1 the shape of rock glaciers is looked at: All online survey participants (63.6% very important, 36.4% rather important) consider a parameter of shape in general, meaning without any specifying information, essential to be integrated into a RGI (compare

Table 2). The more differentiated landform informations including a differentiation of tongue-, lobate-shaped and complex RG are also agreed to be significant. The same conclusion is applicable for an integration of morphological details such as multiroot or multilobe RG into RGI, however, one of eleven participants attributes a higher importance to Shape 3 than to Shape 1 or 2.

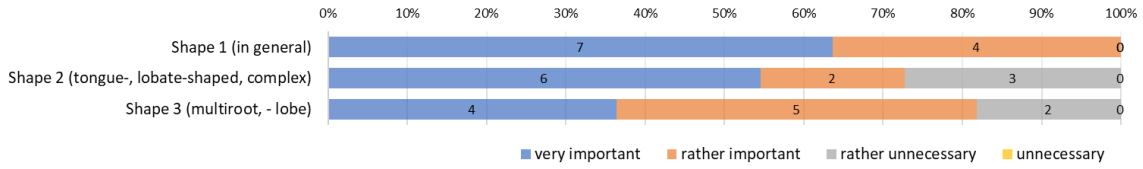


Figure 1 – Online Survey Results, Question 1 on the shape of rock glaciers.

Predominantly the geometric data of RG are considered being necessary informations for RGI as illustrated in Figure 2. The second proposal of surface area which does not consider the side ridges and the front slope, however, is rated less significant with percentages of 18,2% (very important), 9.1% (rather important,72.7%).

The indication of length and width in averaged values is evaluated to be essential in a RGI (54.5% very important, 18.2% rather important, 27.3% rather unnecessary), while and minimal as well as the median geometric data are considered less important.

The importance of thickness as a morphological indicator of landform dimensions is given (27.3% very important, 45.5% rather important) though with two out of eleven unnecessary classifications not unambiguous.

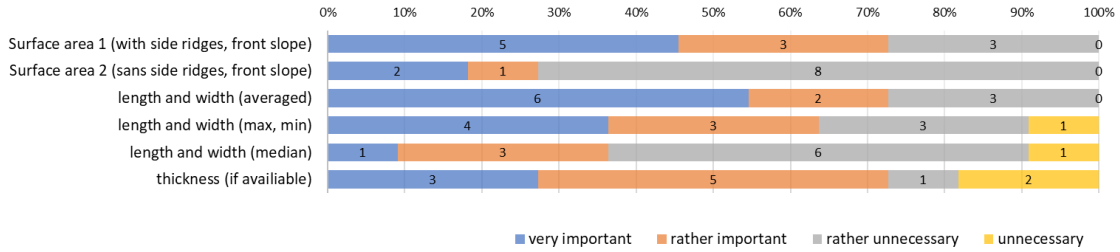


Figure 2 – Online Survey Results, Question 1 on characteristic Surface area, length, width and thickness.

The following Figure 3 displays the orientation of a RG in its topographic context. As the slope can be expressed variably (max, min, mean, etc.) its general importance is asked. The participants agree on its significance in a general RGI (27.3% important, 45.5% rather important, 18.2% rather unnecessary, 9.1% unnecessary). Also, the front slope information of a RG is evaluated as important.

The aspect clearly is considered essential to be integrated into RGI (54.5% important, 36.4% rather important). In the online survey no further differentiation (e.g. aspect classes or degrees) of the aspect details is asked.

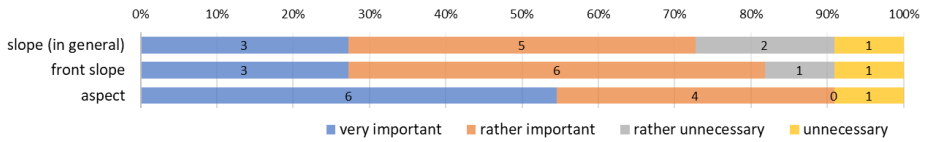


Figure 3 – Online Survey Results, Question 1 on characteristic slope and aspect.

The maximal and minimal altitude values show the most significant consensus of the participants with ten of eleven participants agreeing on “very important” (see Figure 4). The mean or median altitude informations are less unitedly answered.

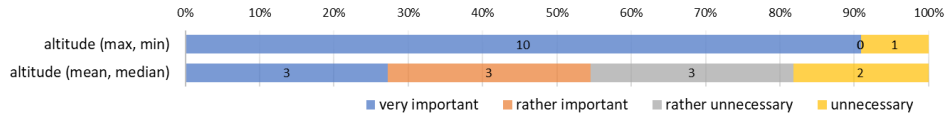


Figure 4 – Online Survey Results, Question 1 on characteristic altitude.

Morphogenetic informations are considered necessary to be assessed in a standardised RGI as shown in Figure 5.

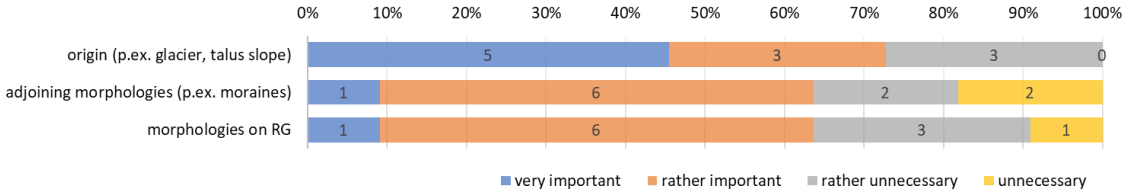


Figure 5 – Online Survey Results, Question 1 on characteristic morphogenetics.

