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Mapping and quantifying sediment transfer between the front of rapidly moving rock glaciers and torrential gullies

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The sedimentary connection which may occur between the front of active rock glaciers and torrential channels is not well understood, despite its potential impact on the torrential activity characterizing the concerned catchments. In this study, DEMs of difference (DoDs) covering various time intervals between 2013 and 2016 were obtained from LiDAR-derived multitemporal DEMs for three rapidly moving rock glaciers located in the western Swiss Alps. The DoDs were used to map and quantify sediment transfer activity between the front of these rock glaciers and the corresponding underlying torrential gullies. Sediment transfer rates ranging between 1500 m^3/y and 7800 m^3/y have been calculated, depending on the sites. Sediment eroded from the fronts generally accumulated in the upper sectors of the torrential gullies where they were occasionally mobilized within small to medium sized debris flow events. A clear relation between the motion rates of the rock glaciers and the sediment transfer rates calculated at their fronts could be highlighted. Along with the size of the frontal areas, rock glacier creep rates influence thus directly sediment availability in the headwaters of the studied torrents. The frequency-magnitude of debris flow events varied between sites and was mainly related to the concordance of local factors such as topography, water availability, sediment availability or sediment type.

Keywords:
Rock glacier
Sediment transfer
Debris flow
Spatio-temporal variations
DoDs

1. Introduction

Active rock glaciers act as efficient sediment conveyors in periglacial mountain environments (Frauenfelder et al., 2003; Delaloye et al., 2010; Gärtner-Roer, 2012), transferring large quantities of debris from their rooting zone (upslope area) to their fronts. Active rock glacier fronts are typically steep, reach up to several tens of meters height and are composed of coarse elements (pebbles, boulders) embedded in a matrix of finer-grained debris. Because of instabilities induced by the motion of the landform, active rock glacier fronts are affected by frequent sediment reworking processes (Kummert et al., 2017). In some cases, mobilized debris accumulate on subjacent slopes and gullies where they become available for further transport, for instance via debris flow events. The amount of easily erodible sediments which can be mobilized by debris flows depends on the erosion rate (reworking rate) characterizing the front of rock glaciers, which can be expected to depend on the rock glaciers kinematical behavior, and on the spatial re-distribution of the sediments on the slopes. In this contribution, both mapping (spatial characteristics) and quantification (erosion rates) of the sediment transfer activity between the front of some selected active rock glaciers and their respective connected torrential gullies are presented.

Active rock glaciers are composed of a mix of various-size rock particles which, under a few meters of non-permanently frozen rock debris (i.e. the active layer), are cemented by interstitial ice. The deformation of the ice explains the downslope movement of a rock glacier (i.e. the rock glacier creep, e.g. Haeberli et al., 2006) and concentrates mostly in one main shear horizon (e.g. Arenson et al., 2002; Buchli et al., 2013), in some cases in several of them (e.g. Kummert et al., 2017). The deformation rate within rock glaciers depends on numerous factors such as topography (slope angle), internal structure (percentage of ice, rock debris and water content into the ground) and ground temperature (e.g. Arenson et al., 2002; Ikeda et al., 2008; Delaloye et al., 2010). In the current context of global warming, the dependency of rock glaciers creep rates on temperature - at least on an annual basis - (Kääb et al., 2007; Delaloye et al., 2008) is of particular importance. In response to the climatically driven increase of the ground temperature, a very substantial acceleration of rock glaciers and other permafrost creeping landforms has been reported especially from the Alps (e.g. Kaufmann et al., 2007; Ikeda et al., 2008; Roer et al., 2008; PERMOS, 2016), but also from other mountain ranges such as the Brooks Range in Northern Alaska (Daanen et al., 2012) or the Kazakh and Kyrgyz Tien Shan (Sorg et al., 2015; Kääb et al., 2016). The sediment transfer rate of rock glaciers is hence being modified and will continue – at least up to a certain point – in response to the ongoing air temperature increase. The availability of unconsolidated sediments downslope from rock glaciers might thus increase accordingly and in some cases influence the frequency-magnitude

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of torrential sediment transfer processes such as debris flows (e.g. Gobiet et al., 2014).

