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RESEARCH ARTICLE

Erosion and sediment transfer processes at the front of rapidly moving rock glaciers: Systematic observations with automatic cameras in the western Swiss Alps

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Abstract

When connected to torrential channels, the fronts of active rock glaciers constitute important sediment sources for gravitational transfer processes. In this study, a 2013–16 time series of in situ webcam images from the western Swiss Alps was analyzed to characterize the erosion processes responsible for sediment transfer at the front of three rapidly moving rock glaciers and their temporal behavior. The main erosion processes comprised rock fall, debris slide, superficial flow and concentrated flow. These processes were induced by (i) changes of the frontal slope angle produced by rock glacier advance, and (ii) increases in water content of the sediments at the rock glacier front due to melt processes and rainfall. Erosion almost ceased during winter, when the front was frozen and snow-covered. The onset of snowmelt triggered an active period of high-frequency erosion events. After the melt period, sediment transfer continued as occasional rock falls, while other erosion processes occurred only during or following rainfall events. Intense regressive erosion phases that triggered debris flows were rare and occurred when enhanced snowmelt and/or recurring rainfall induced substantial groundwater flow on the debris slopes directly below the rock glacier fronts.

KEYWORDS

debris flow, erosion processes, rock glacier, sediment transfer, temporal variability

1 | INTRODUCTION

Rock glaciers on mountain slopes can constitute a significant source of loose debris available for gravitational transfer processes within the sediment cascade.[1] The efficiency of the transport defines the level of connectivity between the different compartments of the cascade (eg, [2]) and strongly relies on both the presence of uninterrupted steep slopes and channels guiding the sediments downslope, and the availability of unconsolidated sediments. Debris delivered to the rock glacier front can be mobilized further downslope, mainly via rock falls, surface runoff and debris flows. As many rock glaciers have accelerated considerably in recent decades—for example in the European Alps (eg, [3–6]), the Brooks Range in northern Alaska[7] and the Kazakh and Kyrgyz Tien Shan[8,9]—the availability of unconsolidated sediments downslope may have increased substantially, potentially affecting the sediment transfer rate within the sediment cascade.

The sediment supply from the upper part of mountainous watersheds strongly influences the development of torrential hazards but its study is commonly neglected.[10] There is a general lack of information about erosion processes in the upper sections of torrential catchments, as hazard assessment is often limited to observations on the alluvial fans where most infrastructure is located (eg, [11,12]). Identifying sediment storage and active debris inputs in the headwaters of high alpine catchments is essential to assess the magnitude and frequency of debris flow events (eg, [13–15]). Along with the quantification of sediment fluxes[16], understanding what controls erosion from the main sediment sources is the key to estimate sediment budgets[17] and to identify debris flow scenarios.[18]

Together with other sediment sources (eg, moraines, talus slopes and weathering accumulations), rock glaciers can occur in catchments located in mountainous periglacial terrain. In the case of a rock glacier advancing over gently inclined terrain, the sediments mobilized from the front by gravity accumulate at its foot, creating a small talus slope that is soon overridden by the rock glacier.[19–21] As a result, a stiff blocky layer forms at the base of the deforming ice-rich permafrost (eg, [22]) and the sediments cannot be mobilized further downslope by debris flows or other gravitational processes (type A on Figure 1). Thus, rock glaciers of type A represent traps in the sediment cascade[23–25], as there is no sediment connectivity with further down the slope. In contrast, an efficient connectivity occurs when the front of an active rock glacier reaches a torrential channel or a steep, often convex slope (type B on Figure 1). The sediments eroded from such a rock glacier front create what we define here as a *debris slope*, ie, a relatively large depositional area consisting of a mixture of fine to coarse rock debris (Figure 1), where sediments can be remobilized later, for instance by debris flows. For the largest boulders, a rock fall with travel distance of tens to hundreds of meters may even be triggered directly from the rock glacier front (Figure 2). Although type B rock glaciers appear to be less frequent than type A ones[21], several examples of the former have been observed in the European Alps (eg, [26,27]). However, few studies have focused on the erosion of the front of active rock glaciers ([28,29] for type A; and [30] for type B) or on the relation between rock glaciers and debris flow occurrence (eg, [26,31]). To our knowledge, no study has detailed the processes eroding rock glacier fronts, their temporal behavior and their controlling factors.

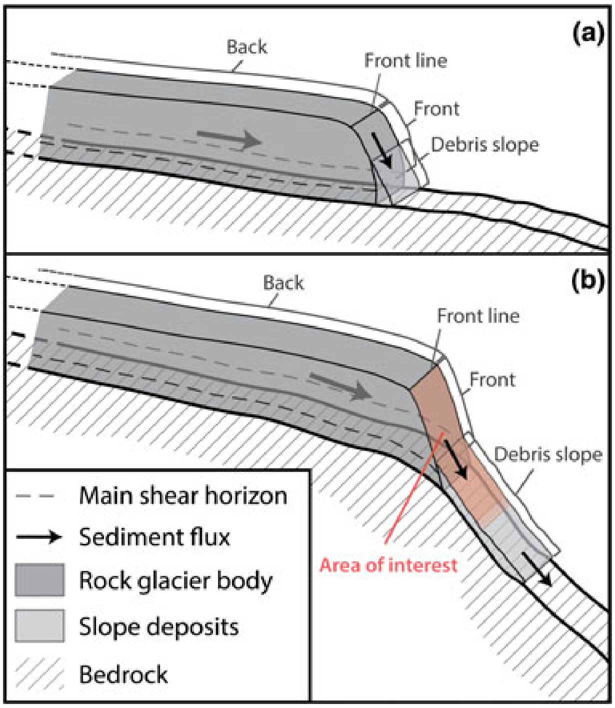

FIGURE 1 Two scenarios that schematically show the connectivity between an active rock glacier and the downward slope. A—No connectivity: The sediments are stored at the foot of the front and will be overridden by the advancing rock glacier; B—Efficient connectivity: The sediments are leaving the rock glacier system. The area of interest corresponds to the front and—at least—the upper part of the adjacent debris slope [Colour figure can be viewed at wileyonlinelibrary.com]

The present study aims to (i) identify and classify the processes that erode rock glacier fronts that are efficiently connected to torrential gullies or steep slopes, (ii) investigate the temporal variability of their dynamics and (iii) identify their controlling factors. For this, an extensive database of in situ webcam images has been collected for three study sites located in the Swiss Alps. Images from January 2013 to December 2016 were qualitatively analyzed and interpreted to reveal both the types and the temporal behaviors of erosion processes occurring at the front of the rock glaciers and within the uppermost part of their connected torrential systems ("area of interest" on Figure 1).

2 | STUDY SITES

The three investigated rock glaciers (Dirru, Gugla and Tsarmine) are located in the southwestern Swiss Alps (Figure 3). They all face west, with a terminus developing over a steep convex slope and dominating a torrential gully, allowing an efficient sediment connectivity with torrents. The adjacent torrential channels collect water from contributing areas of 0.11 km^2 at Dirru, 0.64 km^2 at Gugla and 0.27 km^2 at Tsarmine. None of the three sites displays an organized surface runoff network upslope from the rock glacier front. Along with their topographical setting, the rock glaciers were selected because of their high current flow rate, favoring a substantial sediment transfer between the fronts and the torrential gullies, and thus allowing observations to be made within only a few years. During the documented period (January 2013 to December 2016), each rock glacier was characterized by mean displacement rate of several meters per year (m/y) (Figure 4). In addition, webcam images showed that the position of the respective front lines, ie, the erosion border of the rock glacier surface (Figure 1), did not change much during the study period, while the total movements of the rock glaciers are estimated to have reached approximately 28 m at Dirru, 18 to 53 m at Gugla (18 m for the northern front and 53 m for the southern front) and 17 m at Tsarmine. Therefore, the advance of the three rock glaciers must have been balanced approximately by erosion of their fronts.

