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RGIK guidelines for compiling consistent rock glacier inventories

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A R T I C L E I N F O

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A B S T R A C T

Rock glaciers are characteristic and ubiquitous periglacial landforms. They contain key information for understanding the past and present evolution of the mountain cryosphere, as well as for addressing a range of more applied concerns such as water supply/quality and geohazard assessment, especially in relation to ongoing climate change. Their spatial distribution and characterization, including their state of activity, has long been documented by means of rock glacier inventories (RoGIs). However, owing to the inherent morphological complexity of these landforms, contrasting definitions, and limited international cooperation, most RoGIs compiled around the globe exhibit a high degree of heterogeneity. This is a critical shortcoming that hampers our ability to combine RoGIs across regions towards the compilation of a global inventory. To address this limitation, the International Permafrost Association (IPA) Action Group (2018–2023) on Rock Glacier Inventories and Kinematics (RGIK) has fostered and coordinated international collaborative work to develop widely accepted guidelines for inventorying rock glaciers, including the characterization of kinematic behavior (RGIK, 2023a). Accordingly, a technical definition of rock glaciers and a methodological workflow for inventorying these landforms are provided. This RGIK definition relies on three morphological criteria: the mandatory evidence of a rock glacier front and adjoining lateral margins, and optionally, ridge-and-furrow topography. Deliberately, the definition does not address the questions of formative mechanism(s) and ice origin. To account for landform complexity, a hierarchical classification scheme of rock glacier units (RGUs) and systems (RGSs) is also introduced. The methodological workflow is composed of four steps: (i) detection, which consists of rock glacier identification according to the relevant morphological criteria; (ii) location, which involves assigning a georeferenced primary marker to each RGU and RGS; (iii) characterization, which among a set of optional attributes, entails assigning a geomorphological type of upslope connection and a degree of activity to each RGU; and (iv) delineation, in which the rock glacier outline is mapped and relevant degree of uncertainty is documented. Primarily, this workflow is based on a geomorphological approach, which may be supported with a kinematic approach, when reliable kinematic data is available. The coordination of ongoing testing, training, and prospective developments is entrusted to the IPA Standing Committee on RGIK, which was established in 2024.

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1. Introduction

Rock glaciers are characteristic periglacial features of the mountain cryosphere. They usually form through the downslope, viscous creep of perennially frozen ice-rich debris (Barsch, 1996; Arenson et al., 2002; Cicoira et al., 2021; Haeberli et al., 2024), although it has been suggested that in some instances glacial/former glacial activity can represent an alternative formative mechanism (e.g., Whalley and Martin, 1992; Whalley and Azizi, 1994) within a broader glacier-rock glacier continuum (e.g., Anderson et al., 2018; Jones et al., 2019; Knight et al., 2019). Aside from their genetic origin, which is beyond the scope of this contribution, rock glaciers contain critical information for addressing a range of basic and applied environmental issues, especially in relation to contemporary climate change.

Functionally, rock glaciers constitute prominent sedimentary linkages within the alpine environment that modulate critical components of the coarse sediment cascade (Caine, 1974), either acting as sediment sources (e.g., Lugon and Stoffel, 2010; Kummert and Delaloye, 2018; Kofler et al., 2022), or as buffers/barriers (e.g., Blöthe et al., 2019). Beyond their geomorphic significance, the compilation of Rock Glacier Inventories (hereafter termed RoGIs), including both intact and relict landforms (sensu Barsch, 1996), has found broad application to aid spatial assessment of discontinuous permafrost (e.g., Boeckli et al., 2012; Schmid et al., 2015; Azócar et al., 2017), evaluate water storage/supply potential (e.g., Jones et al., 2018; Schaffer et al., 2019; Wagner et al., 2021; Munroe and Handwerger, 2023), appraise geohazards associated with destabilization, or simply with the downslope movement of their fronts (e.g., Giardino and Vick, 1987; Delaloye et al., 2010; Burger et al., 1999; Scotti et al., 2017a; Marcer et al., 2021). In addition, rock glaciers have proved instrumental for reconstructing post-LGM environmental conditions that supported creeping permafrost development and persistence across a range of spatial scales (e.g., Frauenfelder et al., 2001; Harrison et al., 2008; Scotti et al., 2013; Scapozza et al., 2014; Krainer et al., 2015; Santos-González et al., 2022), and for evaluating the geomorphic response to past climatic changes (e.g., Scotti et al., 2017b; Steinemann et al., 2020; Amschwand et al., 2021; Ballantyne, 2024; Fernandes et al., 2024).

Traditionally, rock glacier inventories have been compiled through a geomorphologic approach that entails visual inspection and interpretation of optical imagery, complemented by field confirmation on a subset of landforms (e.g., Lambiel and Reynard, 2001; Millar and Westfall, 2008; Lilleøren et al., 2013; Scotti et al., 2013; Rangecroft et al., 2014; Falaschi et al., 2015; Schmid et al., 2015; Sattler et al., 2016; Onaca et al., 2017; Charbonneau and Smith, 2018; Pandey, 2019; Harrison et al., 2024). Compared to (clean) glaciers, owing to their intrinsic morphological complexity and the lack of spectral distinction from the surrounding terrain, the unequivocal inventorying of rock glaciers is challenging. Despite improvements afforded by increasingly freely available high-resolution optical imagery and digital topography (e.g., Schmid et al., 2015; Scotti et al., 2024), manual mapping remains an onerous procedure that typically relies on the expert-based assessment of one or more operators and therefore, it is intrinsically associated with some degree of subjectivity. In this context, a series of mapping exercises conducted by international experts (see Brardinoni et al., 2019) have highlighted the existence of significant inter-operator variability with respect to rock glacier delineation (i.e., notably in their upper ends at the transition with the rooting zone) and activity assessment (i.e., especially for inactive, slow-moving landforms).

Indeed, inter-operator variability may be reduced through adoption of a consensus-based multi-operator approach (Way et al., 2021). Equally important, integration of geomorphologic mapping with spatially distributed, remotely sensed kinematic information has led to a more objective assessment of rock glacier activity (e.g., Barboux et al., 2014; Rouyet et al., 2021). Notwithstanding these improvements, the lack of common operational definitions and mapping protocols have represented a major barrier for pursuing consistent inventories and implementing (semi-)automated mapping methods trained on manually delineated landforms (e.g., Robson et al., 2020; Erharter et al., 2022; Hu et al., 2023). This is a critical shortcoming, as it hampers direct comparison of inventories compiled by different experts in different regions (Jones et al., 2018).

To address this limitation, in this contribution we aim to promote the compilation of consistent rock glacier inventories. Specifically, building on a concerted effort conducted by the International Permafrost Association (IPA) Action Group on Rock Glacier Inventories and Kinematics (RGIK), the main objective of this paper is to present a methodological framework for the consistent identification, characterization, and delineation of rock glaciers. Primarily, this framework is based on a geomorphological mapping approach, which may be supported with a kinematic approach, when reliable remotely based kinematic data is available. On the premise that rock glacier inventories span over spatial scales ranging from valleys to regions and up to entire orogens, the use of in-situ information derived from direct coring, thermal monitoring, geophysical investigation, and Quaternary dating, although critical when available at the landform scale, is not explicitly addressed in this document.

This paper relies on a set of working definitions, geomorphological criteria and mapping rules first presented in the RGIK community-based white paper (RGIK, 2023a). The RGIK guidelines are intended to assist operators through the inventorying process, but evidently cannot solve all outstanding issues. They represent a starting point rather than a finish line. Indeed, prospective development and refinement is foreseen as more RGIK-based inventories are compiled across diverse physiographic settings worldwide (e.g., Bertone et al., 2022; Rouyet et al., 2025). This document summarizes and provides improved integration of the conceptual and practical components initially described in the RGIK (2023a) white paper.

2. The RGIK initiative

In 2018, awareness of the growing international interest for RoGIs, increasing number of datasets compiled with disparate protocols, development in remote sensing technologies and greater availability of appropriate satellite imagery motivated the establishment of the IPA RGIK Action Group (Delaloye et al., 2018). Over the five years of activity (2018–2023), the RGIK Action Group developed community-based guidelines and training tools for: (i) compiling RoGIs, and (ii) monitoring Rock Glacier Velocity (RGV) with a climate-focused perspective.

Collectively, the Action Group has involved an international community of about 220 members from 26 countries, facilitating networking and interactions through workshops, seminars, and conference sessions. From a strictly scientific standpoint, the RGIK initiative led RGV (Hu et al., 2025) to be formally recognized as an Essential Climate Variable (ECV) quantity for permafrost by the Global Climate Observing System (GCOS, 2022) and to be included in the monitoring strategy of the Global Terrestrial Network for permafrost (GTN-P) (Streletskiy et al., 2021).

In June 2023, RGIK formally ended its status as an IPA Action Group and transitioned to a permanent entity, whose prospective goals and foundations were laid out in the Puigcerdà Commitment (RGIK, 2023b). This "commitment" was made during the final workshop of the Action Group at the 6th European Conference on Permafrost in Puigcerdà, Spain, in June 2023. On June 16, 2024, following the Bylaws approval by the majority of the voting members, RGIK (www.rgik.org) was officially designated as an IPA Standing Committee by the IPA Council at the 12th International Conference on Permafrost in Whitehorse, Canada.