4.1.3 Question 2

The second questions allowed interested participants to enlarge the catalogue of characteristics by proposing new or more detailed morphological characteristics. Nine out of eleven completed participants made use of this possibility. The answers given are shown in Table 3. The answers are not modified.

Table 3 - Answers to Question 2, unmodified.

Participant	***Answer to question 2 (Comments and proposals to question 1)***
Participant 1	In fact, it depends on the objectives of the study requiring the inventory, but in general any information related to specific unusual morphologies like crevasses or scars (destabilization signs) for example.
Participant 2	Lithology, main grain size, presence of lichens and vegetation, front characteristics (fine sediments, vegetation), destabilization indices (cracks, scarps).
Participant 3	Depends on the scope of the inventory, e.g. if you need RG distribution as a component of a model of permafrost distribution maybe you can try to include also gelifluction lobes, otherwise I would include just RG.
Participant 5	Human intervention. These data are very important to evaluate impact of human activities on rock glaciers.
Participant 6	Average debris size.

Participant 7	Shape 4 (tension cracks, landsliding, surface disintegration, etc.) may indicate surface kinematics/ activity.
Participant 8	I think height of rock wall above a rock glacier also important to form of rock glacier, because it is essential to transport debris onto rock glacier in the development of rock glacier.
Participant 9	Active (inactive), flow velocities (if available).
Participant 10	Furrows/ridges/crevasse like features on the surface - can indicate movement.

4.1.4 Question 3

Question three asks for *rock glacier inventories being considered as exemplary in term of morphological descriptions.* Ensuring private policies, the six answers given to question three (participants 1,2,3,4, 5 and 8) are not listed here but summarised in the following:

In general, the scientists having established their own inventory know rather few other RGI. The RGI mentioned in this question are described in publications which are cited in their own publication. Some publications are listed as for example Scotti et al. (2013): *a regional inventory of rock glaciers and protalus ramparts in the central Italian Alps*.

4.1.5 Question 4

The fourth and last question of the online survey intends widening the knowledge of the authors in terms of single *rock glaciers which might be interesting for the second part of the Bachelor thesis*. Eight (participants 1-8) out of eleven participants listed one or more examples amongst which are RG in Switzerland (Valais), Italy and the Andes. A list is available though not published out of private policy reasons.

4.2 Literature review

4.2.1 Publications analysed

The publications (total number: 31) chosen and analysed are listed in the following

Table 4. For the purpose of a global applicability the chosen publications come from different regions, altitudes and climatic conditions. A full listing of the publications and number of

inventoried rock glaciers, establishment types and informations on altitudes and climate are available in Table 7.

Table 4 - Catalogue of analysed publications with geographic and dimensional information.

Region or Nation	***Publication***
Nepal	Jones et al., 2018
Thien Shan	Wang et al., 2017
Hindukush	Schmid et al., 2015
Swiss Alps	Delaloye and Morand, 1998
	Barboux et al., 2014
South Eastern Alps	Colucci et al., 2016
	Kellerer-Pirkelbauer et al., 2012
	Krainer and Ribis, 2012
Italian Alps	Scotti et al., 2013
	Seppi et al., 2005
	Seppi et al., 2012
French Alps	Bornet, 2014
	Marcer et al., 2017
Alps (various regions)	Cremonese et al., 2011
Carpathians	Onaca et al., 2017
	Uxa and Mida, 2017
Sierra Nevada	Liu et al., 2013
	Millar and Westfall, 2008
San Juan (USA)	Brenning et al., 2007
Argentina	Bornet, 2014
	Angillieri, 2017
	Angillieri, 2009
	Falaschi et al., 2014
	Falaschi et al., 2015
	Trombotto and Castro., 2012
	Martini et al., 2013
Bolivia	Rangecroft et al., 2014
Chile	Azocar et al., 2017
	Janke et al., 2017
Norway	Lillehoern and Etzelmüller, 2011
New Zealand	Sattler et al., 2016

4.2.2 Morphological characteristics integrated into RGI

The following Figure 8 to 10 show whether or not a publication integrates a morphological characteristic into the RGI or not. Each figure shows the approximate percentage as well as the exact number of answers given to the question *"is the following morphological information integrated in this RGI?"*.

As displayed in Figure 6 totally 26 (83.9%) out of 31 publications integrated the area into the RGI. Two additionally considered the perimeter. The length/width mean value is less applied. However, the ratio of length to width is 54.8% of the analysed publications integrated into the RGI.

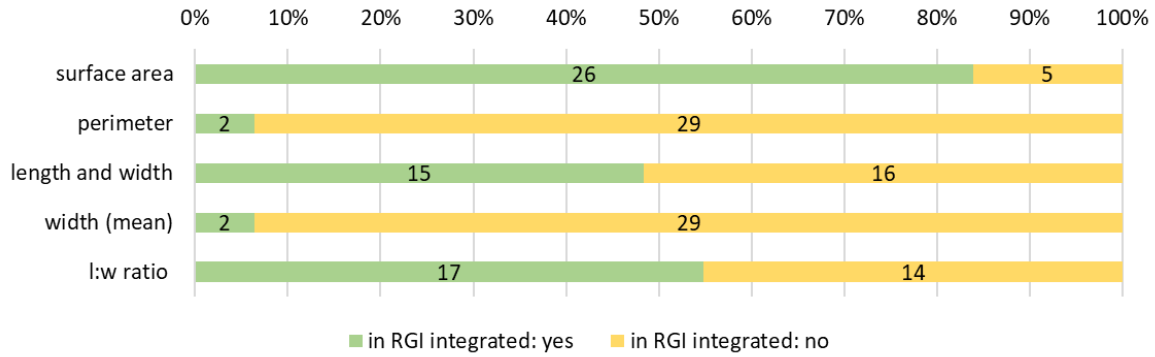


Figure 6 - Literature Review, morphometric characteristics inventoried in rock glacier inventories.