The occurrence of an efficient sedimentary connection between an active rock glacier and the torrential network system requires specific topographical conditions. Fig. 1 represents sketches of two slope configurations leading to differing sediment connectivity, i.e. differing probability for sediments to be transferred from a sediment source (here the rock glacier) to a downward target storage zone (torrential channels) in a given timeframe (e.g. Bracken et al., 2015). If the rock glacier terminus reposes on a gentle slope, sediment reworking simply creates a debris accumulation at the foot of the front where sediments have a very low probability to be mobilized further downslope and will most likely be overridden by the landform (type A on Fig. 1). Rock glaciers of type A represent thus sediment traps (Wahrhaftig and Cox, 1959; Barsch and Caine, 1984; Gärtner-Roer, 2012). Conversely, if the front of a rock glacier is located on top of a steep slope, sediments eroded from the latter can be transferred downward and are available for further mobilization, for instance by torrential sediment transfer processes (type B in Fig. 1). Although they appear to be less frequent than the type A (Kääb and Reichmuth, 2005), several rock glaciers corresponding to the configuration of type B (Fig. 1) have been observed in the Alps (e.g. Lugon and Stoffel, 2010; Delaloye et al., 2013; Kummert and Delaloye, 2015; Kummert et al., 2017; Krysiecki et al., in prep.). In catchments concerned by the latter type, quantitative data about the sediment fluxes between the rock glaciers and the downstream slopes and gullies is needed to estimate proper sediment budgets and debris flow scenarios (Oggier et al., 2016).

The sediment budget approach aims to provide quantitative estimations of sediment transfer rates (Dietrich and Dunne, 1978; Walling, 1983; Fryirs, 2013) by measuring the source to storage relationships within the sediment cascade (Caine, 1974). The recent emergence of remote sensing techniques (e.g. digital photogrammetry, terrestrial and airborne laser scanning) enabling the production of high resolution multi-temporal Digital Elevation Models (DEMs) has enhanced the spatial representativeness of sediment budget studies (e.g. Lane et al., 1994; Brasington et al., 2000) and allowed sediment budgets to be assessed for areas where terrestrial surveys are often not possible, i.e. steep mountain catchment areas (e.g. Bennett et al., 2012). In particular, DEMs of difference (DoDs), i.e. the result of the subtraction of two DEMs of the same area but from different dates (e.g. Williams, 2012), can be used to map and quantify surface elevation changes which very often relate to sediment transfer processes. Hence, DoDs have been successfully used to monitor sediment dynamics and mass wasting processes (e.g. Scheidl et al., 2008; Theule et al., 2012; Heckmann et al., 2012; Cavalli et al., 2017), including rock glacier dynamics (e.g. Abermann et al., 2010; Kenner et al., 2013). However, only few studies focus on changes at rock glacier fronts (Bauer et al., 2003, Avian et al., 2009, Bodin and Trombotto, 2015 for rock glaciers of type A, Micheletti et al., 2017 for type B) and none proposes sediment budgets between the front of active rock glaciers (sources) and torrential gullies (temporary or permanent storages).

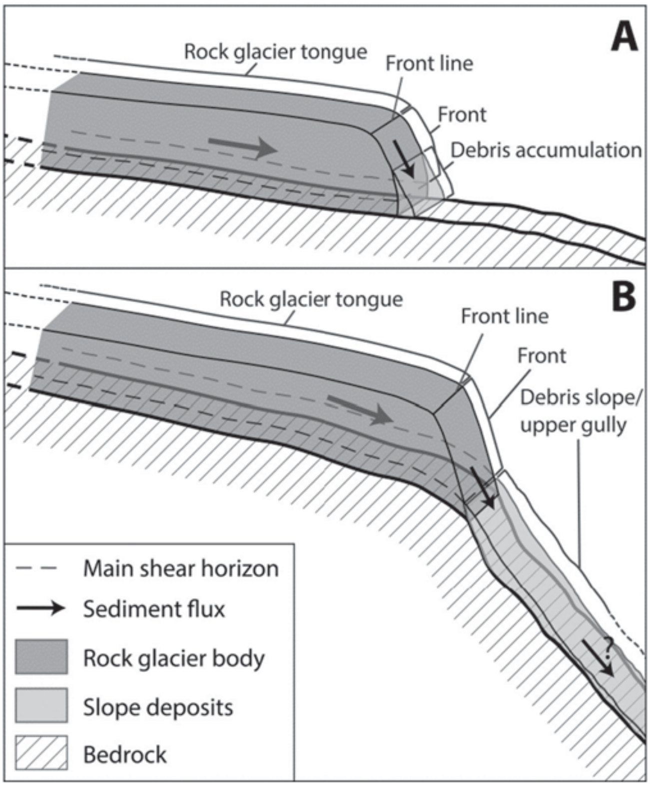

Fig. 1. Two types of connectivity between an active rock glacier and the downward slope. A – No connectivity: the sediments are stored at the foot of the front and will be overridden by the advancing rock glacier; B – efficient connectivity: the sediments are leaving the rock glacier system. In this study, the focus is set on rock glaciers of type B. The study area corresponds to the front and – at least – the upper part of the underlying debris slope/gully.
Modified after Kummert et al. (2017).