3. RGIK definitions and main concepts

3.1. Technical definition of rock glacier

The term "rock glacier" has been around for more than a century

(Capps, 1910) and refers to a periglacial landform that is neither a rock nor a glacier (Haeberli, 2000), despite being included in glacier inventories at times (e.g., Barcaza et al., 2017; Zalazar et al., 2020). Indeed, the genesis (and ice origin) of rock glaciers have witnessed a long-standing debate (Lliboutry, 1961; Whalley and Azizi, 1994; Haeberli, 2000; Berthling, 2011; Anderson et al., 2018; Jones et al., 2019; Haeberli et al., 2025), which has resulted in differing definitions of rock glaciers and their associated nomenclature (e.g., Hamilton and Whalley, 1995; Janke et al., 2013). Beyond any outstanding controversy, the RGIK community has agreed on a technical definition of "rock glacier" tailored for the compilation of consistent inventories worldwide. Accordingly, "rock glaciers are debris landforms generated by the former or current creep of frozen ground (permafrost), detectable in the landscape with the following morphologies: front, lateral margins and optionally ridge-and-furrow surface topography" (RGIK, 2023a) (Fig. 1). Permafrost creep has to be understood here as a generic term referring to the variable combination of both internal deformation within the crystalline structure of the frozen ground (creep stricto sensu) and shearing in one or several horizons at depth, i.e., the so-called shear horizon (or shear layer) (Wagner, 1992; Arenson et al., 2002; Bucki and Echelmeyer, 2004; Cicoira et al., 2021). As landforms resulting from the creep of perennially frozen rock/ice mixtures, rock glaciers should not be confused with debris-covered glaciers, which are "true" glaciers displaying an extensive cover of supraglacial debris (Haeberli et al., 2024). Similarly, rock glaciers are not to be confounded with (much shallower) flow features such as solifluction lobes resulting from the freezing and thawing of saturated soils in cold regions (e.g., Matsuoka et al., 2005; Harkema et al., 2023).

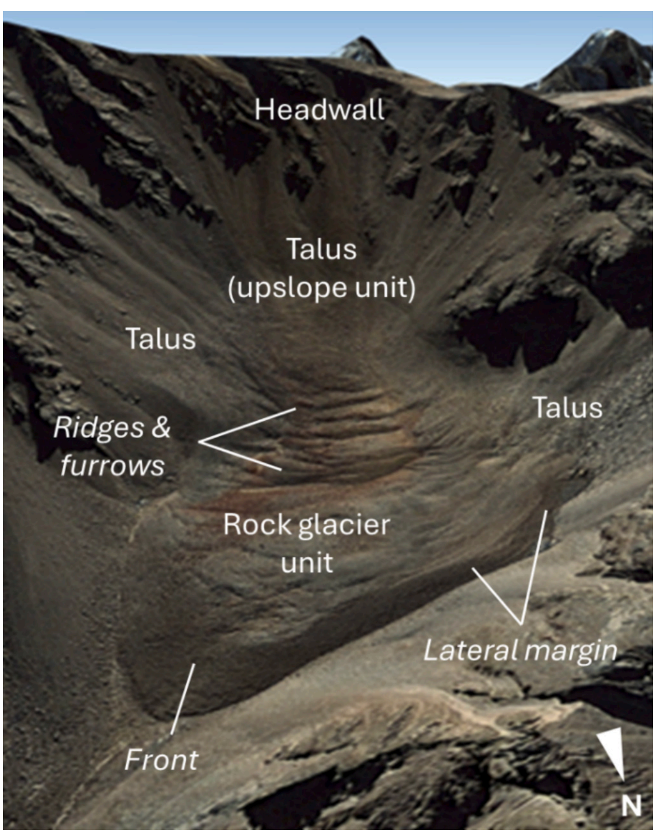

Fig. 1. The anatomy of a rock glacier displaying the primary geomorphological features (in Italics) that characterize the RGIK technical definition. This example depicts the downslope sequence composed of a cirque-like headwall, a set of talus cones and talus slopes (here labelled "talus" for simplicity), and a rock glacier unit at the base of the surrounding walls. Caucasus Mountains, Russia (42.8310°N, 43.9004°E, 3250–3400 m a.s.l.). Length ≈ 330 m, average width ≈ 150 m. Date: 19/09/2011. ©Google Earth/Maxar Technologies.

In a schematic geomorphological sequence, a rock glacier may be seen as a sedimentary conveyor belt that delivers (or has delivered) material from an upslope area down to the relevant developing front (Barsch, 1977; Gärtner-Roer, 2012; Müller et al., 2014). Considering the inherent variability in grain size distribution (e.g., Giardino and Vitek, 1985; Ikeda and Matsuoka, 2006), the proposed definition of a rock glacier does not imply any specific requirement with respect to sediment texture.

Rock glaciers can range in size across several orders of magnitude, from about 10^3 to 10^7 m^2. In line with global glacier inventory standards (i.e., Paul et al., 2009) and to ensure RoGI consistency worldwide, it is recommended that the minimum rock glacier size to be included in an inventory should be 0.01 km^2 (e.g., 100 m × 100 m). Nevertheless, inventories compiled at higher spatial resolution are encouraged.

3.2. Geomorphological criteria

The RGIK definition of a rock glacier relies on the most common and widely recognized geomorphological evidence that is summarized in a set of mandatory (i.e., front, and lateral margins) and optional (i.e., ridge-and-furrow topography) criteria for the unequivocal identification of rock glaciers in the landscape (Fig. 1). In this sub-section, front and lateral margins are described for rock glaciers that exhibit downslope movement (i.e., active rock glaciers, sensu Barsch, 1996). See Section 3.6 for the characterization of (almost) immobile, relict features (Fig. 2).

The **front** (mandatory criterion) refers to the steep terminal section of a rock glacier. When the rock glacier actively moves downslope, it is estimated that this movement involves a depth of around 15 to 30 m due to permafrost creep (Cicoira et al., 2021). The uppermost portion of a moving front is typically susceptible to crumbling, falls of single blocks and larger collapses, which result in exposing fresh material. In most cases the mobilized debris is deposited at the base of the front and becomes gradually buried/incorporated by the advancing rock glacier, thus resembling the behavior of a caterpillar or a conveyor belt (Kääb and Reichmuth, 2005). Rock glaciers, regardless of their degree of activity, may have four distinct front typologies (Figs. 2 and S1):

- A **talus-like** front occurs when debris falls from the uppermost and steepest part (>35–40° for active rock glaciers) and accumulates at the base of the rock glacier front as a talus deposit of limited extension (Wahrhaftig and Cox, 1959). A talus-like front is bounded upslope by a sharp *front edge* that marks an abrupt change in slope (Fig. 2a).
- An **exaggerated** front develops when sediment reworking builds up over steep terrain and a talus deposit that is much greater than the thickness of the rock glacier (uppermost) moving section is formed (Fig. 2b).
- A **truncated** front develops where its downslope movement is limited by topographic constraints, such as where the front approaches a gully headwall and becomes a source of debris flows, or the edge of a scarp where it generates rockfalls (Fig. 2c) (e.g., Lugon and Stoffel, 2010; Kummert et al., 2018). In such instances, the position of the front remains about stationary through time (e.g., Vivero et al., 2022). The front edge is usually sharp, and its long profile can evolve into an exaggerated front.
- A **bulgy** front is a less common but distinct typology characterized by a rounded and sometimes complex topography, which does not develop a clear front edge (Fig. 2d). It mostly occurs in fine-grained (pebbly) rock glaciers.

The **lateral margins** (mandatory criterion) develop in spatial continuity with the front along the sides of the rock glacier. Well-developed lateral margins may not always occur, especially in the upper part of the landform. Three types of margins are identified (Fig. 3):

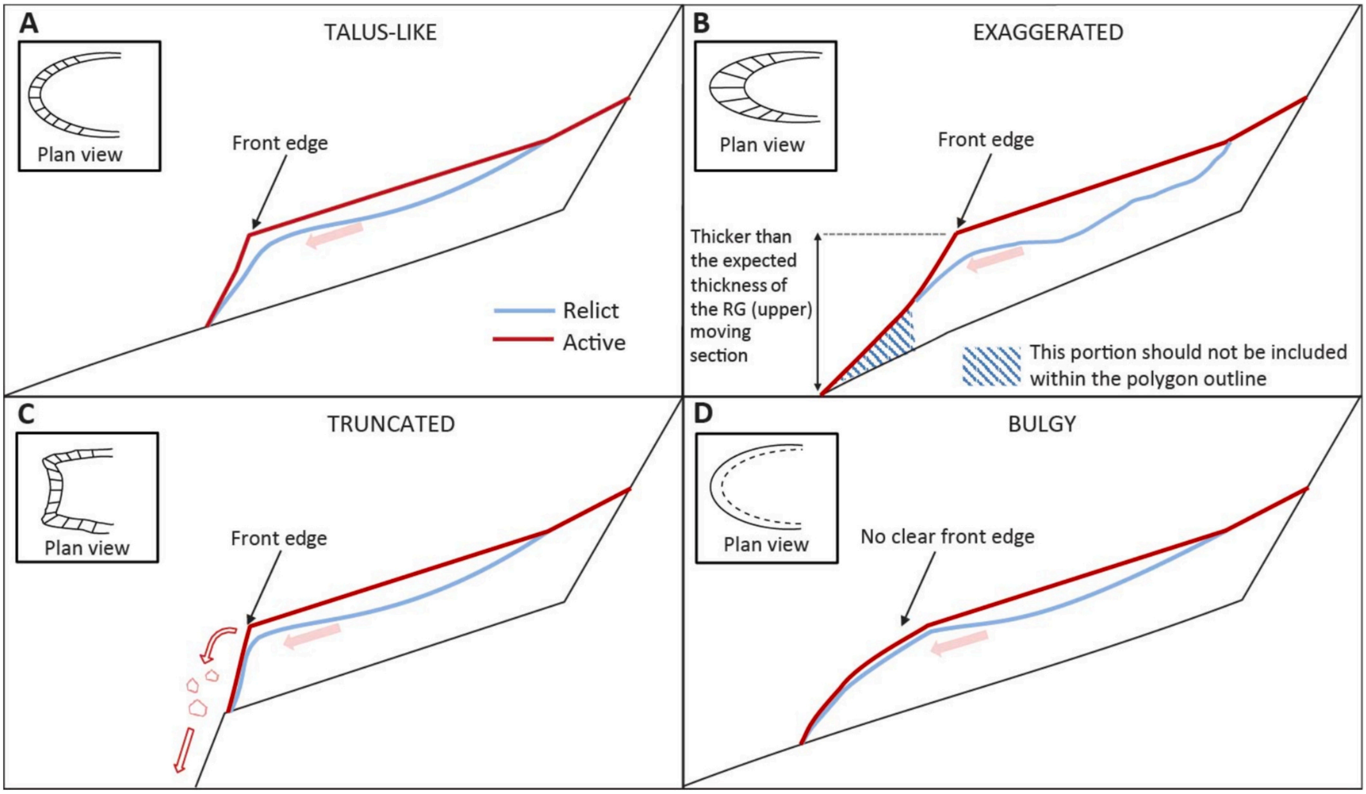

Fig. 2. Schematic, side view representation of rock glacier front typologies: (a) talus-like; (b) exaggerated; (c) truncated; and (d) bulgy. Insets enclose the relevant plan view representations. See Fig. S1 in the Supplementary Material for specific examples of each front typology.