2.1 | Dirru

The Dirru rock glacier (46.12° N, 7.81° E) is located in the Mattertal valley (Figure 3). The elevation of the active tongue ranges from 3000 to 2530 m a.s.l. The lower half of the tongue is more than 350 m long and about 50 m wide. The front is located approximately 150 m upslope on the southern side of the Geisstriftbach torrential channel. The disrupted snow cover observed at a specific horizon of the front in winter indicates the presence of one main shear horizon, ie, the horizon where most of the deformation occurs[32], located ~15 m below the front line. During the past 10 years, the terminal part of the rock glacier tongue has moved continuously at an annual velocity of ~6–8 m/y.[27] The bedrock source of the rock glacier is mainly composed of mica-rich gneisses and schists.[33] The latter consists of a heterogeneous mix of coarse debris, including boulders of up to several cubic meters and a substantial amount of fine-grained sediments (heavily weathered debris) that are particularly visible at the front. Around 1995, a large erosion niche (~230 m long, 35 m wide and up to 20 m deep) developed downslope from the front, strongly

FIGURE 2 Images of long travel distance rock fall events triggered from the front of the Tsarmine rock glacier in July 2015 (left) and from the front of the Grabengufer rock glacier (Mattertal, Switzerland) in June 2009 (right). Both falling boulders exceeded 10 m^3 in volume and traveled several hundred meters downslope [Colour figure can be viewed at wileyonlinelibrary.com]

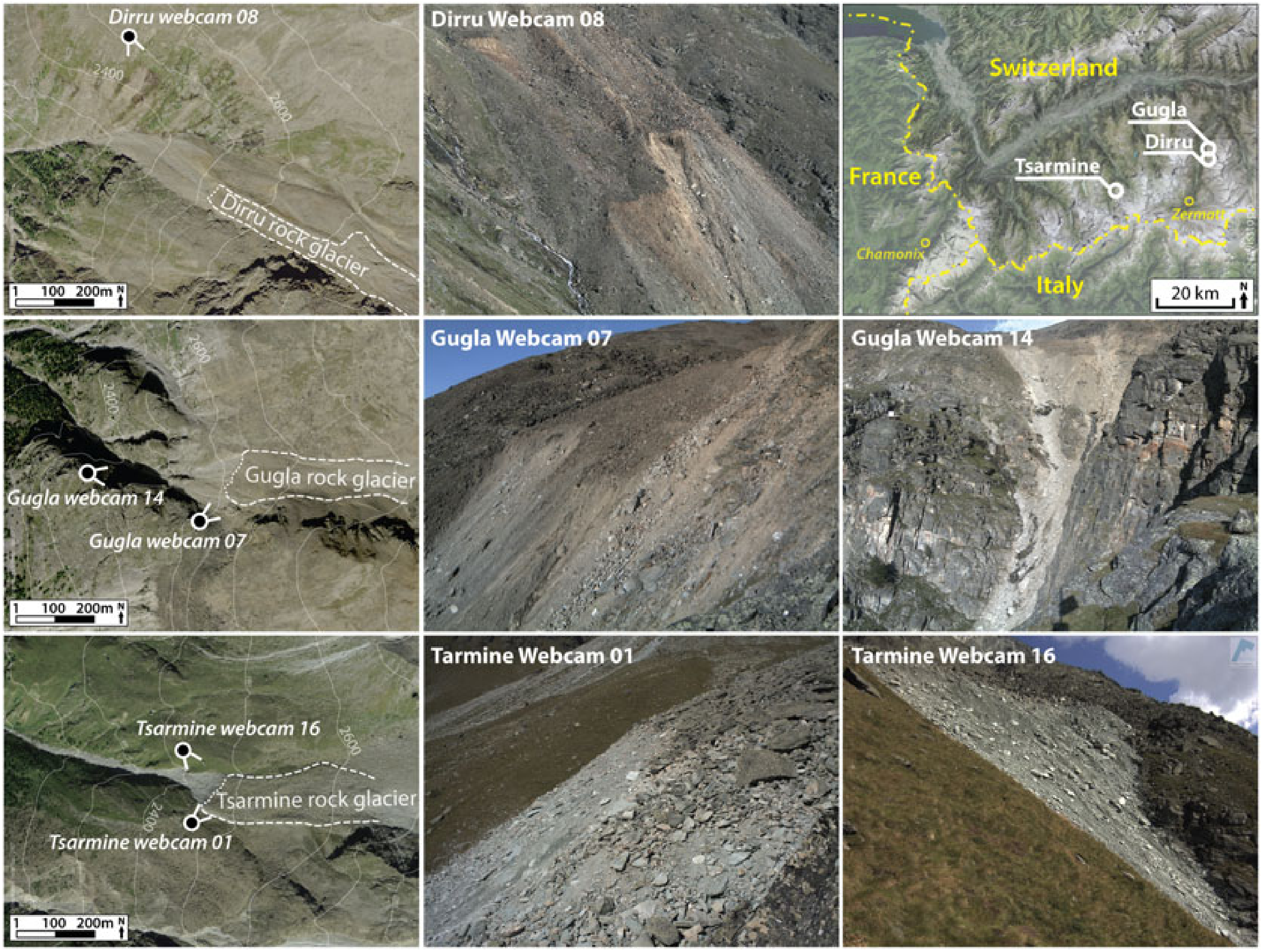

FIGURE 3 Images of the three study sites indicating the rock glacier outlines (white dashed lines), their front lines (white dotted lines), the location of in situ webcams (black and white dots) and examples of webcam images [Colour figure can be viewed at wileyonlinelibrary.com]

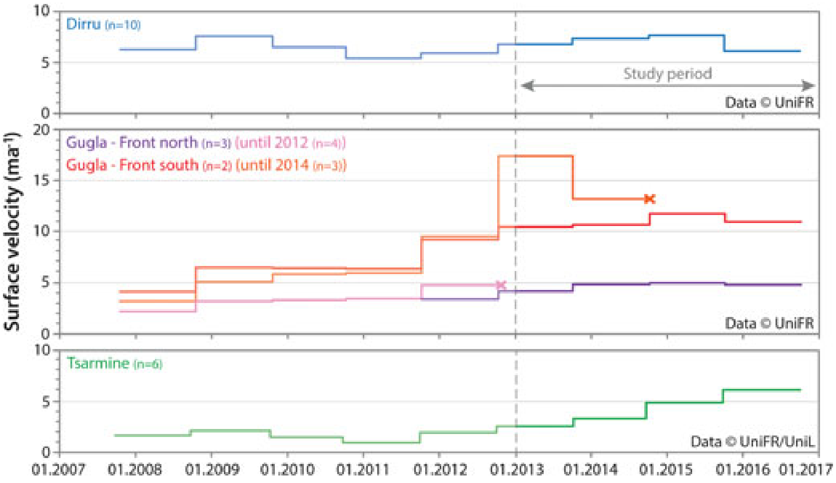

FIGURE 4 Time series of annual three-dimensional surface velocities of the terminal parts the three rock glaciers, measured by differential global navigation satellite system (dGNSS) since 2007 (average of n selected markers). The two sets of curves displayed for the Gugla rock glacier represent the velocities of the northern and the southern part of the front, respectively. The two crosses correspond to the fall of marked boulders on both parts of the front

enhancing the connectivity between the rock glacier and the torrential channel. The niche has been progressively infilled by debris supplied by the rock glacier since then. Small debris flows reaching the Geisstriftbach main channel were triggered in the niche during the snow melt season in June 2013, 2014 and 2016.