Our study aims to provide insights about the rates and the spatio-temporal behavior characterizing the sediment transfer between rapidly moving rock glaciers (of type B) and their respective downstream subjacent slopes and gullies. For that purpose, multi-temporal DEMs covering the frontal area of three rock glaciers located in the western Swiss Alps (Dirru, Gugla, and Tsarmine) were acquired between 2013 and 2016 (study period) using terrestrial laser scanning (TLS). The DoDs generated from the TLS multi-temporal DEMs allowed (i) to map the spatial patterns of erosion and accumulation at the rock glacier fronts and the upper part of the gullies and (ii) to calculate both sediment budgets and sediment transfer rates between these two spatial components (fronts and upper gullies).

2. Study sites and study object

The three studied rock glaciers Dirru, Gugla and Tsarmine are located in the southwestern Swiss Alps (Fig. 2). They all face west and their fronts lie on steep convex slopes dominating torrential gullies. In their respective torrential catchment, each rock glacier represents the most important sediment source for the main channel. The three sites were chosen because of their topographical setting and their high current flow rate which favors high sediment transfer activity and allows observations to be made in only 4 years. Some additional site-specific features can be found in Kummert et al. (2017). Ongoing rock glacier surface velocities have been regularly surveyed by differential Global Navigation Satellite System (dGNSS) since 2004 for Tsarmine (Delaloye et al., 2010; PERMOS, 2016) and 2007 for Dirru and Gugla (Delaloye et al., 2013), while the long-term evolution of their dynamic since the 1960s has been assessed by photogrammetric analysis (Delaloye et al., Unpublished; Fig. 3). The three rock glaciers have been characterized by displacement rates of several meters per year (m/y) between 2013 and 2016 (study period) and are therefore considered as rapidly moving. The photogrammetric analysis has shown that the position of each rock glacier front line, i.e. the erosion border of the rock glacier surface (Fig. 1), has not moved significantly since at least the mid-1990s while surface displacement rates have tended to increase, meaning that over at least two decades the advance of the rock glaciers must have been approximately balanced by the erosion of their fronts.

2.1. Dirru

The Dirru rock glacier (46.12° N, 7.81° E) is located on the west-facing side of the Mattertal valley (Fig. 2). The current active tongue measures