- A **talus-like** margin refers to a morphology that resembles a talus-like front, which may sometimes form an exaggerated talus and, in rare instances, may be truncated.
- A **levee** is a former talus-like margin that has ceased growing, due to the lowering of the rock glacier surface. It could sometimes be confused with lateral moraines, especially in the case of relict rock glaciers.
- A **shear** margin is a shallow, elongated furrow that forms along the mobile portion of a rock glacier due to shearing. It typically develops on the inner lower side of the levees and in the uppermost portion of a rock glacier.

The **ridges and furrows** (optional criterion), which may or may not occur on a rock glacier, are distinct, convex transverse or longitudinal surface undulations linked to the current or past cohesive flow of a rock glacier (Haeberli, 1985). Transverse features result from compression (Fig. 1), while longitudinal features indicate flow convergence, shearing, or deformation between areas moving at different speeds (Kääb and Weber, 2004; Frehner et al., 2015). Ridges and furrows are not to be confused with transverse cracks and scarps associated with destabilization dynamics (Marcer et al., 2019) (cf. Section 3.8).

3.3. Rock glacier units and systems

Rock glaciers with a complex structure (e.g., multiple lobes, coalescent lobes, multiple generations, and heterogeneous dynamics) are common and difficult to characterize unequivocally. This complexity, without a set of common rules, is likely to impart a significant degree of heterogeneity between inventories. To account for landform complexity, previous studies have distinguished between single unit (or monomorphic) and composite, multiple unit (or polymorphic) rock glaciers (e.g., Barsch, 1996; Frauenfelder and Kääb, 2000).

To address this issue more systematically, a two-level hierarchical classification scheme is proposed:

- **Rock glacier unit** (RGU) – Level 1: a single rock glacier landform that can be unambiguously identified based on the technical definition (cf. Section 3.1) and can be distinguished from other adjacent and/or overlapping units according to distinct: (i) timing of formation; (ii) connection to different upslope unit(s) (cf. Section 3.5); and (iii) degree of activity (cf. Section 3.6). In particular, the relative timing of formation may be inferred from the morphological characteristics (e.g., flow lines and surface roughness), weathering stage (e.g., Amschwand et al., 2021), land cover conditions, and by the positioning of a unit with respect to other subjacent (or overlapping) ones.

  Units are further classified according to **simple** and **complex morphology** (Fig. 4). Accordingly, a RGU of simple morphology would exhibit homogeneous attributes conforming to the criteria listed above, whereas a complex one displays some spatial variability but would lack sufficient evidence to unambiguously distinguish different units therein.
- **Rock glacier system** (RGS) – Level 2: corresponds to any landform consisting either of a single RGU or of multiple RGUs that are spatially connected, either in a downslope sequence or through coalescence. A RGS made of a single unit is classified as a **mono-unit** system (Fig. 4a), whereas one composed of multiple units is referred to as a **multi-unit** system (Fig. 4b).

3.4. Rock glacier outline

Representing a rock glacier as a landform requires delineating a distinct outline, and for various practical reasons (e.g., size evaluation, geomorphological mapping, sediment budgeting, and water storage estimation) this outline has to be an enclosed polygon. The manual delineation of a polygon outline involves some degree of heterogeneity,

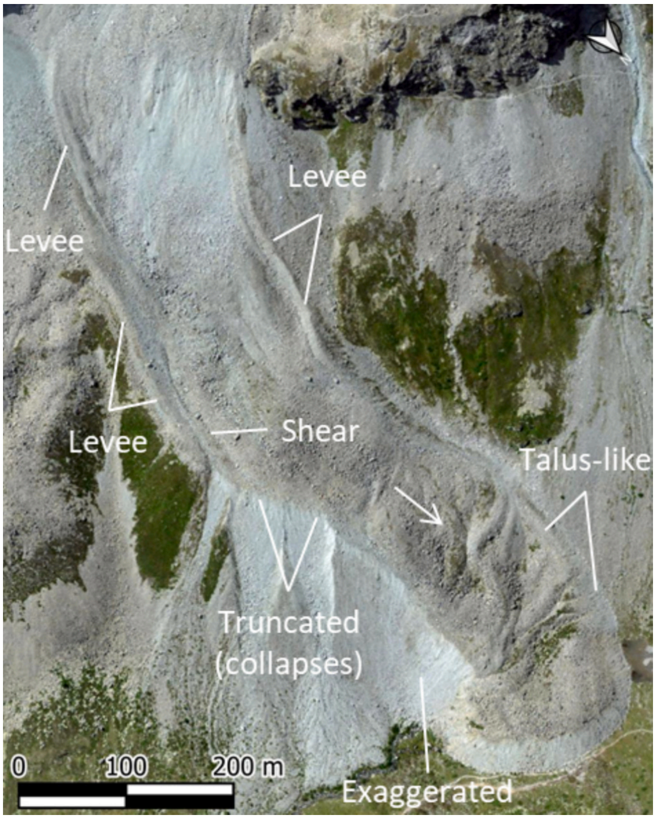

Fig. 3. Talus-like, exaggerated, truncated, levee, and shear margin typologies coexisting along the Suvretta rock glacier, Switzerland (46.4916°N 9.7829°E, 2300–2750 m a.s.l). The arrow indicates the main flow direction and points to the location of ridge-and-furrow topography. Date: 14/08/2022. ©Swisstopo.

depending on the training and experience of the operator (or the inventory team), the quality of the available data, and the complexity of the landforms. To minimize this heterogeneity, yet aid pursuing a variety of potential objectives, two ways for delineating rock glaciers are provided:

- The **restricted outline** embeds the entire rock glacier up to the rooting zone and ***excludes*** the front and the lateral margins.
- The **extended outline** differs from the restricted one in that it also ***includes*** the front and the lateral margins down to their contact with the surrounding terrain.

In case of exaggerated and truncated front (or margin) typologies, to minimize heterogeneity among operators, it is recommended that the extended outline does not exceed 50 m in horizontal distance from the restricted one (Fig. 2b). Although arbitrary, this indicative threshold derives from the empirical recognition that the moving upper layer of a rock glacier ranges in thickness between about 15 and 30 m on a sloping hillside of 20 to 40 degrees (e.g., Cicoira et al., 2021).

In the uppermost end of the rock glacier, the extended and restricted outlines virtually coincide. Here, the delineation rules specifically depend on the typology of rock glacier upslope connection (cf. Section 3.5).

3.5. Spatial connection to the upslope unit

The geomorphological unit situated immediately upslope of a rock glacier unit (or system) directly controls the amount and caliber of sediment supplied. In turn, this can affect rock glacier characteristics – including, but not limited to, internal structure, surface and subsurface texture, ice origin and ice content – and dynamics (Barsch, 1971; Humlum, 2000).

In agreement with the technical definition of rock glacier and the overall objective of the RGIK guidelines, the characterization of this attribute is focused on the spatial (i.e., structural) connection as typically inferred from the visual inspection of optical images. Consequently, a given upslope spatial connection does not necessarily imply any dynamic and/or genetic linkage, while it influences the manual delineation of the rock glacier upper boundary, as well as the analysis of the kinematic behavior. In this context, the following types of upslope spatial connections are detailed:

- **Talus-connected**: The rock glacier is an element of a downslope sequence that consists of a headwall, a talus slope, and the rock glacier itself (Fig. 5a) (Barsch and Jakob, 1998; Gärtner-Roer, 2012). The talus slope, which in some instances may be very small, or nearly absent, is primarily fed by rock-fall activity but can also receive