The analysed RGI predominantly integrate the minimal and maximal altitude of a RG out of which the range and mean altitude can be derived (compare Figure 7). The former is considered in 25,8% of the publications above, the latter in 61.3%. The front elevation, meaning the height of a RG front, is integrated into three out of 31 RGI.

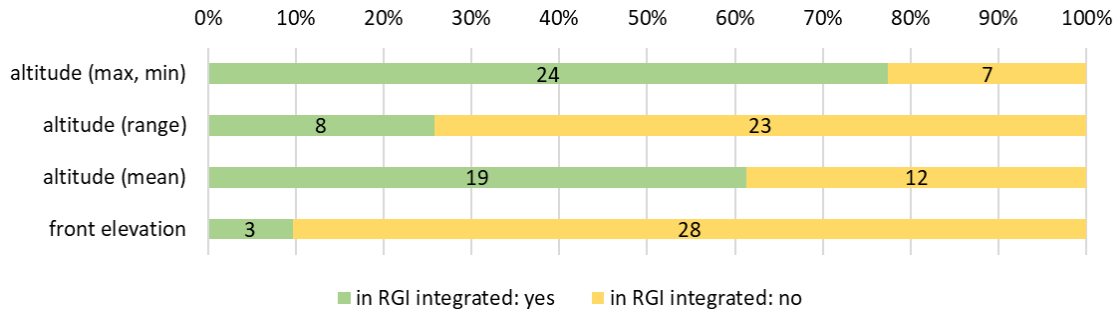


Figure 7 - Literature Review, altitude and front elevation information inventoried in rock glacier inventories.

A general classification of slope informations is found in 45.2% of the analysed RGI. The orientations of RG in form of the aspect in degrees is less often applied (compare Figure 8) in contrast to use of the eight classes N, NE, E, SE, S, SW, W, NW (54.8%).

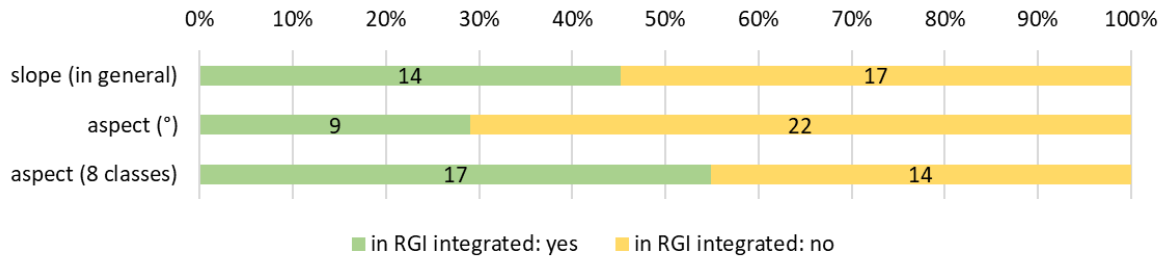


Figure 8 - Literature Review, slope and aspect informations inventoried in rock glacier inventories.

As Figure 9 shows the activity status of a RG is integrated in 93.5% of 31 publications while the velocity is considered in six cases of the chosen publications.

The morphology of RG can be described on different scales such as the general dimension by geometric data (surface, length, etc.) up to detailed form and surface information (compare chapter 4.1.2). The indication of polymorphology introduces the concept of polymorphic and monomorphic RG (compare Frauenfelder and Kääb, 2000: 284). It describes the environmental conditions under which a RG has developed, such as climatic changes or several cycles of activity and reactivations. It is integrated into three out of 31 RGI.

The upslope boundary which is mentioned in more than half of the RGI analysed allows to specify the RG environment and the rooting zone of the RG. Further morphological details such as furrows, crevasses or depressions are considered in 32.3%.

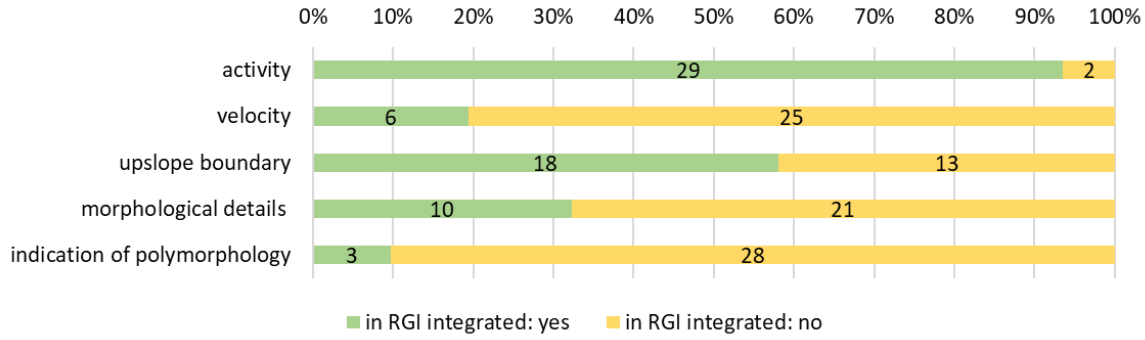


Figure 9 - Literature Review, RG morphodynamic informations inventoried in rock glacier inventories.