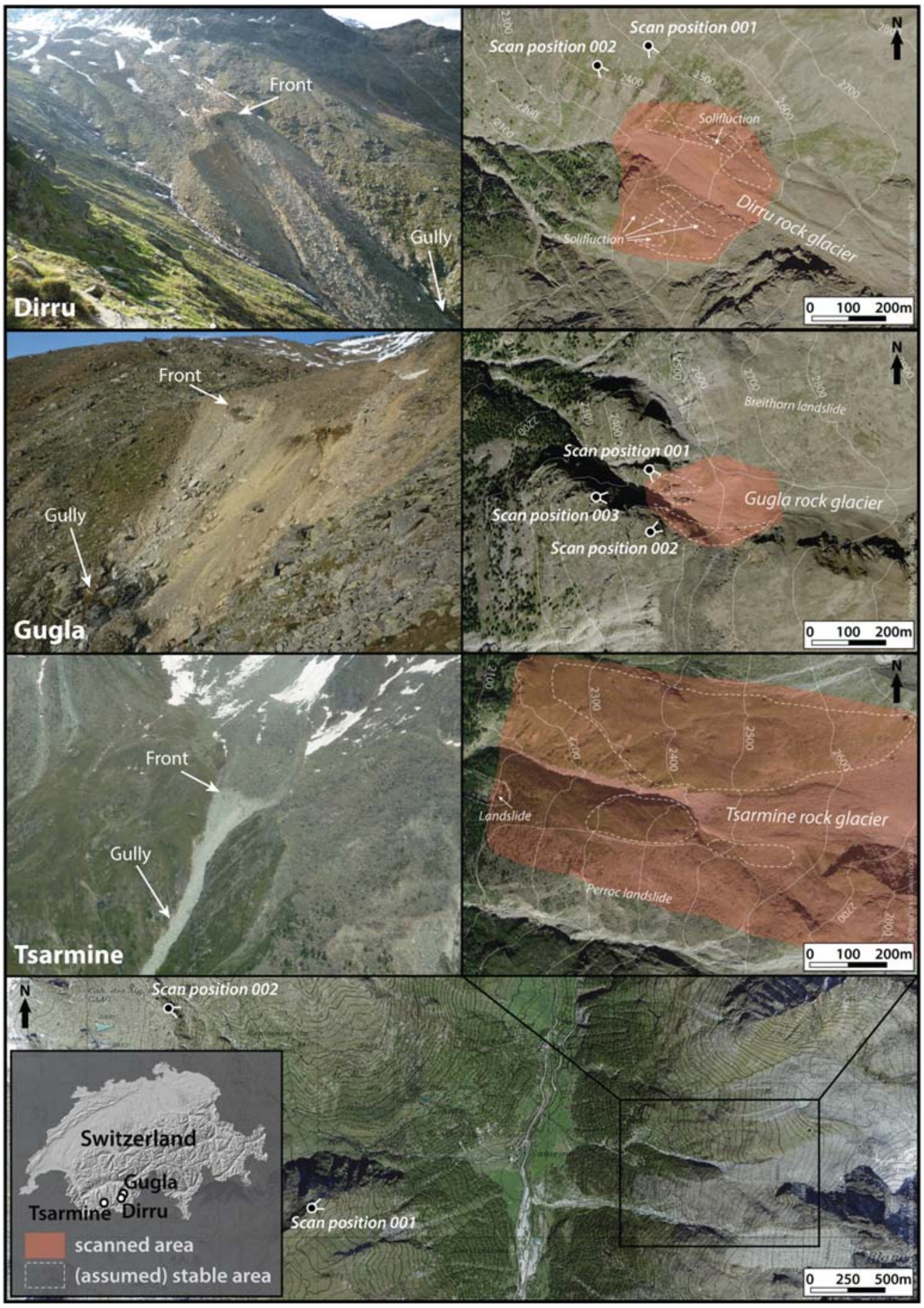

Fig. 2. Localization and illustration of the three study sites. Scanned surfaces are displayed in red. Areas outlined by the white dashed-lines correspond to the assumed stable sectors used for the registration and the accuracy assessment of the LiDAR scans (the delimitation of these stable sectors is further explained in the Data and methods). On the maps, the arrows and the thin dotted-lines indicate the presence of other moving landforms (landslides and solifluction zones).

about 1 km long and 50 m wide (on the lower half of the tongue). The front is located at about 2530 m a.s.l., 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 that the Dirru rock glacier is characterized by one main shear horizon situated approximately 15 m below the front line. In addition to geophysical investigations (Delaloye et al., Unpublished), the significant summer lowering rate of the surface of the tongue (about 10 cm/year) and the observation of permafrost outcrops occasionally visible at the front suggest a relatively high interstitial ice content beneath the permafrost table (at least 50% of the total volume). The terminal part of the rock glacier (last 350 m) has been moving rapidly since 1969 at least, with 2D (horizontal) velocities about 3.7–4.5 m/y at that time (Fig. 3). From 2007 to 2016, 2D surface velocities have been oscillating between 5 and 8 m/y (6 and 9 m/y in 3D) with a slight decreasing trend. Since the development of a deeply-incised erosion niche downslope from the front in the mid-1990s (Fig. 6), the position of the front line has not changed substantially (maximally a few meters of