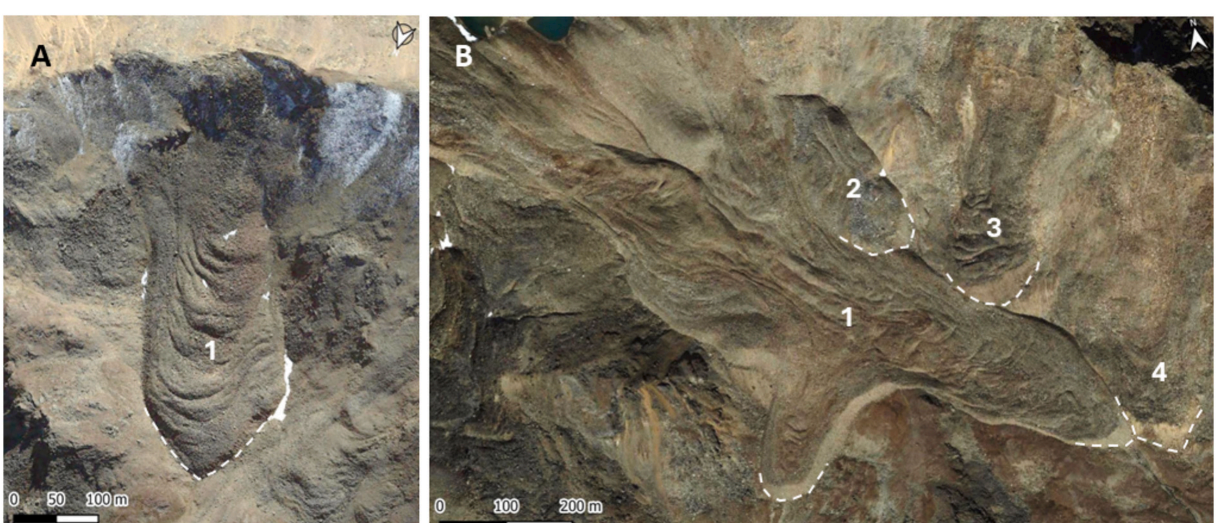

Fig. 4. Examples of rock glacier units and systems. (a) A simple rock glacier unit (also termed mono-unit rock glacier system) with a talus-like front, lateral margins, and ridge-and-furrow topography. Val d'Ultimo, Italy (46.2660°N, 10.4758°E, 2650–2830 m a.s.l.). (b) A rock glacier system (also termed multi-unit rock glacier system) composed of four units characterized by complex (i.e., unit 1) and simple (i.e., units 2, 3 and 4) morphologies. Val Martello, Italy (46.5240°N, 10.6873°E, 2750–3000 m a.s.l.). Date: 24/09/2021. ©Google Earth (a-b).

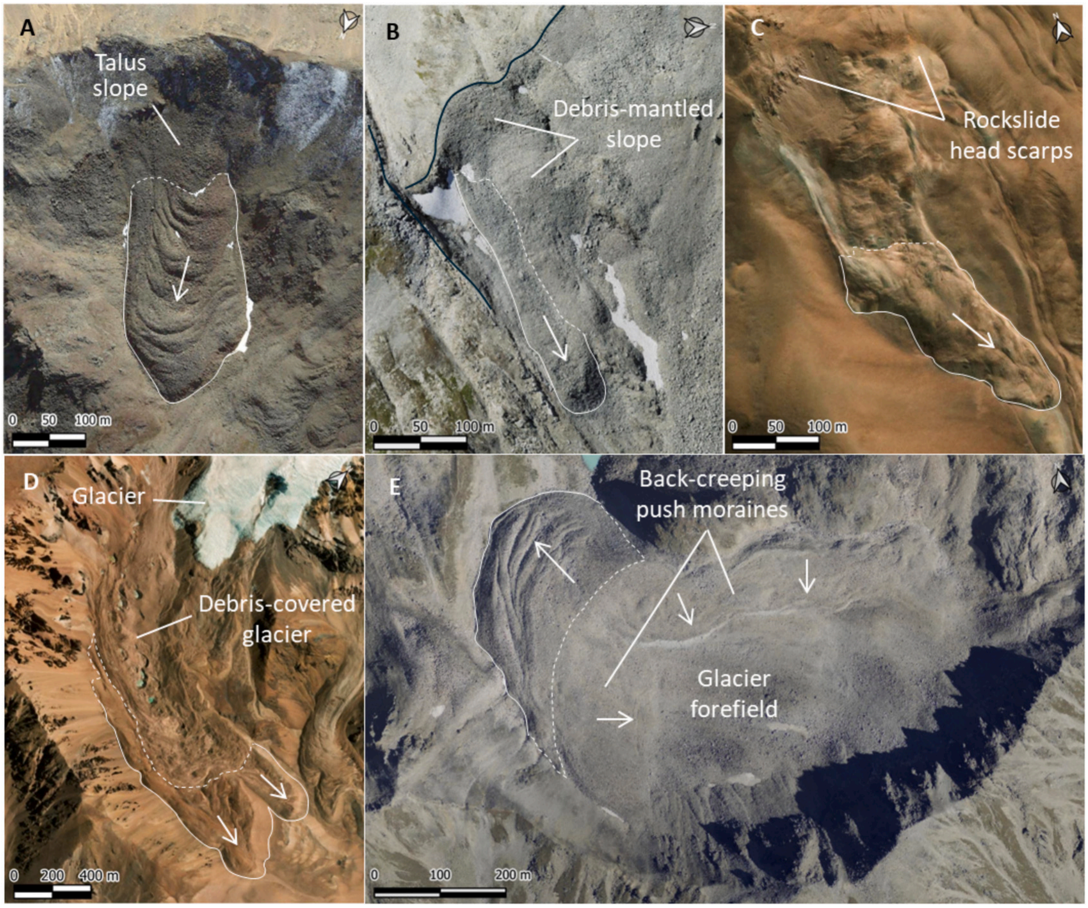

Fig. 5. Examples of upslope connection typologies including: (a) a talus-connected RGU. Val d'Ultimo, Italy (46.2660°N, 10.4758°E, 2650–2830 m a.s.l.) (Date: 24/09/2021); (b) a debris-mantled slope connected RGU Klein Furkahorn, Switzerland (46.5816°N, 8.4120°E, 2700–2790 m a.s.l.) (Date: 11/09/2018); (c) a landslide-connected RGU La Laguna, Chile (30.17028°S, 69.91611°W, 4250–4350 m a.s.l.) (Date: 19/04/2008); (d) a glacier-connected RGUs Tapado, Chile (30.15444°S, 69.91477°W, 4370–4510 m a.s.l.) (Date: 02/03/2020); and (e) a (former) glacier forefield-connected RGU and relevant back-creeping push moraines. Macun, Switzerland (46.71803°N, 10.13631°E, 2750–2840 m a.s.l.) (Date: 05/10/2018). In panel d, note that RGUs are connected to a debris-covered glacier. White, solid linework defines the extended outline of each RGU, and becomes dashed when delineation is considered uncertain. Arrows indicate the main flow direction. ©Google Earth (a-d-e), ©Swisstopo (b), and ESRI/Maxar Technologies (c).

sediment supply from the headwall unit via surface runoff, debris flows, and/or avalanches. The area linking the talus slope to the rock glacier typically exhibits concave topographic curvature. Over time, this area may have experienced the intermittent or persistent formation of long-lasting avalanche cones, snow or ice patches, and occasionally small glaciers or glacierets. In the latter case, although the episodic disappearance of the glacier implies a lack of efficient sedimentary connection with the relevant upslope unit, the rock glacier is still classified as talus connected. In the context of talus-connected landforms, ***protalus ramparts*** are considered as “embryonic” rock glaciers only when they are associated with permafrost creep (e.g., Scapozza, 2015), thus excluding pronival counterparts (e.g., Hedding, 2011). The delineation of the RGU upper boundary follows the depression (e.g., change in slope) located at the base of the talus slope. When a RGU has been previously covered by a small glacier or ice patch, the uppermost end of the rock glacier unit should be delineated in correspondence with any geomorphological (i.e., ridge and furrow topography) or kinematic evidence of motion.

- **Debris-mantled slope-connected**: The rock glacier does not have a well-defined headwall (Fig. 5b). The debris primarily originates from in-situ weathering of bedrock (i.e., debris mantle) and is subsequently mobilized through slow, shallow mass movements, such as solifluction, before developing into a rock glacier (e.g., Hu et al., 2021). Similarly to talus-connected rock glaciers, the delineation of the upper boundary should follow the change in slope, if any. It is critical to avoid incorporating the debris-mantled slope (source zone) within the outline.
- **Landslide-connected**: The rock glacier is located either directly below a landslide or on an active deep-seated gravitational slope deformation (Fig. 5c). Typically, in such slope configurations there is no talus unit. The delineation of the upper boundary must avoid incorporating the landslide above the rock glacier, if any.
- **Glacier-connected**: The rock glacier is directly connected to a glacier, debris-covered glacier, or ice patch (Fig. 5d) (Monnier et al., 2014; Monnier and Kinnard, 2017). In instances involving a glacier or ice patch, there is always a transitional debris-covered glacier area between the clean ice and the rock glacier unit. Although challenging, the discrimination between the debris-covered glacier and the rock glacier unit can be aided by the occurrence of features such as crevasses, thermokarst depressions, and meltwater channels, which suggest the existence of a debris-covered glacier, as opposed to ridge-and-furrow topography that more typically characterize the rock glacier portion (Table 1).
- **Glacier forefield-connected**: The rock glacier has developed within or from a previously glaciated area (Fig. 5e). The interaction between the glacier (or ice patch) and the rock glacier unit is prevalent but has primarily occurred during periods of glacier advance (e.g., Little Ice Age, as exemplified by Lugon et al., 2004; Monnier et al., 2011; Kenner, 2019; Vivero et al., 2021). Glacier ice can be embedded

Table 1
List of geomorphological and kinematic indicators to distinguish rock glaciers from debris-covered glaciers (adapted from RGIK, 2023a).