2.2 | Gugla

The Gugla (also named Gugla-Bielzug or Breithorn) rock glacier (46.13° N, 7.81° E) is located about 2 km north of the Dirru rock glacier, on the same valley flank (Figure 3). The geological setting is very similar to Dirru but the morphology, the topographical setting and the dynamics differ. Gugla has a tongue-shaped morphology and flows toward the west in a small valley between the Breithorn summit on the north side (3178 m a.s.l.) and the Gugla summit on the south (3377 m a.s.l.). The tongue is about 450 m long and 100 m wide, and ranges in elevation between 2820 and 2600 m a.s.l. The terminal section of the rock glacier can be divided into a southern part, which is steeper, thicker (20–30 m) and contains several superimposed shear horizons (the disrupted snow cover observed on webcam images from winter 2011/12 and 2012/13 indicated three superimposed shear horizons); and a northern part, less steep with apparently only one shear horizon located about 15 m below the front line. Since 2008 at least, the surface velocities have been continuously faster on the southern part (~ 10 m/y) than on the northern part (~ 4 m/y; Figure 4).[27] Both parts flow directly into the Bielzug torrential gully, supplying it with rock debris. Such efficient sediment connectivity has been continuously active since at least 1930 (as observed on aerial photographs). Each year from 2012 to 2016, one to several debris flows triggered from an area immediately downslope from the rock glacier front reached the main valley close to the village of Herbriggen (St Niklaus, VS). The volumes involved ranged from 500 to more than 5000 m^3 per event.[18]

2.3 | Tsarmine

The Tsarmine rock glacier is located about 25 km west of the two other sites (46.04° N, 7.50° E), in the Val d'Arolla (Figure 3). It is tongue-shaped, about 450 m long, 100 m wide and ranges in elevation between 2680 and 2460 m a.s.l. The rock glacier surface has an openwork structure of gneiss boulders up to several cubic meters in size. A matrix of finer sediments—apparently coarser than at the two other sites—is visible at the front, and probably underlies the openwork structure. The main shear horizon is approximately 15 m below the front line according to webcam images in winter (Figure 5). The rock glacier ends on the top of a deep torrential gully where debris has accumulated since at least 1946 (oldest available aerial photograph). During the last 5 years, the annual rock glacier velocity has continuously accelerated from about 1 m/y in 2011 to more than 5 m/y in 2016 (Figure 4).[6] No evidence of debris flow triggered from the front or adjacent debris slope and reaching the main valley has been observed since 1946.

3 | METHODS

The erosion processes linking the front of the rock glaciers to the adjacent debris slopes were characterized from year-round time series of webcam images obtained from January 2013 to December 2016, complemented by some direct in situ observations. The approach relies on (i) acquiring a time series of images and (ii) visually identifying erosion processes from them.

The three sites were equipped with one or two Mobotix (M12, M15 or M24) webcams. Each webcam ran autonomously on a battery powered by a solar panel. Images with a resolution of about 3 megapixels (2048 × 1536 pixels) were taken at hourly intervals during daylight, occasionally at 15-min intervals during highly active periods (eg, during intense snowmelt). The images were sent via a

FIGURE 5 Webcam image showing lightly disrupted winter snow cover (arrows) that indicates the presence of the main shear horizon at the front of the Tsarmine rock glacier (webcam16, January 22 2017)

GSM (Global System for Mobile Communication) internet connection to a server where the data were stored and accessible. The webcam system allowed remote live access but did not permit recording of movies. The first camera was installed in 2009 in Tsarmine and the last in 2015 there. Webcam characteristics are detailed in Table 1, and image examples for each webcam are shown in Figure 3.

Installation of cameras is often challenging in steep and remote environments. The location must allow the camera to have a good connection to a GSM signal for the data to be regularly sent to the server, and the solar panel must receive enough sunlight to charge the battery. The location must also be safe from rock falls and avalanches. The camera should be close enough to the rock glacier front to provide images with a resolution sufficient to detect erosion events of small scale (< ca 3 m^3). At Gugla and Tsarmine, one webcam was installed near the rock glacier front (cam07 at Gugla, cam01 at Tsarmine; Table 1) to visualize the general movement there. These webcams provided a good view on the erosion processes at the front but did not cover the entire area of interest. Therefore, additional webcams were installed later to view the debris slope adjacent to the rock glacier fronts (cam14 was installed in June 2013 at Gugla and cam16 in May 2015 at Tsarmine). At Dirru, the lack of suitable positions led to only one webcam being installed quite far from the rock glacier front, which offered a good general view of the area of interest but not of small-scale erosion processes.

Geomorphological information was extracted from the image series by examining them visually and stored in a database. Between two or more consecutive images, changes such as the loss or movement of rock debris at the surface of the front were identified as erosion events and attributed to an erosion process, as illustrated in Figure 6. The high frequency of image acquisition also allowed monitoring of erosion events through time. Although some images could not be analyzed due to poor weather conditions (especially fog) and some images were missing because of technical issues (eg, low battery), almost the whole study period was covered for each site by several images taken every day by at least one webcam (Table 1). The information collected was stored in tables where each observed change at the surface of the front of the rock glacier was recorded with its date and associated with a type of erosion process. For each day of the study period, additional information such as general weather conditions (ie, rainfall, snowfall, sun, clouds) or the characteristics of the snow cover at the surface of the front (ie, full snow cover, partial snow cover, snow-free) was also inferred from the images and recorded in the database.

4 | RESULTS

4.1 | Erosion processes

Four different types of events were detected from the images, based on categories of erosion processes (eg, [34,35]), namely rock fall, debris slide (without rupture), widespread superficial flow and concentrated flow (including debris flows).

TABLE 1 Webcams and images characteristics

Site	Name	Date of installation	Number of images (01.01.2013–31.12.2016)	Distance to the front line (m)	Focal length (mm)	Covered area
Dirru	Cam08	01.07.2011	17 636	407	65	Rock glacier back, front and debris slope
Gugla	Cam07	28.06.2011	16 874	152	32	Rock glacier back and front
	Cam14	13.07.2013	17 125	387	32	Rock glacier front and debris slope
Tsarmine	Cam01	15.10.2009	16 819	78	43	Rock glacier back and front
	Cam16	07.05.2015	9911	172	38	Rock glacier front and debris slope