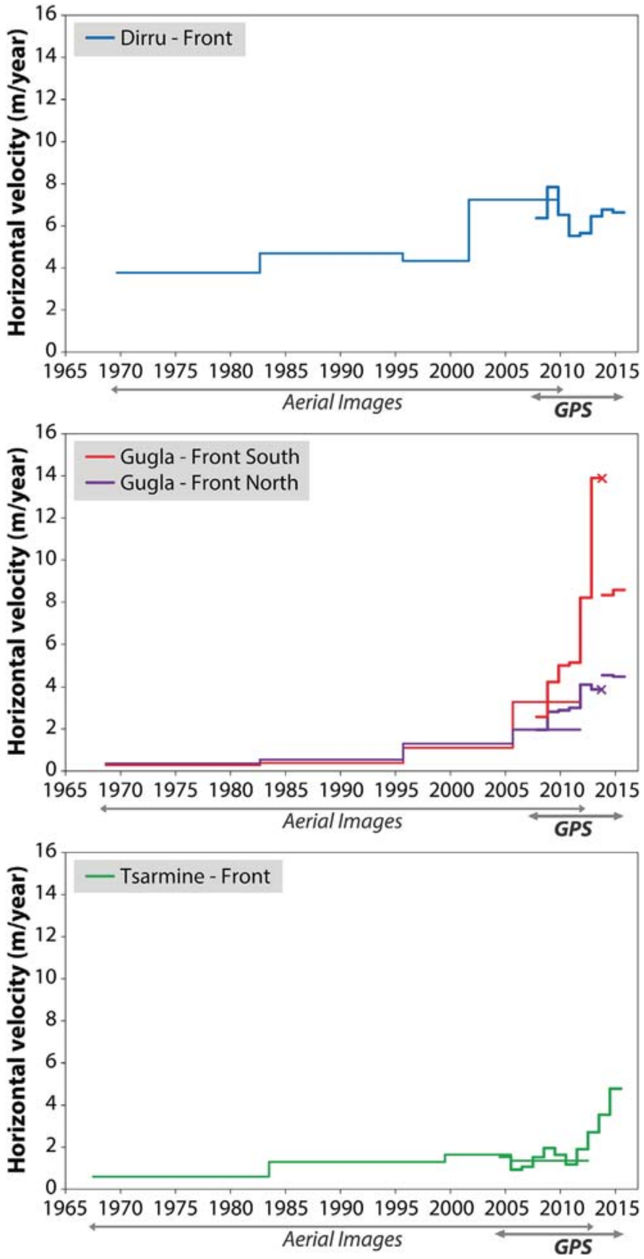

Fig. 3. Long-term evolution of the horizontal velocities in the terminal part of the three investigated rock glaciers. The thin lines represent the results from a photogrammetric analysis of old aerial images while the thick lines are values derived from geodetic surveys (average of several markers measured each year by dGNSS). The two sets of curves displayed for the Gugla rock glacier show respectively the velocities of the northern and the southern parts of the front. In addition, the two X indicate the fall of the marked boulders on both parts of the front, respectively.

fluctuation). Nowadays, the erosion niche is infilled by sediments and small debris flows reaching the Geisstriftbach torrent have been observed there in 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 from Dirru, on the same valley flank (Fig. 2). Gugla is a tongue-shaped rock glacier about 350 m long and 100 m wide. Its terminus, with a front line located at approximately 2620 m a.s.l., can be divided in two sectors with different morphologies and dynamics. The southern part of the front is steeper, thicker (20 to 30 m) and characterized by the occurrence of several distinct shear horizons (at least three could be identified on images in 2012 and 2013). The northern part of the front is less steep and has only one main shear horizon located about 15 m below the front line. Geophysical investigations (Delaloye et al., Unpublished), direct visual observation at the front and the absence of surface lowering during summer indicate that the ice content is relatively low (presumably less than 50% of the total volume). Surface horizontal velocities also differ between the two parts of the front, with averages of respectively 10 m/y for the southern front and 4 m/y for the northern one. The velocities have gradually increased during the past decades, especially since the mid-1990s. In the most rapid part of the terminal tongue, the horizontal surface velocities went from less than 0.5 m/y (period 1968–1982) up to approximately 1.5 m/y (period 1995–2005), and reached more than 15 m/y in 2013 (Fig. 3), with a strong destabilization phase starting in 2010. The whole frontal part of the rock glacier is directly flowing into the Bielzug torrential gully providing the torrent with rock debris. This sediment connectivity has apparently existed since at least 1930 as the position of the front line identified on old aerial images remained constant (except small local variations) over the last 85 years (Delaloye et al., Unpublished). Several significant debris flows (ranging from 500 to more than 5000 m^3 per event) reaching the valley bottom have been each year from 2012 to 2016 (Oggier et al., 2016).