Geomorphological/Kinematic indicator	Rock glacier	Debris-covered glacier
Transverse ridges and furrows	Frequent	Infrequent
Talus-like front	Frequent	Infrequent
Crevasses with exposed ice	Infrequent	Frequent
Abundant thermokarst	Infrequent	Frequent
Abundant supraglacial lakes	Infrequent	Frequent
Ice cliffs	Infrequent	Frequent
Supraglacial streams/channels	Infrequent	Frequent
Subsidence rate (order of magnitude)	≈ cm/yr	≈ m/yr
Flow field coherence	High	Reduced, due to differential melt

within the rock glacier (e.g., Gärtner-Roer et al., 2022; Haeberli et al., 2024; Wee et al., 2024). When retreating, the glacier may have become detached from the rock glacier or may have completely vanished (e.g., RGU #1 in Fig. 4b). This category encompasses rock glaciers that are made of glacial till, in agreement with the traditional definition of "debris rock glaciers" (Barsch, 1987), and push-moraines exhibiting postglacial rock glacier-like morphology due to subsequent (outward or backward) creep activity (e.g., Reynard et al., 2003; Bolch et al., 2019; Gärtner-Roer et al., 2022; Kunz et al., 2022; Wee and Delaloye, 2022). The formerly glaciated area may be characterized by well-developed lateral moraines, the evidence of previous glacier flow-like fluted moraines or the presence of stream channels flowing on alluvial deposits and ponds. The upper end of the rock glacier unit should be traced in correspondence of geomorphologic (i.e., ridge and furrow topography) or kinematic evidence of deformation related to permafrost creep.

- **Poly-connected**: The rock glacier is characterized by two or more typologies of upslope connections. The utilization of poly-connected should be limited to situations where there is no clear prevalence of one connection type.
- **Other**: Other geomorphological configurations upslope of a rock glacier.

3.6. Activity

Rock glaciers have been traditionally categorized based on the presumed flow behavior and, in relation to this, ice occurrence (Barsch, 1996; Giardino and Vick, 1987). They include: (1) active rock glaciers, which bear excess ice (porosity supersaturated with ice) and are in effective downslope motion; (2) inactive rock glaciers, which exhibit (almost) no downslope motion, yet still contain ice; and (3) relict rock glaciers, which have ceased to move downslope due to the loss of (almost) all of their ice. In turn, active and inactive rock glaciers have been combined into the so-called "intact" category for discriminating permafrost bearing landforms from (almost) devoid counterparts (Haeberli, 1985; Barsch, 1996). This classification is primarily based on the qualitative evaluation of geomorphological (e.g., front slope angle) and vegetation-related attributes (Imhof, 1996), which may vary locally and regionally due to differing topographic, lithologic, and climatic conditions.

Recent developments in radar and optical remote sensing have opened the opportunity to evaluate rock glacier activity across regions by means of kinematic data in a more quantitative and objective way (e.g., Liu et al., 2013; Barboux et al., 2014; Kääb et al., 2021). These data have also shown how annual rates of rock glacier displacement can grow up to two orders of magnitude or decrease nearly down to a state of inactivity (e.g., Marcer et al., 2021; Vivero et al., 2021; Abermann and Langley, 2022; Kellerer-Pirklbauer et al., 2024; Pellet et al., 2024; Blöthe et al., 2024). Awareness on the contemporary transient nature of rock glacier kinematics, together with the ongoing technological advances, have highlighted the need to reconsider the traditional, and somewhat static classification of rock glacier activity (sensu Barsch, 1996). To this purpose, we propose a classification of rock glacier activity that refers exclusively to the efficiency of sediment conveyance – as inferred from the morphological expression of the relevant landforms at the time of observation – and disregards any consideration about the actual ice content. In this context, it is important to note that downslope movement should not be confused with thaw subsidence, which can be caused by melting of excess ground ice (e.g., Kääb et al., 1997; Vivero and Lambiel, 2024).

The RGIK classification is still largely based on geomorphological attributes (Fig. 6), which may need to be adjusted regionally, depending on the physiographic setting. If point or areal kinematic data is available, this information should be integrated as a supplementary kinematic attribute and considered in the classification of rock glacier activity. The proposed updated definitions are:

- **Active**: rock glacier moving downslope over most of its surface. If no kinematic data is available, an active rock glacier shows morphological signs of downslope movement, including a steep front (steeper than the angle of repose) and lateral margins with recently exposed material (Fig. 6a and d). If suitable kinematic data is available, an active rock glacier exhibits coherent downslope movement over most of its surface. As a first-order indication, the displacement rate ranges from a decimeter to several meters per year.
- **Transitional**: rock glacier with slow movement only detectable by measurements or movement restricted to areas of non-dominant extent. According to the topographic and/or climatic context, transitional rock glaciers can either evolve towards a relict (degraded) or an active kinematic state. The latter development is particularly expected to occur in cold permafrost regions where rock glaciers are moving very slowly. If no kinematic data is available, a transitional rock glacier exhibits less obvious morphological signs of ongoing downslope movement compared to active rock glaciers in the same regional context. The front may retain subvertical steepness, yet in some cases display incipient vegetation patches, and develop solifluction sheets fed by debris collapsed at the front base (Fig. 6b and e). If suitable kinematic data is available: a transitional rock glacier shows little to no downslope movement over most of its surface. As an indication, the average displacement rate is less than a decimeter per year in an annual mean over most of the rock glacier surface.
- **Relict**: rock glacier with neither geomorphological evidence nor detection of current movement associated with permafrost creep over most of its surface. The relict state can be indicated by subdued topography, smoothed lateral and frontal slopes/margins, and by the development of lichens, grass and forest cover (e.g., Nicholas and Garcia, 1997), although vegetation may not be able to colonize relict rock glaciers in extremely dry environments (e.g., Brenning, 2005), and where a coarse (blocky) carapace imparts high surface porosity. Relict rock glaciers are often located at lower altitudes compared to active ones (e.g., Scotti et al., 2013; Falaschi et al., 2015; Onaca et al., 2017).

Compared to the front typologies described for active rock glaciers (cf. Section 3.2), relict landforms – consistent with their characteristic subdued topography – display much shallower and gentler fronts in which the change in slope associated with the front edge is generally ill defined, or not defined (Fig. 2).

3.7. Kinematic attribute

The kinematic attribute (KA) is semi-quantitative velocity information. It reflects the multi-annual movement rate of the rock glacier unit at the time of an inventory and relies on in situ or remote sensing measurements. It provides generic velocity information that allows

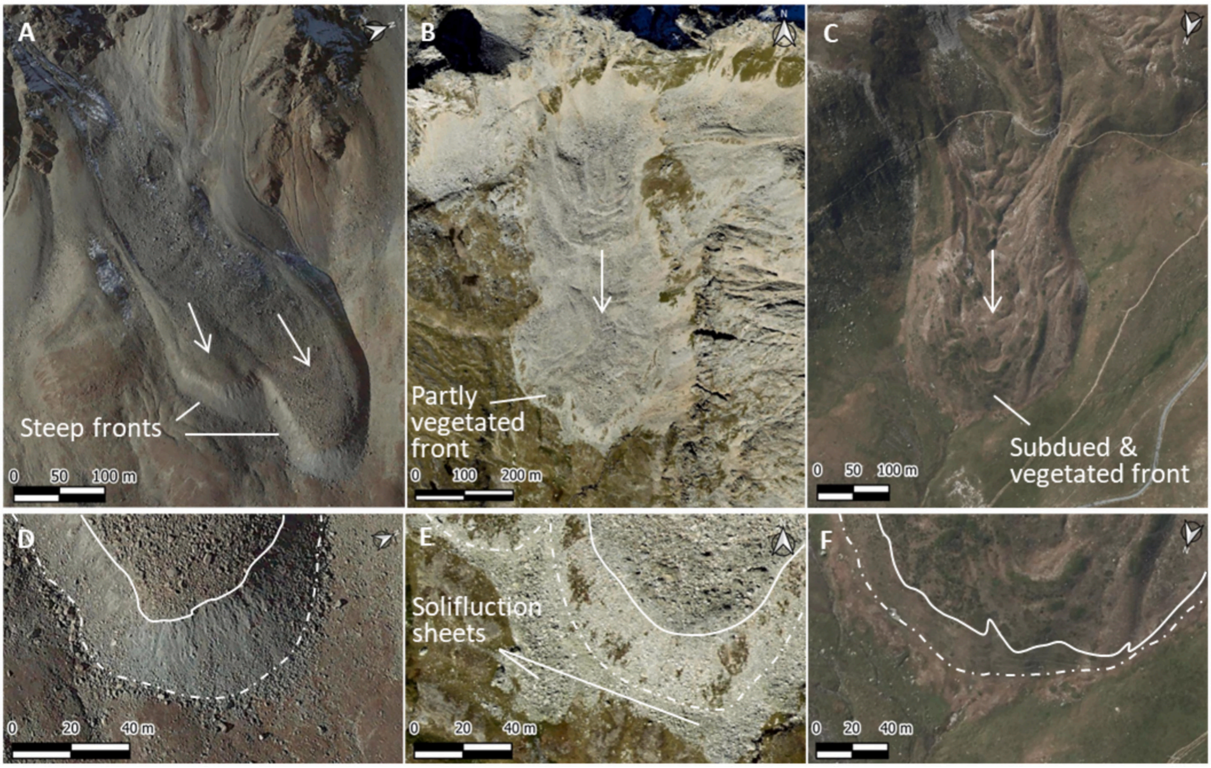

Fig. 6. (a) Active rock glacier at Piz da las Sterlas, Switzerland (46.5130°N, 9.9600°E, 2700–2900 m a.s.l.) (Date: 17/10/2022). (b) Transitional rock glacier at Cima di Gana Bianca, Switzerland (46.4667°N, 8.9843°E, 2350–2500 m a.s.l.) (Date: 26/10/2019). (c) Relict rock glacier at Lanserlia, France (45.3487°N, 6.8405°E, 2300–2450 m a.s.l.) (Date: 24/07/2022). Close-up views of the three rock glacier fronts are displayed in panels d, e, and f. Solid and dash-dotted linework mark respectively the restricted (top) and extended (base) outlines about each front. Arrows indicate main flow directions. © Google Earth (a-f).

comparisons within and between RoGIs at regional and global scales. It is a refinement of the activity categories, which also helps to the activity classification. Contrary to RGV, it has however no monitoring purpose.