5. Catalogue of RG characteristics to be integrated into a general RGI

Based on the importance attributed to the list of morphological RG characteristics in Table 2 and the discussions and the findings in chapter 4 and 6 the following Table 5 is compiled.

The RG characteristics considered important to be integrated into a standardised RGI are named in Table 5 and completed by the parameters necessary (compare Table 6). The presented catalogue of RG characteristics therefore is derived from both qualitative and quantitative parameters describing a RG. Further discussions of the presented list are presented in chapter 6.

Table 5 – Rock glacier characteristics considered important to be integrated into standardised rock glacier inventories.

Rock glacier characteristic	***Parameters inventoried***	***description***	***Descriptions and further references***
Shape (outline)	Shape of the RG	Polygon of the landform, allows the derivation of morphometric indications like area, length, etc.	Chapter 6.1.1 Jones et al., 2018: 126 Barsch, 1996: 19,21
Area	RG outline polygon	GIS calculated area, along the side ridges on front slope	Chapter 6.1.1, 6.1.2, 6.1.3 Wang et al., 2017 : 1002 Jones et al., 2018 : 125 Barsch, 1996 : 21
Altitude	Maximal and minimal altitude allowing the derivation of range and mean	Altitude of the lowest and highest pixel of the shape	Chapter 6.1.3
Aspect	In classes N, NE, E, SE, S, SW, W, NW	GIS derived from aspect degrees (e.g. 0°= N).	Chapter 6.1.4
Slope	In degrees	GIS derived	Chapter 6.1.4
Velocity	Absolute velocity or categories	Process specification of active RG	Chapter 6.1.6
Activity status	Active, inactive, relict, r.p. (rapidly moving)	r.p. might have to be renamed	Chapter 6.1.6
Upslope boundary	To be deterimined	Description of geomorphological environment in keywords (e.g. glacier, rock wall, etc.)	Chapter 6.1.8
Commentary	Text	General subjectivity assessement, detailed surface morphologies, acquisition date	Chapter 6.1.5, 6.1.9

Table 6 – Rock glacier parameters necessary to describe rock glacier characteristics considered important to be integrated into standardised rock glacier inventories.

Parameter	***[unit], explanation***
Area (shape polygon)	[-]
Width (maximal, minimal, mean)	[m], in regular intervals
Length (maximal, minimal)	[m], maximal RG extension parallel to flow direction
Altitude (maximal, minimal)	[m a.s.l. (meters above sea level)], measured by the maximal and minimal pixel value of the RG outline (GIS)
Aspect	[N, NE, E, SE, S, SW, W, NW], GIS derived, categorised aspect degrees (e.g. 0°= N)
Slope	[°], GIS derived
Velocity	[to be determined, in categories or absolute velocities]
Activity status	[active, inactive, relict, r.p. (rapidly moving)]
Upslope boundary	[text], geomorphological description of the RG environment in keywords (to be determined)
Commentary	Subjectivity assessment, complexity of RG aggregation

6. Discussion

6.1 Discussion of RG characteristics and their integration into RGI

6.1.1 Morphological description: shape

The majority of the online survey participants considered the general shape and indication of tongue- or lobate or complex form to be important in a RGI which is derivable by the ratio of length to width (e.g. Barsch 1996: 19). The majoritarian integration of length, width and its ratio into existing RGI confirms the online survey results (done so in e.g. Jones et al., 2018: 126).

The online survey category Shape 3 (multiroot, - lobe) primarily introduces a more distinctive notion of complexity describing RG aggregations, however, can be summarized in the *complex* formed RG. Comparably polymorphology in the context of Frauenfelder and Kääb (2000: 284) is mentioned in three out of 31 publications though not requested in the online survey.

The integration of the RG shape in general is demanded. The above-mentioned terms traditionally are derived by the length/width ratio, however, it might be critically asked, whether or not such a differentiation is necessary in a standardised RGI. The delimitation of the RG outline implies a visual representation of the landform in a polygon, which may, if indications on the length/width ratio are demanded, allow GIS calculations. However, the information whether or not a RG is part of a complex aggregation of landforms might be of interest.

In this thesis it is therefore proposed not to specify the shape of a RG other than the delimitation of the *RG outline* and in case of a complex RG aggregation the notion of *complexity* in the commentary.

6.1.1.1 Shape delimitation of rock glaciers

The definition of a RG outline opens the discussion of how to delimitate a RG shape by a polygon (GIS). It is further linked to the determination of the minimal and maximal altitude (compare below). One of the main points of discussion in delimitating the RG outline is whether or not to integrate the very bottom of the RG front. This question is illustrated in the following Figure 10 and discussed below. Further the upper limit of the RG delimitation is analysed.