2.3. Tsarmine

Tsarmine (46.04° N, 7.50° E) is a tongue-shaped rock glacier located in the Val d'Arolla (Fig. 2). It is about 450 m long and 100 m wide and its front line is located at about 2460 m a.s.l. The main shear horizon is situated approximately 15 m below the front line, as confirmed by the disrupted snow cover observed on webcam images in winter. No specific information about ice content is available but the absence of measured or observed summer surface lowering seems to indicate that very high ice content is probably to exclude. The Tsarmine rock glacier has encountered a gradual acceleration since 1967 which has intensified since the mid-1990s (Fig. 3). From 2011 to 2016, a continuous acceleration has been measured by geodetic surveys (Fig. 3), 2D velocities fluctuating in the frontal part from about 1 m/y in 2011 to more than 5 m/y in 2016. The rock glacier terminus is located on the top of a deep torrential gully where rock debris have accumulated since at least 1946 (oldest image available). Even though the torrential channel displays a substantial amount of accumulated sediments, the debris fan is rather flat and completely vegetated. Except for a small event occurring in the 1980s and triggered from an alternate sediment source (a small landslide, Fig. 2), no trace of debris flow reaching the valley bottom has been observed on the different aerial and oblique photographs dating back to 1946.

2.4. Sediment cascade

In their respective torrential systems, each of the studied rock glacier belong to a chain of processes which links high altitude sediment accumulations (e.g. talus slopes, moraines) to the main valleys. In order to understand the sediment transfer between the rock glaciers and the torrential gullies as well as the sediment budget of each zone individually, four main morphological units need to be described (Fig. 4). Starting upward, the first zone consists of the *rock glacier tongue* which is delimited downslope by the front line. The sediments constituting the rock glacier tongue (above the shear horizon) are continuously creeping towards the front. *The front* of the rock glacier is delimited upward by the front line and downward by the location of the main shear horizon. At the front, the sediment budget (ΔV_F) is mainly the result of sediment inputs from the moving rock glacier body (ΔV_{Fadv}) and outputs through erosion and transfer of sediments downward (ΔV_{Fre}; Eq. (1)). If the

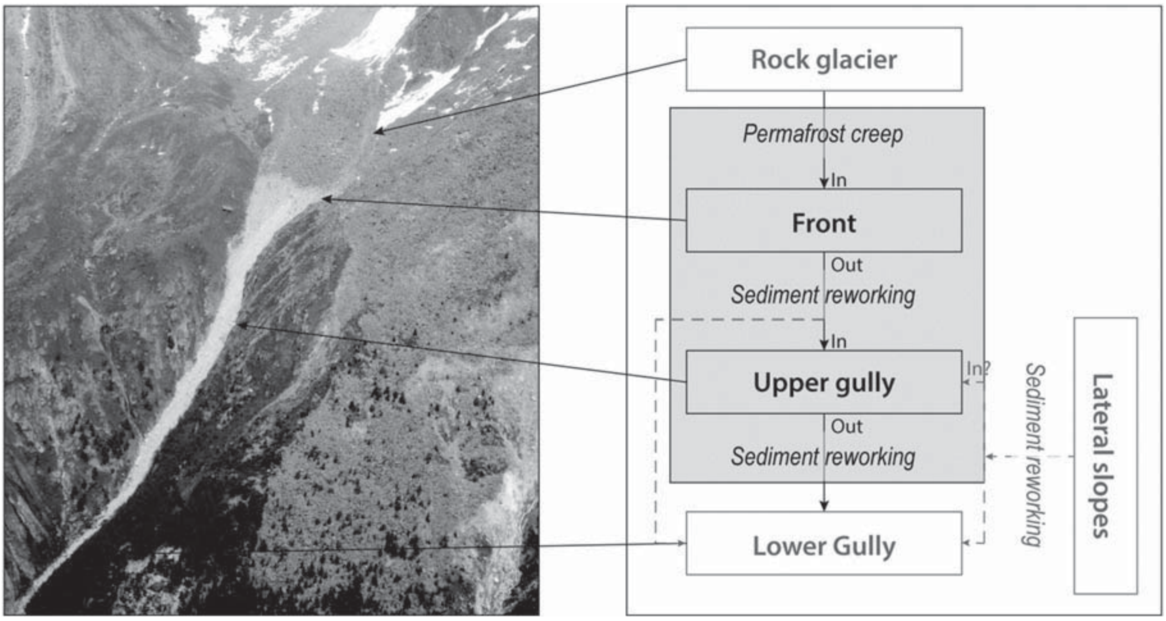

Fig. 4. Systemic sketch of the chain of processes and morphological units that intervenes in the sediment transfer activity between rock glacier fronts and torrential gullies (right), and their corresponding location in the example of the Tsarmine rock glacier (left, photo from July 7, 2013).