A two-step procedure, possibly iterative, is proposed to assign a KA to inventoried rock glacier units. It consists first of identifying moving areas (MAs) on rock glaciers based on adequate kinematic data (e.g., optical, InSAR, and in-situ survey) and assigning them to a velocity class. A MA is defined as an area at the surface of the rock glacier in which the observed direction and velocity of the flow field are spatially consistent and homogeneous during a documented timeframe. It must represent the downslope motion rate (permafrost creep) of the rock glacier, where confusion with movement related to other processes (e.g., melt-induced subsidence or subjacent deep-seated landslide) should be avoided. The KA is then the category assigned to a rock glacier unit based on the MA's characteristics (i.e., extent, velocity class, and timeframe). The KA consists of semi-quantitative categories (each spanning across half order of magnitude) expressing the multi-annual downslope velocity of an entire rock glacier unit (Table 2).

KA is assigned to a rock glacier unit only when the latter is documented by consistent kinematic information on a significant part of its surface. There is only one kinematic category per rock glacier unit, generally defined by the dominant MA. However, when a rock glacier unit hosts multiple moving areas, to minimize inter-operator heterogeneity a set of specific rules applies (e.g., Bertone et al., 2022). In the case of two equally dominant (i.e., of comparable extent) moving areas, characterized by contiguous velocity classes, the velocity class of the one closer to the front is considered for KA assignment. When more than two moving areas of comparable extent and spanning across a range of velocities are hosted in a given rock glacier unit, the relevant median velocity class is considered for KA assignment. As a practical example, we report the case of a rock glacier that encompasses the manual delineation of the restricted and extended outlines (Fig. 7a), as well as the kinematic characterization of the relevant moving areas from optical feature tracking (Fig. 7b) and InSAR analysis (Fig. 7c).

Table 2
RGIK kinematic attribute for characterizing single RGUs, and as an indication, the corresponding degree of activity (adapted from RGIK, 2023a).

KA category	Description	Activity
Undefined	No or unreliable kinematic information	Undefined
< cm/yr	No motion up to very little movement	Relict
cm/yr	Order of magnitude ≈ 0.01 m/yr	Transitional
cm/yr to dm/yr	Order of magnitude ≈ 0.05 m/yr	Transitional
dm/yr	Order of magnitude ≈ 0.1 m/yr	Active
dm/yr to m/yr	Order of magnitude ≈ 0.5 m/yr	Active
m/yr	Order of magnitude ≈ 1 m/yr	Active
> m/yr	More than ≈ 3 m/yr	Active

3.8. Destabilization

Rock glaciers may experience intense and abrupt increase(s) in surface displacement rates and the appearance of geomorphological signs of instability, such as scarps and cracks (Fig. 8). This anomalous landslide-like behavior, which can cause a portion of the landform to dynamically decouple from the rest of the rock glacier is known as destabilization (Lambiel et al., 2008; Roer et al., 2008; Marcer et al., 2019), also referred to as a "surge" (Schoeneich et al., 2015) or a "crisis" (e.g., Delaloye et al., 2013; Vivero and Lambiel, 2019).

Destabilized rock glaciers often undergo an initial phase of strong acceleration, followed by a period of sustained high velocity, which ultimately ends with a phase of slowdown. However, owing to the limited number of case studies, a universal kinematic behavior cannot be depicted yet. The cracks and scarps can remain preserved for an extended period following the conclusion of the surge in velocity (Delaloye et al., 2013). While the presence of these surface features can

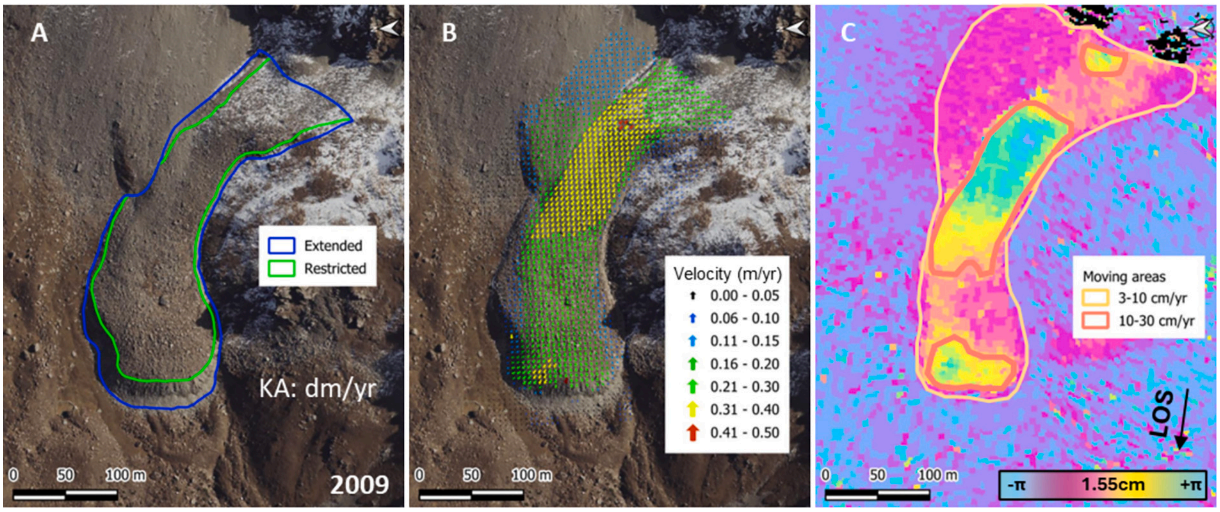

Fig. 7. Example showing the manual delineation of a talus-connected, mono-unit rock glacier and snapshots of the characterization procedures that led to assigning to the rock glacier a kinematic attribute (KA) of dm/yr. (a) Extended (blue linework) and restricted (green linework) RGU outlines. (b) Surface flow field (i.e., color-coded arrows) based on feature tracking of optical images acquired from UAV surveys between 2021 and 2022 (modified from Vivero and Lambiel, 2024). (c) Moving areas detected and delineated on a set of interferograms, among which is illustrated a TerraSAR-X 11-day interferogram (Descending orbit - 20,140,927-20,141,008). Note that both techniques shown in panels b and c converge in assigning to the relevant RGU a kinematic attribute of dm/yr. Les Cliosses, Switzerland (46.1441°N, 7.5028°E, 2400–2600 m a.s.l.). Owing to its limited size (≈ 10 m × 50 m) the adjacent small lobe flowing westward was not considered. ©Bing Aerial (a-b).

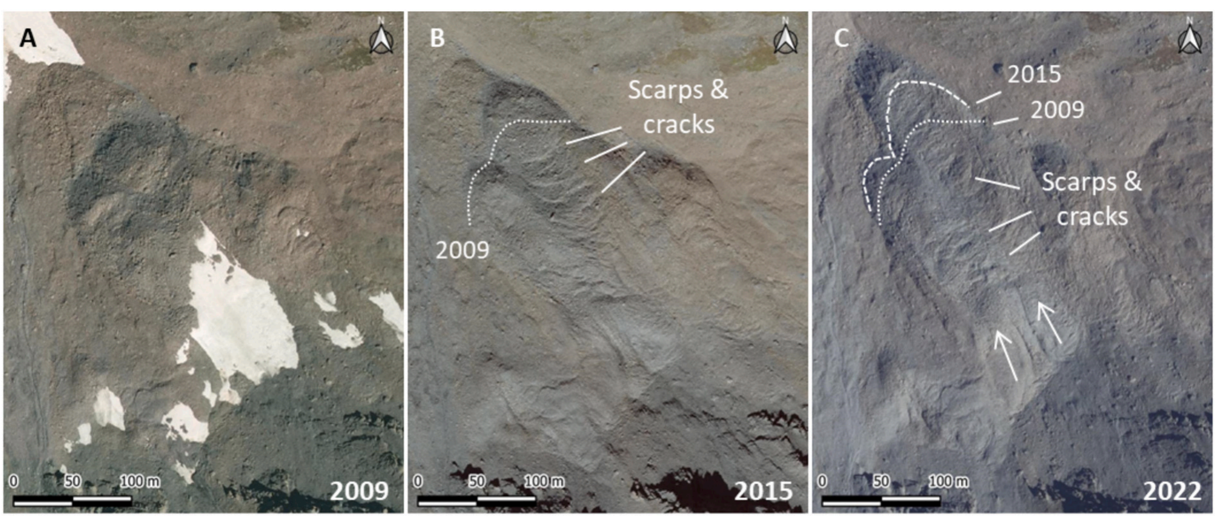

Fig. 8. Decadal evolution of a destabilization surge in: (a) 2009; (b) 2015; and (c) 2022. By 2015 the front has advanced (by about 20 m) and multiple cracks and scarps (signs of destabilization) have appeared in the mid portion of the northern rock glacier tongue. These signs are still visible in 2022, and further advancement of the front is evident. Interestingly, the southern tongue has remained substantially stable. Dotted and dashed linework indicate respectively the position of the front base in 2009 and 2015. Tête du Longet, France (44.6611°N, 6.9086°E, 2700–2900 m a.s.l.). Arrows indicate main flow directions. ©IGN France.

be documented in an inventory as proof of a present or previous phase of destabilization (Marcer et al., 2019), the determination of an ongoing phase of rock glacier destabilization can usually only be accomplished through kinematic data (e.g., Lambiel et al., 2008; Vivero et al., 2022; Hartl et al., 2023). Multi-annual time series showing displacement rates of several meters per year can attest to the current destabilization phase. Destabilization is not meant in a geotechnical, slope stability sense, but solely used to illustrate the above-described temporal variability in surface deformation.