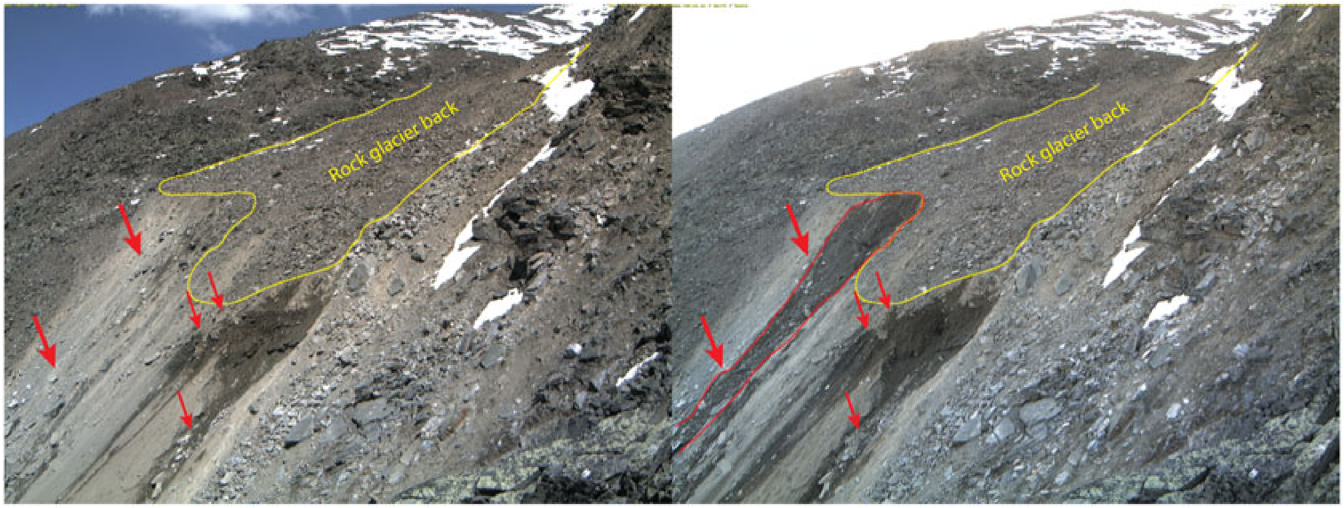

FIGURE 6 Webcam images showing evidence of erosion (arrows) at the front of Gugla rock glacier between June 17 2013 (left) and June 18 2013 (right). Deep incision due to concentrated flow is indicated by the two large red arrows and by the red dotted line on the right-hand image. The smaller red arrows point to more localized areas where smaller changes can be detected between the two images, mainly related to small rock falls (two arrows close to the front line) and to the accumulation of debris eroded from the front (lower small arrow) [Colour figure can be viewed at wileyonlinelibrary.com]

Rock fall consisted of the fall of one or a few boulders from the rock glacier front, and was the most common erosional process observed. On the image series, rock fall events were detected when boulders moved from their initial location (Figure 6), while no other notable changes affected the surrounding area. Some missing boulders could be identified downslope in the images. The fall of smaller debris (< ca 30 cm in diameter) was usually not recorded because the associated morphological changes could not be detected. The fall or collapse of parts of the permafrost body (frozen debris) was not observed.

Debris slide consisted of the translational downward motion of a restricted mass of debris (ca 3–30 m^3) in the unfrozen superficial layer of the rock glacier front. Sliding events were characterized by the absence of rupture or fall and were usually traceable on several consecutive images and often over several days. Debris slides commonly led to a single or multiple ruptures, which then sometimes triggered localized rock falls. Many slides were therefore associated with rock fall activity, but rock fall events were not necessarily preceded by a slide. Sliding of frozen debris (permafrost) was not observed.

Widespread superficial flow was associated with low-discharge water circulation at the surface or within the top few decimeters of the rock glacier front and downstream debris slope. It was typically an areal process (unconcentrated wash), but did sometimes lead to the development of small linear erosional features, such as rill wash and small mudflows. Superficial flow events were identified by a wet ground surface (during snowmelt or rainfall), and were commonly associated with the small movement of debris over the entire surface of the rock glacier front. In addition, water temporarily flowing on the surface of the front and the downstream debris slope was commonly identified by the presence of small superficial mudflows (Figure 7: 1a, 2a and 3a).

Concentrated flow was exclusively associated with significant linear erosion. It was characterized by both greater water input and incision than superficial flow, mobilizing up to several hundred cubic meters of material, mainly from the debris slope downstream of the rock glacier front. Concentrated flow events always related to the occurrence of water springs, which were commonly easy to detect (Figure 7: 1b, 2b and 3b). When discharge was high enough to mobilize large amounts of sediment, concentrated flow could lead to the occurrence of debris flows. Such events were triggered on the rock glacier fronts or on the adjacent debris slopes and some traveled for several kilometers.

4.2 | Temporal occurrence of the processes

The temporal resolution of the observations allowed the seasonal behaviors of the four main erosion processes at Dirru, Gugla and Tsarmine to be assessed (Figure 8). Temporal patterns of the different processes were similar for each site, though slight differences in timing occurred between some years and sites.

Generally, erosion events did not occur when the rock glacier front was covered by snow (Figure 8). Only a few rock fall events were observed when snow cover was present, mostly in winter 2015/16 and December 2016. Erosion events were more frequently observed once snow cover began to melt in March or April. Initially, rock falls and debris slides involving small amounts of sediments were more common. Widespread superficial flow began later, typically in late April or May, once the snow had melted from at least part of the front. Initiation of these three processes was restricted to the rock glacier front (up to the front line). They were most frequent between May and June, when the front was snow-free but snowmelt was still active further upslope. Concentrated flow events were associated with intense snowmelt in the upslope catchment, sometimes coinciding with heavy or repeated rainfall. They were triggered either on the debris slope downstream of the rock glacier front or on the front itself, depending on the location of water springs.

The frequency of all processes tended to decrease gradually from the beginning of July until autumn. In July and August, rock fall was the most frequent process, and its occurrence was not necessarily associated with rainfall. Debris slides and widespread superficial flow events occurred more sporadically between July and October than during snowmelt and were usually associated with rainfall events. Concentrated flow events were rare during summer and autumn and required heavy or repeated rainfall. In autumn, the frequency of erosion events decreased substantially as no heavy rainfall occurred. Erosion event initiation almost completely ceased with the refreezing of the active layer and the establishment of winter snow cover, generally in October or November.

5 | INTERPRETATION

5.1 | Causes of the erosion processes

Two main causes of erosion can be highlighted based on the timing and physical characteristics of each process: (i) rock glacier advance and (ii) water inputs (Figure 9). The rock glacier movement, characterized by a higher displacement rate at the surface than at depth (deformational flow), causes the frontal slope to steepen, which increases the shear stress on the sediment particles reposing on the front. When a certain threshold is passed, the rock particles which are not cemented by ice begin to reorganize by gravity.[35] This action causes individual or cascading gravitational movements in the form of isolated rock falls, which usually occur randomly in space and time. The increasing ice content resulting from the active-layer freezing in late autumn and winter most likely cements the rock particles and therefore essentially prevents rock falls during the cold season, even though the rock glacier still moves.

The decrease in cohesive strength between rock particles, which relates to the second main cause of erosion, can be triggered by water input from (i) rainfall and/or snowmelt on the rock glacier front, (ii) thaw of the active layer or upper permafrost, or (iii) lateral groundwater flow in saturated or unsaturated horizons. In the two first cases, the ground humidification is commonly shallow and mainly results in the occurrence of rock falls, debris slides and widespread superficial flow events. Mudflows may also be generated. Conversely to rock falls, debris slides and superficial flow events affect larger areas on the frontal slope and occur only when water is added. Subsurface saturation of the ground by shallow (suprapermafrost) or deeper (intra- or subpermafrost) groundwater flow can initiate water springs at the surface of the rock glacier front or on the debris slope downstream (Figure 7: 1b, 2b and 3b). The consecutive concentrated flow commonly triggers linear regressive erosion, beginning downstream from the outflow locations. Depending on the total discharge and the location of the activated water spring, the regressive