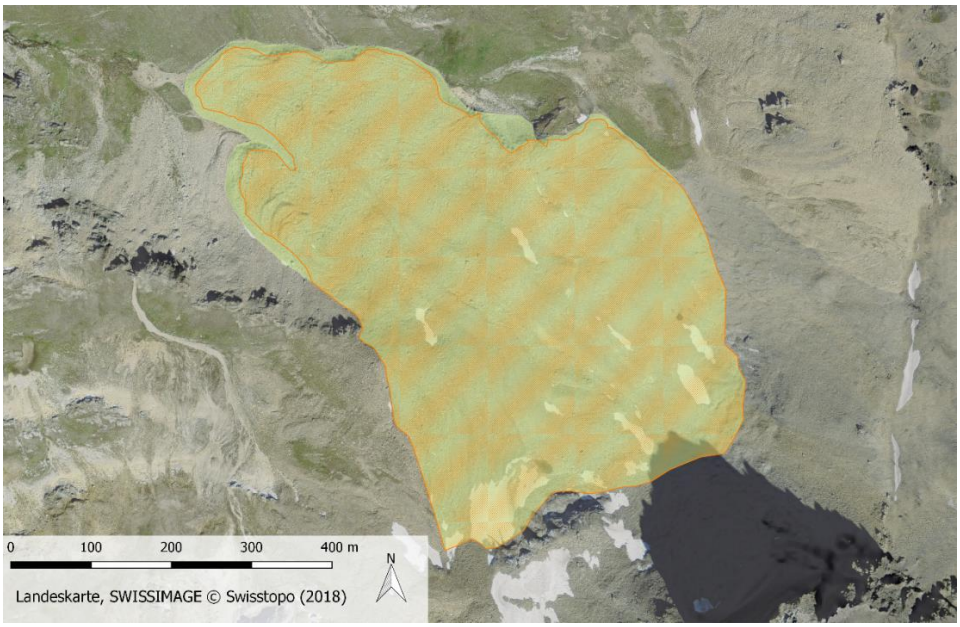


Figure 10 – Rock Glacier Réchy/Becs-de-Bosson (Valais, Switzerland. In yellow the entire surface occupied by the landform is shown, in orange the side ridges and the front are not included.

The surface occupied by the RG includes the side ridges and the front. It defines the area influenced by the RG. This includes the debris rolling down the front and the side ridges through the movement of the landform. In contrast, the orange coloured area delimitates the actual form where the indicative geomorphological process is identifiable. The difference in size here is 5%, which is neglectable in this case, but also in general especially in RG of larger dimension, as the investigated landform is not influenced and the delimitation error (especially in the rooting zone of the landform) might be of a similar importance .

Though RG forms not always are as easy to delimitate as in Figure 10. Figure 11 shows the example of the Gugla RG, where the front of the rock glacier is difficult to detect as it ends in a steep slope which is continuously eroded. Similar difficulties often occur in situations where RG end in debris slopes. It these cases the front ridge often is the only characteristic determinable in the field. In general, the lower limit of a RG is hard to delimitate and is highly subjective.

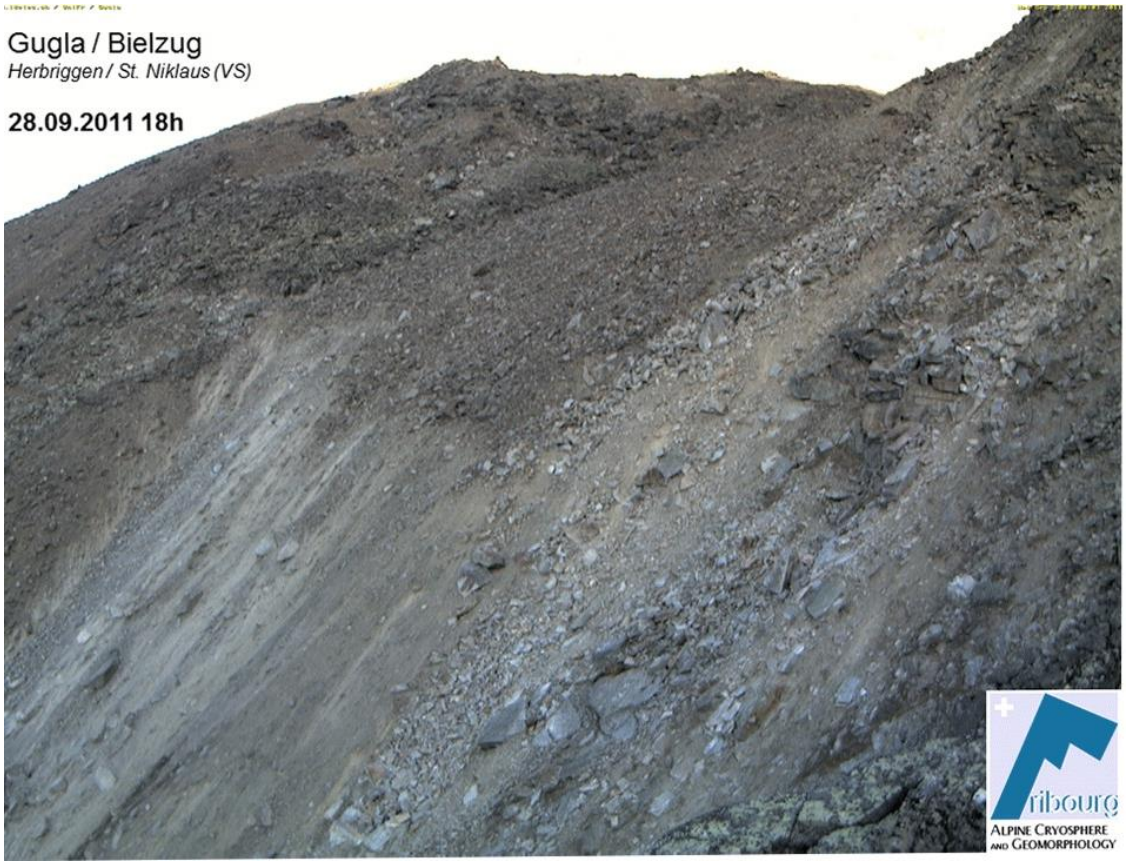


Figure 11 – Front of the Gugla rock glacier (Valais, Swizerland).

The identification of the upper limit of a RG traditionally is based on morphological and upslope boundary observations (signs of movement, debris orientation, etc.) and may be extended by remote sensing technologies such DInSAR (Barboux et al., 2014) or very high-resolution DEM

(Bodin et al., 2018). These technologies allow to verify the suggested upper limit of the RG, however, this approach is work intensive.