The primary causes of rock glacier destabilization have been attributed to increased permafrost degradation following atmospheric temperature rise (e.g., Roer et al., 2005; Bodin et al., 2017) and associated consequences such as increased water content (e.g., Ikeda et al., 2008; Wirz et al., 2016; Buchli et al., 2018; Cicoira et al., 2019). Overloading promoted by a sudden increase in sediment supply through large rock falls (Delaloye et al., 2013; Scotti et al., 2017a), or associated with mining waste piles (Valenzuela, 2004) have also been suggested as additional causes leading to destabilization dynamics.

4. Inventorying procedure

The compilation of a RoGI may be driven by a variety of basic and applied objectives – for example, to evaluate rock glacier hydrologic significance, assess geohazard potential, conduct paleoclimatic reconstructions, or for modeling permafrost occurrence – that are inevitably going to dictate the database structure (i.e., the set of attributes considered), as well as the composition of the inventorying team. To reduce inherent variability and to converge towards consistent RoGIs internationally, a four-step inventorying strategy is proposed (Fig. 9). This strategy is based primarily on a geomorphological approach and optionally, depending on data availability, integrated with a kinematic approach that entails iterative refinement. The methodological steps include:

- **Detection (mandatory):** the identification of the relevant landforms (RGU/RGS) to be inventoried, based on the geomorphological criteria outlined in the technical definition of a rock glacier (cf. Sections 3.1 and 3.2). Detection is chiefly performed through visual inspection/interpretation of optical imagery and DEM-derived products (e.g., hillshade, slope, curvature, and roughness). However, machine learning techniques and kinematic data, such as InSAR, are also encouraged as complementary approaches.
- **Location (mandatory):** the assignment of a unique point identifier and the relevant primary attributes (i.e., ID attribution and georeferencing in Tables S1 and S2) – the so-called ***primary marker*** (PM) – to each RGU and RGS (see Fig. S2 in the Supplementary Material). The PM represents a key element of a RoGI. All additional attributes assigned to each landform during the characterization step refer to and are connected to this PM. Additional practical information is presented in the Supplementary Material.
- **Characterization (optional):** the assignment of essential characteristics (e.g., attributes such as morphology, upslope connection, activity, and destabilization) (cf. Sections 3.3, 3.5, 3.6 and 3.8) to each RGU or RGS, including a kinematic attribute if adequate data is available (cf. Section 3.7). The latter requires ground motion information, which may be derived from on-site monitoring (e.g., GNSS surveys) and/or acquired through remote sensing techniques. Additional practical information on rock glacier characterization is summarized in the Supplementary Material (cf. Tables S1 and S2).
- **Delineation (optional):** the manual delineation of the RGU/RGS outline involves mapping a polygon that captures the landform's spatial extent and its associated uncertainty (see Supplementary Material). Indeed, an outline is drawn only if sufficient geomorphological evidence is available. To minimize heterogeneity among operators, delineation follows specific rules that depend on the typology of the rock glacier front, lateral margins, and upslope connection (cf. Sections 3.4 and 3.5). However, it is important to highlight that these rules are not exhaustive and may not be able to address all inherent challenges.

In the inventorying procedure, while detection and location are regarded as mandatory steps, characterization, and delineation, which involve the morphologic and kinematic evaluation of RGU/RGS attributes, remain optional, since they depend on data availability/suitability and may require periodic updates as rock glacier morphodynamics evolve.

To ensure RoGI consistency and reduce variability, a further consolidation step is recommended for any set of rock glaciers inventoried, or when RGU/RGS attributes are periodically updated. This step requires the systematic control and validation of the data by at least one (but ideally multiple) additional operator (i.e., the inventory team). In this context, a consensus-based approach, although onerous and time consuming, has proved to ensure accuracy and reliability in the characterization and delineation steps, ultimately leading to more consistent RoGIs (Way et al., 2021).

5. Current progress and future work

5.1. Recent implementations and research needs

Since 2023, the RGIK guidelines have been implemented (fully or partly) in recent RoGIs around the world. Accordingly, some studies have fully integrated the morphological and kinematic approaches (e.g., Lambiel et al., 2023; Rouyet et al., 2025), some have adopted the geomorphological criteria for characterizing and delineating rock glaciers (e.g., DGA, 2022; Harrison et al., 2024; Li et al., 2024; Sun et al., 2024), and others have utilized the RGIK kinematic classification scheme on existing (pre-RGIK) rock glacier footprints (e.g., Bertone et al., 2024; Hassan et al., 2024; Onaca et al., 2025).

Lambiel et al. (2023) characterized the spatial distribution and kinematics of active and transitional rock glaciers in New Zealand. Rouyet et al. (2025), adopting a consensus-based multi-operator framework, have built a RoGI database that served for evaluating inherent methodological advantages and limitations, as well as for providing practical working/training examples to the broader international community. This collaborative effort has involved areas across the European Alps, the Carpathians, Troms, Finnmark and Spitsbergen in Norway, the Central Andes in Argentina, Northern Tien Shan in Kazakhstan, the Brooks Range in Alaska, Disko Island in Greenland, and the Southern Alps in New Zealand. This study concludes that the application of RGIK guidelines enhances the robustness and consistency of RoGI products around the globe. Comparing RoGIs from different regions becomes

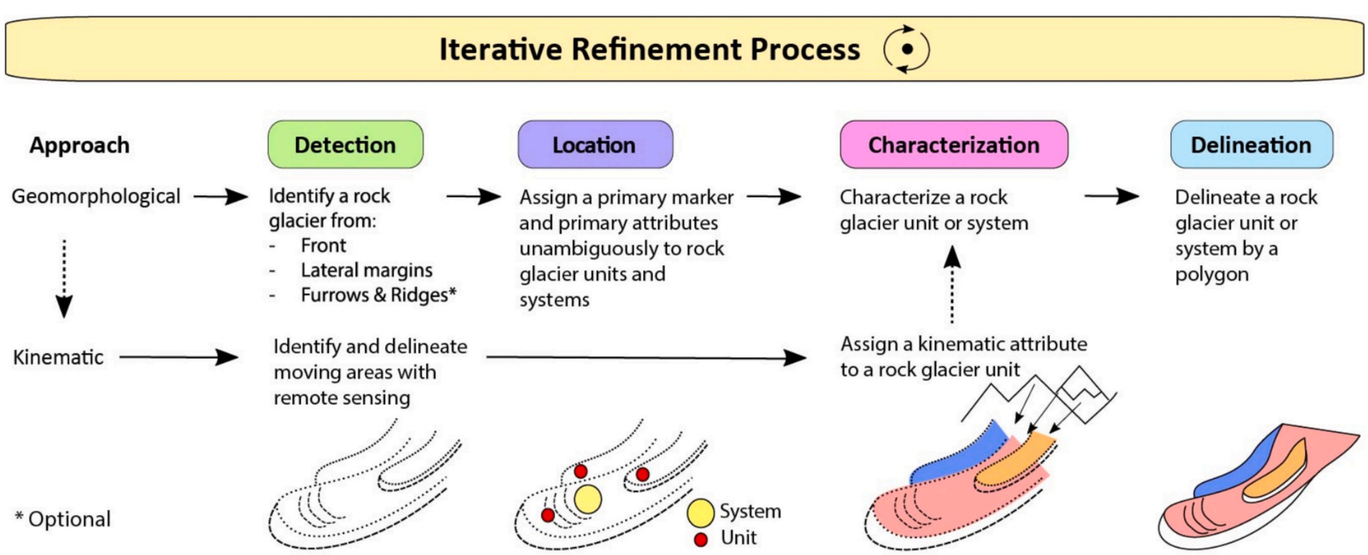

Fig. 9. Schematic workflow of the four-step strategy recommended for compiling a RoGI. The inventorying strategy relies primarily on the application of a geomorphological approach and can be optionally (depending on data availability) integrated with a kinematic approach through an iterative refinement process. Filled polygons denote rock glacier units characterized by a different kinematic attribute.

possible because: (1) the same terminology and rules have been applied; (2) a set of GIS standard tools associated with the RGIK guidelines have been used; and (3) all data has a similar format, with comparable layers and attributes. Rouyet et al. (2025) also highlighted the educational value of the RGIK guidelines and associated tools, especially when applied by teams of multiple operators.

Harrison et al. (2024) and Sun et al. (2024), working respectively across the Himalaya and the entire Tibetan Plateau, have compiled geomorphological RoGIs – complemented by an upscaling approach in the first case and by deep learning in the second – as benchmarks for investigating rock glacier spatial distribution, for evaluating water storage at the orogen scale, and for prospective kinematic characterization.

In South Tyrol, the integration of geomorphological mapping and InSAR-based kinematic characterization showed the added value of the iterative RGIK methodology to improve RoGI completeness and significantly revise the morphologically based activity classification (Bertone et al., 2024). This methodological integration, which was critical for constraining a direct functional relation between elevation, average rock glacier kinematics and percent moving area cover, holds potential for evaluating the state of creeping permafrost across physiographic regions. In this context, Onaca et al. (2025) have shown the relict and transitional state of rock glaciers in the Southern Carpathians, highlighting the critical importance of complementing geophysical surveying and ground temperature monitoring with InSAR-based kinematics to characterize such marginal periglacial environments, where clear altitudinal dependences are more difficult to capture.