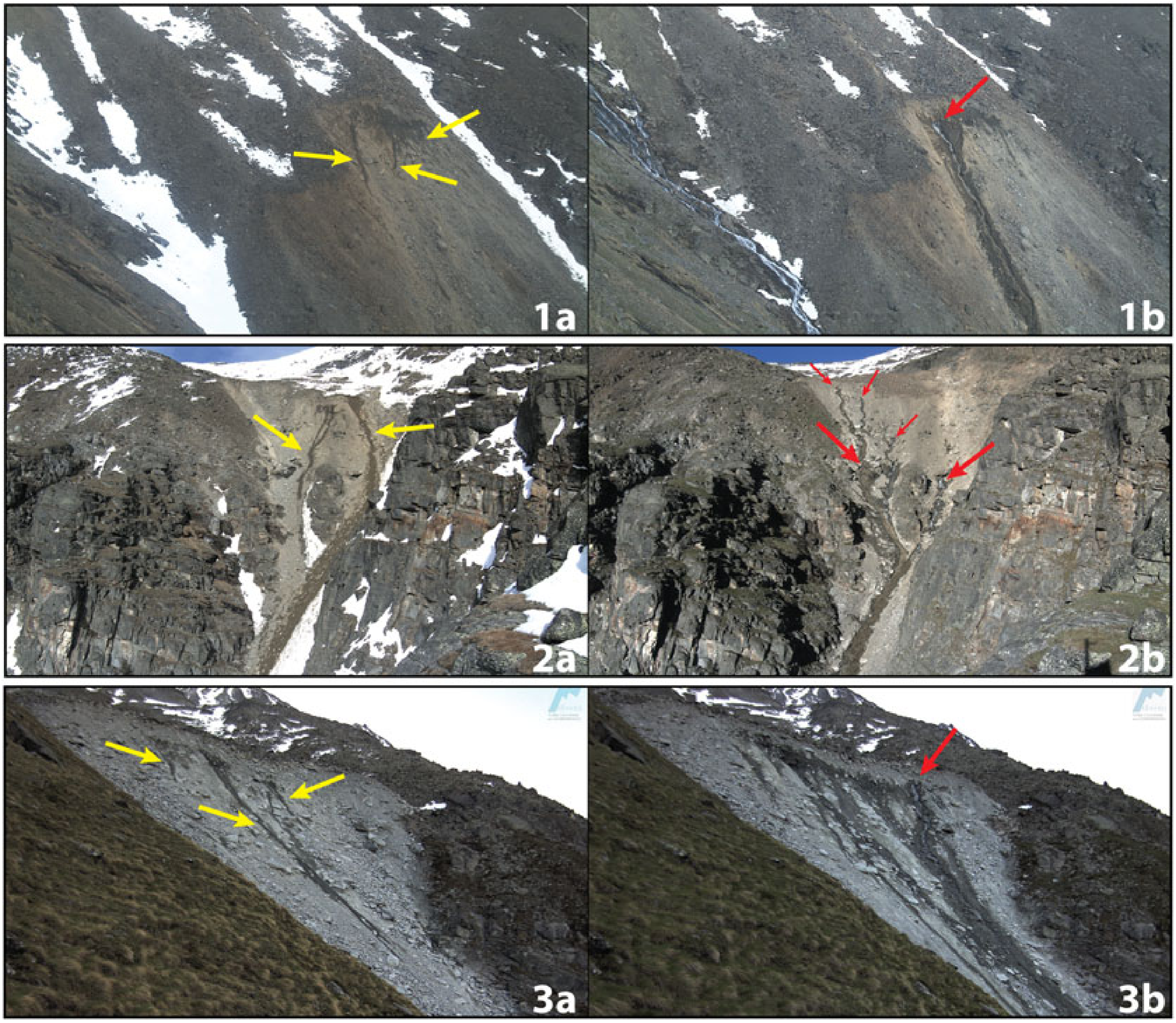

FIGURE 7 Webcam images showing examples of erosional activity resulting from water flow at the front of Dirru (top), Gugla (middle) and Tsarmine rock glaciers (bottom). Mudflows due to superficial flow (yellow arrows) are shown in 1a for Dirru (webcam08, may 11 2015), 2a for Gugla (webcam14, may 20 2014) and 3a for Tsarmine (webcam16, June 3 2015). Water springs generating concentrated flow erosion (red arrows) are shown in 1b for Dirru (webcam08, June 10 2014), 2b for Gugla (webcam14, June 23 2016) and 3b for Tsarmine (webcam16, June 24 2016)

erosion can mobilize large volumes of sediment and ascend to the rock glacier front (see video at http://www.youtube.com/watch?v=0k8OYEvHD_Y), where it may be constrained by the exposure of resistant frozen ground (permafrost). At the three sites, the initiation of concentrated flow events required specific weather conditions that provided adequate water infiltration rates into the ground upslope of the rock glacier fronts. Such conditions occurred relatively infrequently and resulted from intense snowmelt phases at the catchment scale, heavy or recurring rainfall, or both.

5.2 | General erosional behavior during an annual cycle

During an annual cycle, the timing of erosion events was similar at all three study sites. The erosion activity at the front of rock glaciers can be separated into three main periods: winter, melting, and summer (Figures 8–10).

1. During winter (roughly from November to March), when the active layer was entirely frozen and the front was covered by snow, very few erosion events were observed. Some rock falls were detected, however, for instance during winter 2016, at all three sites. These may be explained by the lack of snow between December 2015 and February 2016, which exposed the surface to direct solar radiation in the afternoon. Superficial thaw could therefore have occurred on the fronts, facilitating small rock fall events. Rapid rock glacier movement may also enhance rock fall activity during winter. When rock glaciers move faster than 10 or 20 m/y, as recorded during the 2008–11 destabilization phase affecting the Grabengufer rock glacier in Mattertal, Switzerland,