The delimitation of the RG outlines proposed in this thesis is proposed to be based on the morphological features like the ridge line of the RG front, the side ridges and the boundary of movement in the rooting zone of the RG. In the upper part of a RG, where kinematic morphologies are less visible, it is suggested to verify the boundary of movement by technologies such as DInSAR. An example of such an outline delimitation might be the orange outline of the Réchy RG in Figure 10.

6.1.2 Morphometric parameters: area, perimeter, length and width

Geometric informations allow to morphometrically describe RG which is interesting for comparisons of RG dimensions between different regions (Bornet 2014: 52) and introduce more quantitative properties of RG compared to exclusively morphological approaches.

The basic and usually into RGI integrated parameters are the surface area, length and width (see Figures 2 and 6). GIS calculation and GIS tools allow efficient and accurate results based on the shape polygon. It is both possible to work with the maximal length/width of a polygon or the average out of several lines. Traditionally (often based on Barsch, 1996) in non-complex RG the maximal or average length in the direction of flow and an average in width are used. As the delimitation of the shape may influence the values significantly (rooting zone) the exact definition of length and width for a general RGI needs to be discussed further.

The perimeter of a RG is not integrated into the online survey and the missing commentaries in Table 3 imply no significant importance of this morphological characteristic for standardised RGI.

6.1.3 Morphometric parameters: altitude

Another important morphometric parameter is the altitude of a RG as both the online survey (compare Figure 4) and the actual integration into RGI (compare Figure 7) show. Both the altitude ranges as also the mean values are easily derivable from the minimum and maximum values which might be partially an explanation for their generally “less important” rating.

The integration of the minimum and maximum altitude data therefore includes all necessary informations on altitudes which are important for a general RGI. Where and how altitude

informations are collected is part of the discussion about the RG outline (compare chapter 6.1.1.1).

The above discussed upper limit of a RG is detected by the morphological and kinematic information about the moving landform. The maximal altitude of a RG therefore is proposed to be derived by GIS calculation of the uppermost pixel of the RG outline polygon. The notion of subjectivity induced by the determination of the polygon delimitation must be indicated in the commentary and must be considered in the use of the derived data.

The altitude of the lowest pixel of the delimited RG shape polygon (compare Table 5) is proposed to be used for the minimal altitude. Morphologically speaking the minimal altitude is derived from the ridge of the RG front. As explained in chapter 6.1.1.1 RG in mountainous areas often end in steep debris slopes so the difference between the altitude of the RG front and the bottom of the front slope may vary significantly and the latter is difficult to detect.

Additionally, to the altitude values three out of 31 publications also integrated the elevation of the front of a RG (compare Figure 7). This characteristic is not asked in the online survey and neither is it mentioned in the commentaries. It is not considered to be important for a general RGI as it is difficult to gather the necessary informations in an acceptable quality.

6.1.4 Morphometric parameters: slope and aspect

The slope of a RG terrain is considered important (compare Figure 3) and are applied in RGI (compare Figure 8). An overall slope can be derived from DEM by GIS which is ideal parameter to specify the RG context in an efficient and simple manner.

Likewise (compare Figure 3 and 8), the aspect of a RG offers important informations on the characteristics as well as on its context. The aspect is considered essential to be integrated into standardised RGI. Comparable to the velocity a continuous data (in °) allow continuous values but also a categorisation (often N, NE, E, SE, S, SW, W, NW). The categorisation of the aspect is efficient and sufficient for the purpose of a standardised RGI.

6.1.5 Detailed morphological (surface) characteristics of RG

As the category *morphologies on RG* of the online survey shows, a majority of RG experts demand further informations on the RG surface morphologies such as crevasses, furrows, etc. (also mentioned in Table 3). The corresponding, rather unspecific, parameter in the literature review (morphological details, Figure 9) shows its integration into RGI though less united than

in the online survey. A possible explanation is that surface morphologies such as crevasses are used in the detection and activity status gathering process though not systematically integrated into the RGI (compare Table 7).

The so far justified importance implies an integration of surface morphologies of RG into RGI. But how? A further parameter of surface description may offer the curvature (Brenning et al., 2007: 4) derived from a DEM, however, even if depressions in the RG surface may indicate a relict RG (Baroni 2004: 9) there are no other surface morphologies such as flow lines and crevasses integrated. Alternatively, Jones et al. 2018: 127) offers the integration of several morphological informations by of the *certainty index*. For every RG the parameters evaluated are *the external boundary, the snow coverage, the longitudinal flow structure, traverse flow structure, the front slope* altogether aggregated according to their individual certainty. An integration of such a certainty score allows a) the integration of detailed morphological characteristics to the identification and analysis process of an individual RG additionally to e.g. the shape and b) the overall certainty of a RGI can be assessed. Especially RGI derived from remote sensing data may be mapped more completely (Jones et al., 20 18: 127) as also poor image quality sectors can be integrated.

However, the evaluation of these factors is very work intensive and in themselves subjective. For a standardised RGI the qualitative notion of the subjectivity and the data accuracy in the commentary is considered to be sufficient.

6.1.6 Activity status of RG

As introduced in the definition of a RG and in Table 1, the geomorphological description of a RG includes the process which forms the landform RG. It includes all energy flows, processes and interactions finally contributing to the formation of a RG, such as debris accumulation, the presence of interstitial ice and ice lenses, air circulation in the active layer, etc.