With respect to the variability in rock glacier delineation and morphological characterization performed by different operators, applying the RGIK guidelines to RoGIs promises to reduce this intrinsic limitation around the globe. The outcome of a mapping exercise conducted by fourteen international experts before the RGIK guidelines were compiled is instructive, as it displays a great degree of heterogeneity (Brardinoni et al. (2019) (Fig. 10a). Overall, a main area of uncertainty among operators may be identified between a “conservative” approach (e.g., operator #5) that includes just the frontal part of the RGU, and a more “liberal” one (e.g., operator #6) that extends the RGU outline up to the edge of the topographic depression, at the lower end of the so-called rooting zone. Indeed, rock glacier delineation adhering to the main “mandatory” RGIK criteria would warrant exclusion from the RGU footprint of: (1) the areas located outside of the lateral margins (e.g., operators #8 and #10 in Fig. 10a); and (2) the upslope talus cone and portions of the glacier forefield (e.g., operators #3, #6 and #7 in Fig. 10a). Most importantly, application of the delineation rules described in Section 3.5 for glacier forefield-connected rock glaciers would reduce greatly the area of mapping uncertainty, as illustrated in Fig. 10b.

Although drastically reduced, these uncertainties raise the question of how the lower end of the rooting zone is defined, which in some instances is clearly distinguishable while in (many) others is not (e.g., the presence of a rooting zone could become an optional criterion of the RG definition in the future). To some extent, the presence (or lack) of a discernible rooting zone is likely to depend on upslope connection typology (e.g., well-defined for talus types and potentially ill-defined for debris-mantled, glacier forefield and poly-connected types) and the type/quality of information available (e.g., resolution/quality of optical imagery, interferograms, and offset tracking outputs).

Access to reliable, spatially distributed kinematic data is indeed critical for assuredly discriminating between active, transitional, and relict rock glaciers (see Section 3.6). In the current guidelines' version (RGIK, 2023a), description of the set of morphological attributes that could characterize different states of rock glacier activity have been intentionally left vague, especially for transitional and relict landforms. This is primarily due to the awareness that further systematic investigation is needed to try establishing robust correspondence between kinematic categories and morphological expression. In this context, future work coordinated by the RGIK Standing Committee, besides fostering the foregoing systematic analysis on morpho-kinematic correspondence, will aim to identify a provisional set of morphological attributes to be adopted for regions with limited (or no access to) reliable kinematic data.

Even if RGIK guidelines do not solve all ambiguities regarding the delineation and characterization of the landforms, they provide a valuable framework and a set of common rules necessary for multi-operator mapping processes. In this respect, Rouyet et al. (2025) concluded that it was the collective application of the guidelines by a group of operators with different skills and background that brought an added value to the results. The final products are more than the simple summation of individual contributions, as the RoGI teams discuss discrepancies and consensually agree on solutions. This discussion represents one of the main differences in comparison with automatically generated outputs. The combination of different points of view and

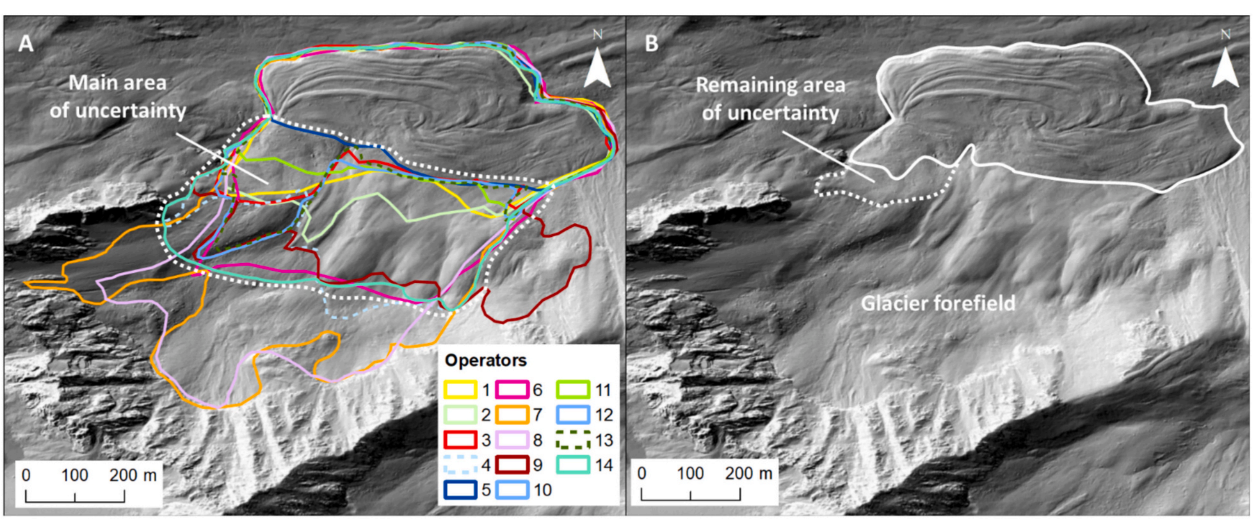

Fig. 10. Polygon outlines of a rock glacier unit bearing upslope connection to a (former) glacier forefield, as delineated: (a) by 14 operators superimposed on LiDAR-derived hillshade (modified from Brardinoni et al., 2019); and (b) following the RGIK delineation rules detailed in Section 3.5. Kaiserberg, Austria (46.9111°N, 10.6771E°, 2600–2700 m a.s.l.). White dotted outlines indicate respectively the main area of uncertainty among operators in panel a, and the reduced one resulting from the application of the RGIK guidelines in panel b. The hillshade base was accessed as WMS at: https://gis.tirol.gv.at/arcgis/services/Service_Public/terrain/MapServer/WMSServer?

experiences from several regions around the world ensured that various morpho-kinematic elements were identified and discussed within and across the 12 mapped areas.

5.2. Automatic detection and mapping

Automated and semi-automated methods for detecting and mapping key elements such as river networks (e.g., Garber et al., 2024), shallow rapid landslides (e.g., Mondini et al., 2011), and glaciers (e.g., Raup et al., 2007a), are becoming more and more popular. For rock glaciers, detection was originally conducted exploiting multispectral, medium resolution, satellite acquisitions and terrain parameters (e.g., topographic roughness and curvature) derived from DEMs (Brenning, 2009; Janke, 2001). More recently, deep-learning approached complementary to expert-based detection and manual mapping have been explored on selected study areas (e.g., Erharter et al., 2022; Hu et al., 2023; Marcer, 2020; Robson et al., 2020) and extended across entire regions (Sun et al., 2024). At present, the accuracy and reliability of existing workflows for mapping rock glacier are primarily constrained by the quality of training data. This limitation stems from two key factors: (1) the resolution and interpretability of remote sensing imagery, and (2) the precision of manually inventoried rock glacier outlines. Variations in these inputs can significantly impact the performance of automated detection systems, leading to inconsistencies in the produced RoGIs.

In this context, the RGIK initiative is committed to fostering collaborative efforts to enhance the automated detection and mapping of rock glaciers using novel machine learning techniques. With the advancement of AI-based algorithms in computer vision, and the emergence of high-quality remote sensing images, the RGIK-standardized RoGIs will become a key element in developing the best workflow.

5.3. Mapping, training, and global database

The compilation of widely accepted international guidelines on inventorying rock glaciers marks the first step towards the homogenization and standardization of RoGIs worldwide. To further promote and develop the use of the RoGI guidelines, operational implementation tools and infrastructure to collect, combine and analyze the data are needed. First steps have been taken through the development of GIS layer templates including easy to use user-interfaces tailored to collect all required and optional attributes as defined in the RoGI guidelines (see https://www.rgik.org/resources/). Additionally, two multi-operator inventorying exercises have been performed in the Goms and Dirru-Steintälli valleys in Switzerland. These exercises are openly accessible (see https://www.rgik.org/resources/). Another multi-operator exercise has been undertaken in twelve regions worldwide (Rouyet et al., 2025), thereby testing the applicability of the guidelines in regions with different terrain (e.g. vegetation, snow, shadow), landforms (e.g. size, activity), and data constraints (e.g. resolution, accuracy). In a similar manner to the Global Land Ice Measurements from Space (GLIMS) project (Raup et al., 2007b), the RGIK initiative is currently working on developing a centralized database to collect, store, and combine rock glacier products including RoGI and RGV.

The utilization of open access software and an open access versioning platform facilitates the design of a relational database and an open access visualization platform, thereby ensuring the extensive dissemination and accessibility of RoGI products. This aspect is aligned with the "FAIR Guiding Principles for Scientific Data" (Wilkinson et al., 2016). Indeed, the FAIR principles require the data to be findable (F), accessible (A), interoperable (I), and reusable (R), and all these criteria will be met in the future database.

The critical mass of RGIK-based inventories is currently growing through active international efforts across Asia (selected regions of Bhutan, China, India, and Mongolia), the Andes (selected regions of Chile and Peru), Western Canada, the European Alps (nation-wide in Switzerland and France, and across the Aosta Valley in Italy) and the Rila Range in Bulgaria.

CRediT authorship contribution statement

Francesco Brardinoni: Writing – original draft, Visualization, Methodology, Conceptualization. **Sebastián Vivero:** Writing – original draft, Visualization, Methodology. **Chloe Barboux:** Writing – original draft, Methodology. **Xavier Bodin:** Writing – original draft, Methodology. **Alessandro Cicoira:** Writing – original draft, Visualization, Methodology. **Thomas Echelard:** Writing – original draft, Visualization, Methodology. **Yan Hu:** Writing – original draft, Methodology. **Nina Jones:** Writing – original draft, Methodology. **Christophe Lambiel:** Writing – original draft, Methodology. **Shelley MacDonell:** Writing – original draft, Methodology. **Cécile Pellet:** Writing – original draft, Methodology. **Line Rouyet:** Writing – original draft, Methodology. **Lucas Ruiz:** Writing – original draft, Methodology. **Nicole Schaffer:** Writing – original draft, Methodology. **Mishelle Wehbe:** Writing – original draft, Methodology. **Reynald Delaloye:** Writing – original draft, Visualization, Methodology, Conceptualization.

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Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:https://doi.org/10.1016/j.geomorph.2025.110050. These data include the Google maps of the most important areas described in this article.

Data availability

No data was used for the research described in the article.

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