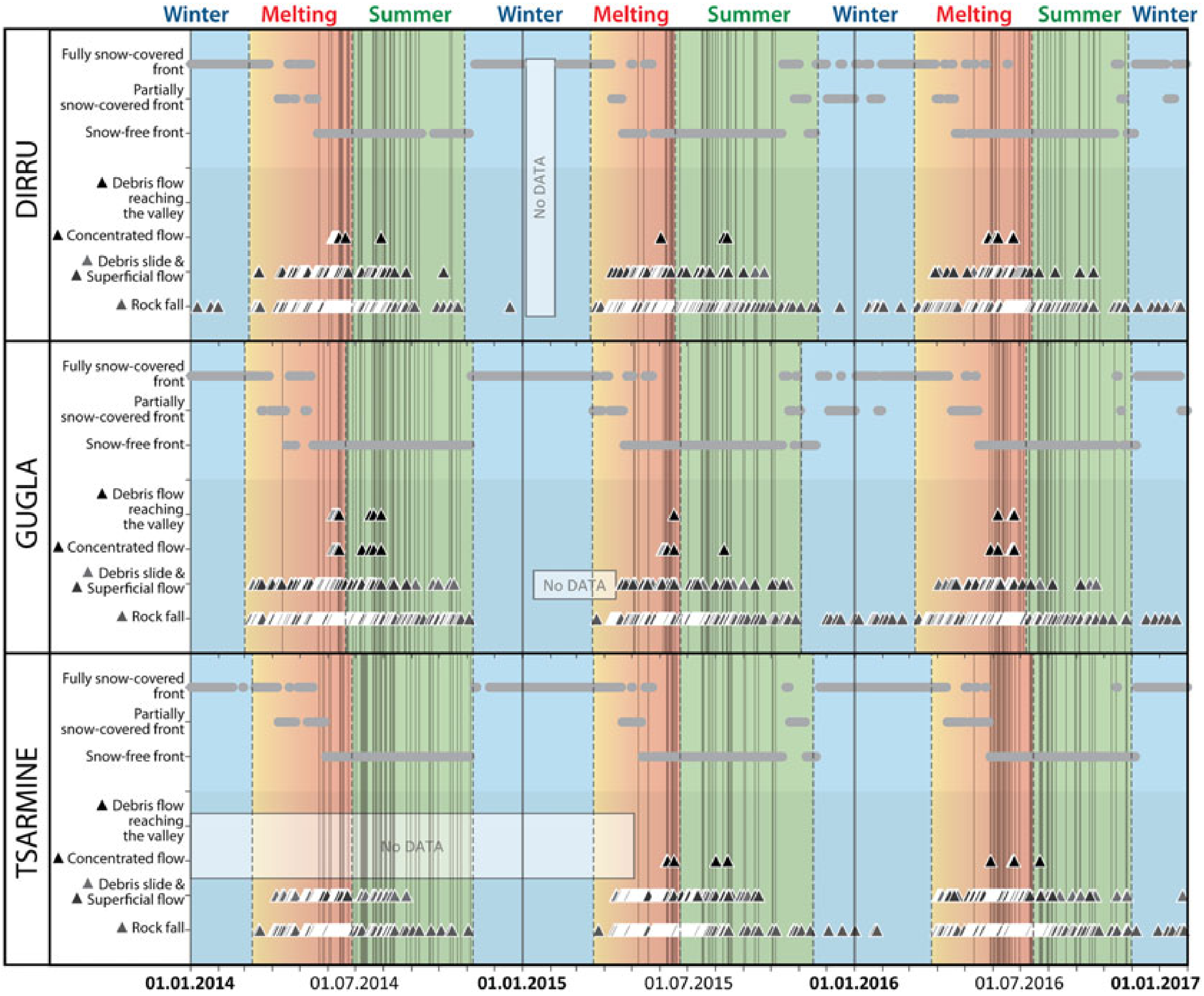

FIGURE 8 Summary of the timing of erosion processes at the front of Dirru, Gugla and Tsarmine rock glaciers for the years 2014–16. Debris slides and superficial flow events are associated in one line as they shared similar triggering conditions. Information about the snow cover on the front of the rock glacier (horizontal light grey lines) and the interpreted occurrence of rainfall events (vertical dark grey lines) are indicated. Different colors divide each year into three main periods differing in terms of erosion activity: Winter (blue), melting (yellow to red) and summer (green). Periods with no data are due to technical issues at Dirru and Gugla, and the absence of webcam from which the debris slope could be observed before 2015 in Tsarmine

rock fall activity may occur through the cold season (Figure 11).[27] Nevertheless, sediment erosion activity in winter can typically be considered negligible. However, the rock glacier still advances in winter, even when no erosion occurs, moving significant volumes of material forward and increasing the slope angle between the front line and the debris slope below.

2. The transitional melting period (between March and June) began with the onset of snowmelt on the rock glacier. During this period, erosion activity rapidly increased in response to both the steeper frontal slope (favoring gravitational instabilities) and the input of water, first from snowmelt and active-layer thaw, and later from permafrost thaw. In the early melting period (March–May; Figure 10), snowmelt and the active-layer thaw mainly triggered rock falls, rock slides and widespread superficial flow. Later (May–June, Figure 10), the removal of debris on the rock glacier front may expose the permafrost table at the surface or leave it protected only by a thin layer of debris. Continuous adjustment of the permafrost table occurs on the rock glacier front, and permafrost thaw contributes to the initiation of further frequent but low-intensity erosion events, which lead to a progressive decrease of the slope angle between the front line and the debris slope. In addition, when snowmelt affects the whole catchment area (usually in June), substantial water infiltration rate may increase the discharge at the water springs and trigger concentrated flow events, usually characterized by larger erosion volumes. The timing, duration and intensity of the melting period varied from year to year but typically lasted several weeks between late March and late June (sometimes even early July). For all sites in all years, the highest erosion activity was in the melting period, due to the increased and unbalanced slope angle and availability of water inputs.
3. During summer (roughly from July to October), the active-layer usually continued to deepen, but at a lower rate than earlier in

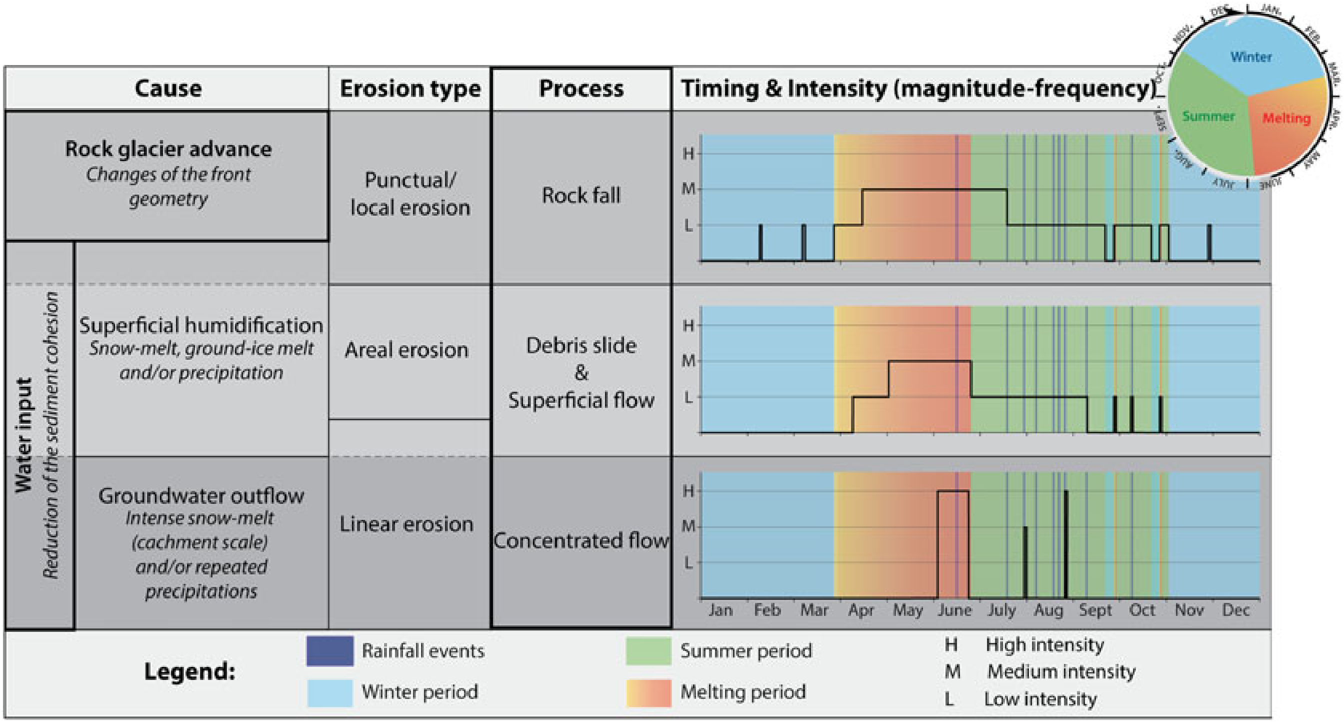

FIGURE 9 Summary of erosion processes in relation to their cause, type, timing and intensity during the three main periods (colors and circle). The graphs on the right show the timing and intensity of the different processes and summarize information gathered from all sites for all documented years

the season. The gradual changes in the frontal slope geometry induced by the rock glacier advance are directly balanced by erosion events (mainly rock fall). Hence, the slope angle between the front line and the debris slope remains almost unchanged over summer. In general, the frequency of erosion events decreases gradually until the ground freezes again in October or November. Rainfall is the main source of ground moisture and can temporarily increase erosion intensity via widespread superficial flow, debris slides and rock falls. Heavy or recurring rainfall events may allow sufficient water infiltration to episodically reactivate or increase the discharge of local water springs and trigger high-magnitude regressive erosion events (concentrated flow).

6 | DISCUSSION

6.1 | Differences between the sites and controlling factors.

The most frequently observed erosion mechanism at all sites was rock fall, followed by debris slide and superficial flow, which require wet conditions near the ground surface. All three processes were observed each year at all study sites and usually involved the transfer of small amounts of sediments per event (typically ca 3–30 m^3) over relatively small distances (up to ca 50 m). They were therefore high-frequency but low-magnitude events (Figure 9). Conversely, erosion triggered by concentrated flow was less frequent but mobilized much larger volumes of sediment per event (ca 100 to more than 1000 m^3). The groundwater flow discharge must have been intense enough to induce a major increase in water content within the sediments on the debris slope downstream from the rock glacier front. Such conditions only developed when intense snowmelt affected a large part of the catchment area, during substantial or repeated rainfall over a period of up to a few days, or a combination of both. In the latter case, the amount of rainwater necessary to trigger a major debris flow was less important, because the debris had already been wetted from snowmelt.