There are two traditional approaches (Barsch, 1996: 8ff) to describe the functionality of the geomorphological process of a RG: *active, inactive and relict (fossil)* or *intact, relict (fossil)*. The definition of active and inactive is determined by the RG velocity rates: RG which arecontaining ice but though no morphological or measurable movements are detectable are classified as inactive, due to the physical stabilisation of the movement or due to climate related reasons. RG forms free from permafrost and movement, often with vegetation and negative morphologies, are called relict (or fossil). Intact, however, includes both categories of active and inactive RG.

The word *intact* implies the functionality of the geomorphological process which is, however, difficult to assess properly. Similar difficulties occur for the determination of an *active/inactive* RG as modern technologies are able to detect even minimal kinematic displacements. Due to the gravity most, mountainous terrain is moving slightly, which is also valid for inactive and even relict RG. Modern technologies can detect these (cm/y) movements. Therefore, velocity rates for the definition of the activity status must be used carefully.

The use of the *active, inactive and relict* classification of the activity status based on the geomorphological process and the morphological description (compare 6.1.5) of a RG though allows a characterisation of the RG minimising misleading interpretations. Velocity rates must not be confused with the activity status of a RG though allow the identification and placement of a moving RG into the categories active or inactive. Morphological, and if available geophysical measurements, allow the interpretation of the ice content.

The RG activity status and its velocity rates are continuous, though slowly changing characteristics. The occurrence of rapidly moving (suddenly accelerating or destabilized) RG so far is not considered in RGI. The reasons for such accelerations are complex and the term destabilized may not necessarily be precise enough (Delaloye et al., 2013). Nevertheless, for general RGI and monitoring purposes an integration of this information into RGI is important.

In future RGI it is proposed to integrate the activity status of RG in four categories: *active*, *inactive*, *relict* and *rapidly moving*. The latter must be discussed further.

6.1.7 Velocity of RG

Kinematic informations are less often integrated in RGI than indications on the activity status (six out of 31 publications), partially due to methodological difficulties (compare e.g. Barboux et al., 2014). Delaloye et al. (2018). The integration of velocity informations into RGI is important in order to optimally acquire changes in the RG and especially in general mountain permafrost regions.

The so far used approaches are dependent on the methodology and can be distinguished into two sections*: a)* velocity data are given in continuous values as Wang et al. (2017: 999) shows or *b)* in categories such as cm/day or dm/month (Barboux et al., 2014: 9). General RGI aim to be efficient and widely applicable (compare Table 3 and chapter 2). The details of the integration of kinematic informations into a standardised RGI is subject of current research (Delaloye et al., 2018) in order to avoid both false precision and imprecision.

6.1.8 Upslope boundary

Figure 5 shows the interest of the researchers to integrate informations on the RG origin and its morphological environment, such as for example debris covered glaciers or moraines. Figure 9 and the answers given to question 2 of the online survey confirm these results. The origin of RG are various and hard to classify into categories, however, there are attempts to do so, such as glacier- or talus-derived RG (Barsch, 1996: 184).

It is proposed to integrate informations in form of key words or categories into a general RGI in order to generate an overall comprehension of an inventoried RG. The details, however, must be discussed and developed in a more precise manner.

6.1.9 Commentary on RG

RGI allow a general description of RG in characteristics and parameters, often aggregated in categories. Though the classification of certain aspects may not always be possible or only occurs in a minority of the inventoried objects.

In this thesis it is proposed to include the subjective assessment of every RG integrated in the RGI into the category *commentary*. The detailed formulation in keywords, however, has to be discussed and defined. Such an indication of the subjectivity of the informations may significantly improve the quality of the RGI.

A second information essential to integrate into a RGI is the date of the data acquisition in order to assess data. In this thesis the *acquisition date* is mentioned in the commentary, which however, may be integrated otherwise.

Further informations in commentary's are possible, though it is important not to include to many informations.

6.1.10 Further RG characteristics

RG may be described with various additional parameters, however, their scientific usefulness in a standardised RGI is not given. Based on a standard RGI according to Delaloye et al. (2018) certain characteristics of RG are not considered being important to be integrated. In the following some examples are described:

Both the literature analysis as the first question of the online survey did not consider the geological context, grain size analyses or the vegetation coverage of RG though participant two introduced

it in the commentaries to question 1 (see chapter 4.1.3). These characteristics have to be explored further.

The thickness of a RG may cause both methodological (how can data be collected accurately and time-efficiently) and content-based discussions as both strongly depend on the purpose of a RGI. A general RGI as described above may not necessarily need an indication of thickness as the global availability of DEM and GIS tools significantly a local data gathering if required.

6.2 Reflexion on results

The methodological approach of the listing is despite of the so far conduced work influenced by the subjectivity, of the author i.e. a limited experience. Advanced studies absolutely must include further practical exploring of different RGI in GIS. Subjectivity in relation to the results is discussed in chapter 6.1.9.

The results presented in chapter 5 and discussed in chapter 6 are based on a literature review and an online survey which may be criticised for lacking execution details and empirical application in this thesis. For further ascertainment of the list of RG characteristics and parameters the proposed approaches must be revised. However, the thesis allows an overview on the existing approaches as well as the general opinion of RG experts.

7. Conclusion

The scientific interest on RG and their versatile application in permafrost research has led to various RGI designs. Despite the fact that the RGI integrate similar morphological characteristics describing the geomorphological feature “rock glacier” the detailed approaches are not directly comparable. The proposal of standard guidelines for a RGI may introduce a certain homogeneity into RGI enabling a global use of the data even if there are several independent projects and contexts included. Detailed information on single RG may be derived individually.