Small differences in the timing or frequency of erosion events existed between the sites, mostly related to weather conditions controlling rainfall and snowmelt, which can be highly variable in space. For example, thunderstorms may affect very small areas, whereas snow cover development can differ at a local and regional scale depending on wind exposure and location within the mountain range. Other parameters such as the material erodibility on the frontal slope also play a role. Erosion from widespread superficial flow was more frequently observed at Gugla and Dirru than at Tsarmine because their fronts contain finer sediments, favoring the development of small mudflows. In addition, the occurrence of debris flows was always related to concentrated flow and depended on site-specific factors.

Variations in local groundwater circulation and the number and location of water springs influenced the occurrence of concentrated flow. These local variations explain some of the differences observed between sites, such as the frequency and magnitude of debris flows. At Tsarmine, there was only one visible spring close to the front (Figure 7: 3b), which probably corresponded to intra- or suprapermafrost flow and was rarely active. It was usually characterized by a low discharge, inhibiting the development of high-magnitude debris flows. At Dirru, one main spring was identified each year during intense snowmelt periods. It seemed to be linked to intrapermafrost

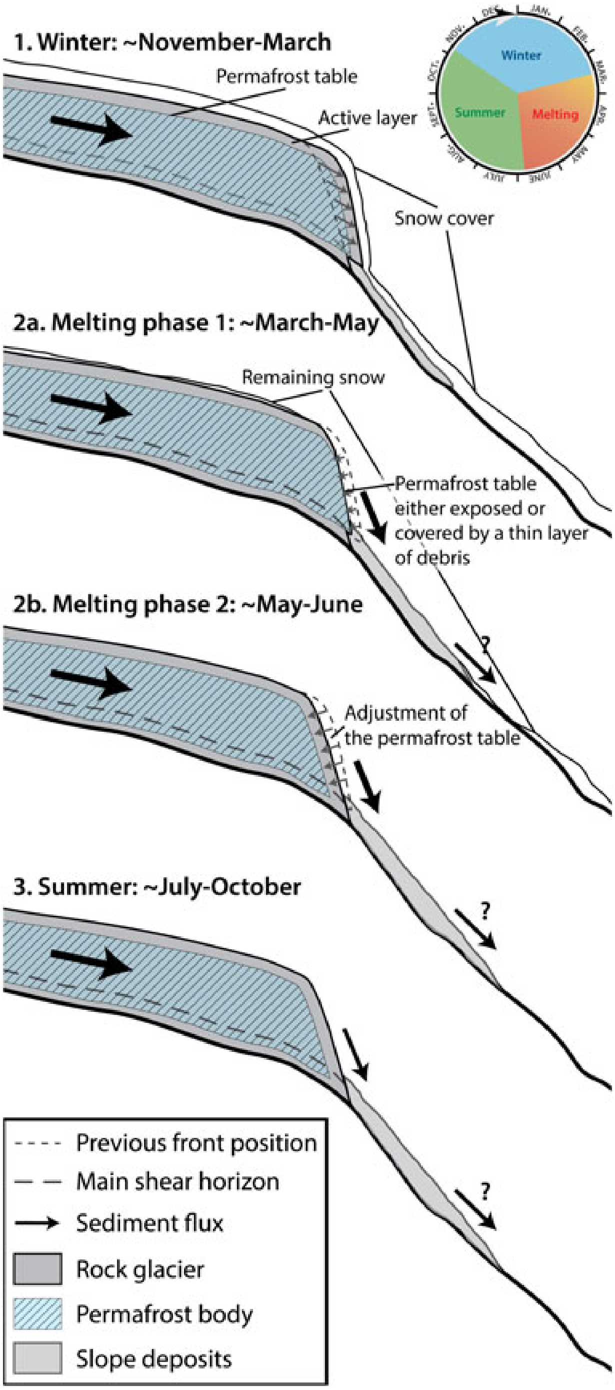

FIGURE 10 Schematic vertical profiles of a rock glacier front undergoing different periods of erosion activity within a 1-year cycle (1-3). In winter (1) the rock glacier advances but no erosion occurs and the frontal slope steepens. During the melting period (2a and 2b), the steep slope angle associated with water input from snowmelt, active-layer thaw (2a) and permafrost thaw during the readjustment of the permafrost table (2b) enhances erosion activity, which results in the adjustment of the frontal slope. During summer, erosion is less intense and balances approximately rock glacier advance (3)

flow and sometimes coincided with emergence of low-discharge suprapermafrost water (Figure 12). When the discharge was highest at the main spring, the concentrated flow triggered debris flows, which sometimes reached the main channel of the Geisstriftbach torrent (Figure 7: 1b). At Gugla, several water springs were often visible either during intense snowmelt periods and/or during persistent rainfall events. Most of the discharge from these springs was concentrated on the debris slope downstream from the rock glacier front and seemed to gather water from supra- and subpermafrost flows (Figure 7: 2b). No evidence of intrapermafrost flow was observed at Gugla. The notably larger catchment area at Gugla than at the two other sites may have favored higher discharge at the springs. Concentrated flow leading to debris flows was thus most frequent at Gugla, where the largest magnitude events were observed (several thousand cubic meters). At Dirru, only small to medium-sized debris flows were recorded (up to several hundred cubic meters), and rarely reached the main valley. At Tsarmine, only very small events restricted to the upper part of the debris slope were observed (several tens of cubic meters).

6.2 | Significance of rock glaciers as sediment sources

Despite differences related to local and external factors, the erosion processes observed at the three sites were the same and their occurrence followed similar temporal patterns. At each site, the frequency–magnitude of the erosion processes was closely related both to the presence of permafrost and to the rock glacier dynamics. The presence of frozen ground explains the lack of erosion during winter when the active layer was frozen, and the high-frequency events during snowmelt and active-layer thaw due to the frequent supply of water to the sediments. Frozen ground also controls the magnitude of the erosion events as it limits the volume of thawed, erodible sediment. These temporal considerations are also important in other sediment accumulations such as moraines and talus slopes in mountain permafrost environments. However, the rock glacier dynamics generate instabilities on the frontal slope, which allow a high frequency of rock fall events. The progressive steepening between the front line and the debris slope downstream promotes high erosional activity during the melting season. Finally, the magnitude of rock glacier movement controls the continuous renewal of sediment available at the front. At the three study sites, the high surface velocity rates ensure a substantial availability of new sediment for further gravitational transfer by debris flows.[30] Torrents fed by rapidly moving rock glaciers can therefore be considered as supply-unlimited at an annual time scale, given that the sediment supply is renewed and sometimes even increased each year (eg, [13]).

6.3 | Limitations of the method

The results of this study relied on observations from webcam images, an approach that has several inherent limitations. First, the temporal coverage of the images was not always optimal. Erosion events at night may not leave visible traces and may therefore not all be recorded. Some images were missing or unusable because of technical problems or fog. The inventory of erosion processes presented here is therefore not exhaustive due to these data gaps. Moreover, some webcams were installed only recently to complement existing visual information. For example, at Tsarmine, webcam16 was set up in May 2015 (Table 1). Before this, images were only available from webcam01, which only recorded some parts of the rock glacier front. At

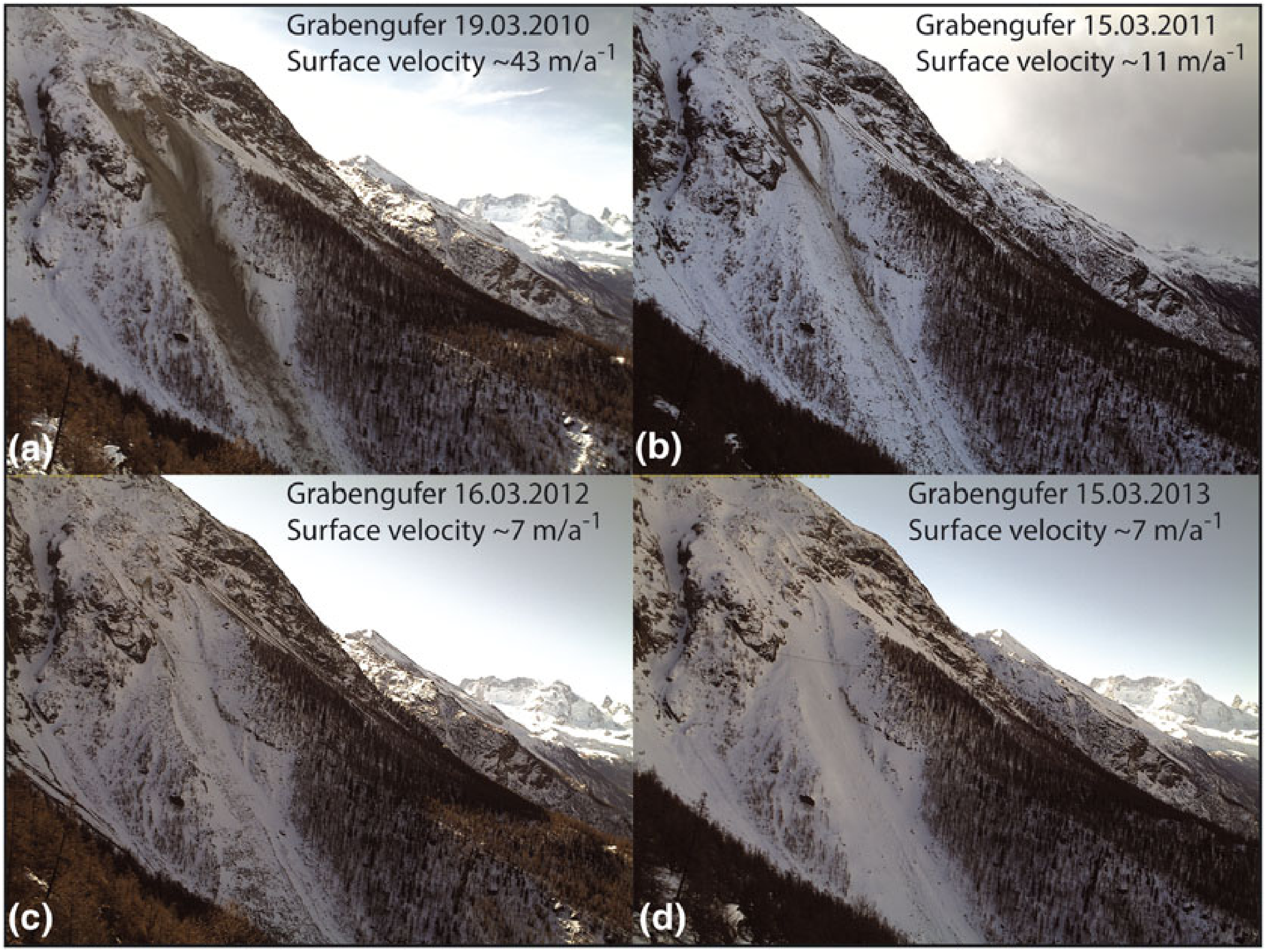

FIGURE 11 Photographs showing the evolution of winter debris production from rock fall activity at the front of the Grabengufer rock glacier between 2010 and 2013 in relation to surface velocity. Above a velocity of about ~10 m/y (a, b) winter ground freezing was insufficient to prevent erosion at the front. Below this velocity (c, d), rock fall during winter almost ceased [Colour figure can be viewed at wileyonlinelibrary.com]

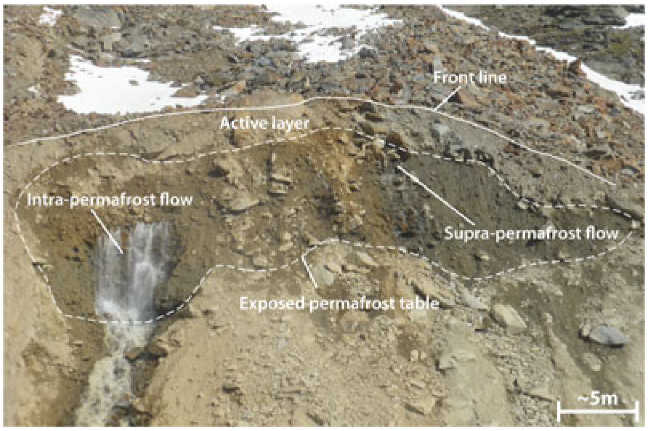

FIGURE 12 Photograph of the front of the Dirru rock glacier during a melting period (June 17 2013). Substantial removal of debris during the first part of the melting period exposed the permafrost table at the ground surface. Intense snowmelt activated two water springs visible on the image [Colour figure can be viewed at wileyonlinelibrary.com]

Gugla, the installation of webcam14 in June 2013 improved observations of some processes, particularly those related to superficial or concentrated flow (Table 1).

The detection of erosion events and their classification into process types was completed visually. Therefore, some small-scale events may not have been recorded. The classification of such events is based on several visual clues. Hence, the inventory of the events and their categorization rely on the subjective judgment of the observer. However, the possible misinterpretation or nondetection of some events and the lack of usable images for short periods was somewhat counterbalanced by the relatively long, 4-year study period.

7 | CONCLUSION

Quasi-continuous sequences of webcam images revealed four main types of erosion processes at the front of three rapidly moving rock glaciers: rock fall, debris slide, superficial flow and concentrated flow. The main causes of erosion were either changes to the rock glacier front slope angle due to deformational flow, or the increase in moisture content of the rock debris constituting the fronts. Rock fall, debris slide and superficial flow were characterized by low magnitudes but relatively high frequencies, which varied between three main periods annually: winter (November to March), melting (March to June) and summer (July to October). Winter was characterized by a very low frequency of erosion events because the ground is usually entirely frozen. Rock glaciers continue to creep forward in winter, steepening their frontal slopes. Most erosion events were observed during the melting period in association with the increased front slope angle and water input from snowmelt, active-layer thaw and permafrost thaw. In summer, rock glacier movement induces gradual changes of the front slope angle, which are usually balanced by rock falls.

Occasional inputs of water from rainfall can temporarily increase the frequency of erosion events. Groundwater emerging in the debris slope or at the front of the rock glacier may cause significant regressive erosion (concentrated flow) and sometimes trigger debris flows. Concentrated flow is generated by water inputs from intense snowmelt and/or heavy or repeated rainfall, and is generally characterized by low frequency (a few days per year) and relatively high magnitude, depending on local factors such as the potential for groundwater discharge.

Compared to other high-mountain sediment sources, the fronts of rapidly moving rock glaciers connected to torrential channels show high erosion and sediment transfer activity. Rock glacier movement favors the initiation of erosion by continuously changing the frontal slope, which causes instabilities. It also ensures a continuous renewal of sediments available for erosion. Erosion intensity can vary substantially within and between years, controlled by weather conditions and by the kinematical behavior of the rock glacier. Although quantifications of erosion rates are still lacking, the observations showed that higher rock glacier velocities can be expected to increase the sediment renewal rate at their fronts and favor sediment transfer between rock glaciers and torrential systems. The recent increase in rock glacier velocities therefore implies substantial modification of the sediment cascade by locally increasing sediment availability in the headwaters of high-mountain torrential catchments.

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