Describing and integrating RG into RGI implies the integration of several qualitative and quantitative characteristics from which the morphological parameters are derived. The objectives of a standardised RGI based on GIS allow a versatile comprehension of RG in their context, avoiding the integration of too much or too complex data. However, further practical applications must to be tested, especially considering, that not all GIS systems are compatible.

The morphological characteristics considered to be important for an adequate acquisition of a RG into a RGI are the shape, the area, the altitude (max, min), the aspect, the slope, the velocity, the activity status, the velocity, the upslope boundary and the commentary. The parameters necessary to describe the morphological characteristics are listed in Table 6.

The presented results are primarily derived from literature review, the online survey and basic experience in working with RGI. Further investigations must include more practical methodological approaches combined with its application in GIS aiming to develop and specify the rock glacier characteristics and parameters.

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10. Appendix

10.1 Detailed catalogue of analysed publications

Table 7 - Detailed catalogue of analysed publications with geographic and dimensional information.

Region or Nation	***Publication***	***Main method (number of inventoried RG)***	***Environmental informations***
Nepal	Jones et al., 2018	Satellite images (Google Earth) (1137)	≥ 4000 m a.s.l (meters above sea level); Topographic extremes imply climates from subtropical (south region) to arctic in the north; Asian summer (June-September).
Thien Shan	Wang et al., 2017	DInSAR, Google Earth (261)	Mean altitude ≥ 4000 m a.s.l; West Thien Shan rather humid and cold, East TS rather dry and cold.
Hindukush	Schmid et al., 2015	Google Earth (702)	Between 3500 and 5500 m a.s.l.; various from wet and cold to dry and cold.
Swiss Alps	Delaloye and Morand, 1998	Stereoscopic analysis of aerial images, field (320)	Between 2000 and 4000 m a.s.l.; inner Alpine climate (rather dry).
	Barboux et al., 2014	DInSAR (908)	Between 2300 and 3000 m a.s.l., climate see above.
South Eastern Alps	Colucci et al., 2016	Orthophotos, digital elevation model (DEM based on LiDAR) (53)	Max. altitude ca. 2800 m a.s.l.; alpine (rather wet) to inner Alpine climate.
	Kellerer-Pirklbauer 2012)	(1647)	≥ 2100 m a.s.l; alpine (rather wet) to inner Alpine climate conditions.
	Krainer and Ribis, 2012	Orthophotos, laserscan images (3145)	≥ 2000 m a.s.l; alpine (rather wet) to inner Alpine climate conditions.
Italian Alps	Scotti et al., 2013	Orthophotos and DEM (1514)	Between 200 and 4000 m a.s.l.; various climate types from Mediterranean to Alpine.
	Seppi et al., 2005)	Stereoscopic analysis of aerial images, field (32)	Alpine climate.
	Seppi et al. 2012	Orthophotos and DEM (705)	≥ 1600 m a.s.l; Alpine to inner Alpine climates.

French Alps	Bornet, 2014	Orthophotos and DEM (1864)	Between 1500 and 3000 m a.s.l.; Alpine though significantly influenced by the Mediterranean from south.
	Marcer et al., 2017	No informations (3261)	Between 1500 and 4000 m a.s.l.; climate see above.
Alps (various regions)	Cremonese et al., 2011	Several inventories compiled (4796)	Between 1000 and 4000 m a.s.l.; Alpine and inner Alpine climates.
Carpathians	Onaca et al., 2017	Orthophotos, DEM (306)	Between 1800 and 2200 m a.s.l.; Alpine climate though rather continental (dryer, colder).
	Uxa and Mida, 2017	DEM, aerial images, field (383)	Between 1300 and 2400 m a.s.l.; climate see above.
Sierra Nevada	Liu et al., 2013	DInSAR (59)	Mediterranean/semi-arid climate.
	Millar and Westfall, 2008	(289)	Between 2200 and 4000 m a.s.l.; Semi-arid climate.
San Juan (USA)	Brenning et al., 2007	(2933)	≥ 3400 m a.s.l; continental semi-arid climate.
Argentina	Bornet, 2014	DEM, satellite images (1864)	Central Andes (dry)
	Angillieri, 2017	(500)	Between 3500 and 4500 m a.s.l.; Dry Andes.
	Angillieri 2009	Aerial images, DEM (140)	≥ 3400 m a.s.l; Dry Andes (arid to semi-arid climate).
	Falaschi et al. 2014	ALOS PRISM (488)	≥ 4100 m a.s.l; Dry (desert) Andes.
	Falaschi et al., 2015	ALOS PRISM (177)	Between 1200 and 2200 m a.s.l.; Wet Andes (maritime to continentally influenced).
	Trombotto and Castro, 2012	DEM (ASTER) (182)	≥ 3300 m a.s.l; Central Andes
	Martini et al., 2013	DEM, Google Earth (635)	≥ 3800 m a.s.l; Central Andes
Bolivia	Rangecroft et al. 2014	Google Earth, DEM (ASTER) (97)	Between 4400 and 5500 m a.s.l.; Upper end of Desert Andes though influenced by humidity from north.
Chile	(Janke, Ng, and Bellisario 2017) Azocar et al., 2017	Microsoft Bing Maps Imagery (3575)	Semi-arid Andes.
	Janke et al., 2017	Existing inventory and photogrammetry (699)	Between 2500 and 5000 m a.s.l.; Semi-arid Andes.
Norway	Lillehoern and Etzelmüller, 2011	Geological and geomorphological maps, aerial images, field (307)	≥ 1000 m a.s.l; Mid-latitude climate influenced by humidity in the west and continentality in the east.
New Zealand	Sattler et al., 2016	Google Earth (387)	Between 1400 and 2400 m a.s.l.; Temperate, maritime climate.