position of the front line remains constant in time, the sediment budget of the front should be close to zero.

$$\Delta V_F = \Delta V_{Fadv} - \Delta V_{Fre} \quad (1)$$

Following the sediment cascade, the next unit consists of what we call the *upper gully*, i.e. the part of the gully directly subjacent to the front and which is comprised in the TLS scans (Fig. 2). The area encompassed in the upper gully zone is thus limited downward by the scanning possibilities (see Data and methods). The word gully is used here as a generic term to designate the steep slopes developing downward from the fronts. At Gugla and Tsarmine it corresponds to actual morphological gullies but at Dirru it takes the form of a talus-slope-like depositional area. The sediment budget of the upper gully is mainly driven by sediment inputs from the erosion of the front (ΔV_{Fre}), and sediment outputs from the removal and the transport of sediments downward (ΔV_{UGre}; Eq. (2)). Sediment inputs from the erosion of lateral slopes (e.g. surface runoff, shallow landslides) may occur but are very likely negligible at our study sites (ΔV_{Lat}).

$$\Delta V_{UG} = \Delta V_{Fre} - \Delta V_{UGre} \ (+\Delta V_{Lat}) \quad (2)$$

The sediments leaving the upper gully are expected to accumulate within the *lower gully* or to transit through it. The lower gully corresponds to the portion of the gully located downward from the scanned area and which links the upper gully to the valley bottom and the alluvial fan. Note that sediments may sometimes be directly transferred from the rock glacier fronts towards the lower gully without being temporarily stored in the upper gully, for instance via long distance rock fall events or debris flows triggered on the front itself. The focus of the study is here set on the sediment transfer activity between the rock glacier fronts and the upper gullies, and therefore only the sediment transfer activity and the sediment budgets characterizing these two zones are investigated.

3. Data and methods

At each site, DoDs covering successive time intervals were produced to map surface elevation changes and calculate volumetric changes at the fronts and in the upper gullies. The DoDs were computed by comparing multi-temporal DEMs derived from TLS point clouds.

3.1. Data acquisition and processing

Basically, a TLS device calculates the distance of a targeted surface by measuring the time for the laser signal reflected by this surface to return to its source. The result is a dense point cloud which can then be interpolated into a rasterized DEM (of the investigated surface). By repeating the operation at different dates on the same targeted surface, time series of DEMs can be created. When possible, TLS campaigns were carried out twice a year between 2013 and 2016 at Gugla and Tsarmine, and between 2014 and 2016 at Dirru (details in Table 1). The aim was to get information about both the inter-annual and the seasonal variations of sediment transfer activity. The number of scanning campaign was limited to two per year both for logistic reasons and more importantly because scanning was only possible once the snow had completely disappeared from the investigated areas. Each year, the first scanning campaign usually took place end of June, while the second one was generally planned in October before the first snowfall. Some additional scans were also acquired occasionally to investigate shorter time periods (Table 1). Running at the lower range of the near infrared, a long-range Riegl VZ®-6000 terrestrial laser scanner was used here and allowed fast surveys (up to 222,000 measurements per second) to be performed at great distance from the target (several hundred meters, theoretically up to a maximum of 6000 m). Given the complexity and the steepness of the terrain, it was difficult to find good and accessible viewpoints on both the fronts of the rock glaciers and the underlying slopes and gullies. For each study site, 2 or 3 scan positions were used (Fig. 2) in order to increase the point clouds density and to make sure that the largest possible part of the area of interest has been covered (Fig. 2). Generally, the surface of the fronts could always be entirely included within the scans while the spatial coverage of the gullies was limited 200 to 400 m downslope. At Tsarmine, the use of the VZ®-6000 appeared to be particularly useful as the lack of good positions near the rock glacier forced us to scan from the other side of the valley (up to 4 km, Fig. 2 and Fig. 5).

The point clouds time series were registered relatively to each other using the RiSCAN PRO® software. The registration procedure applied in this study and described hereafter is similar to the one used by Fischer

Table 1
Dates, characteristics and registration errors of the different LiDAR scans acquired in this study. The difference of DEMs resolution between the three sites is mainly related to the varying distances between the scanning positions and the targeted surface.

Year	Dirru (6 scans) DEM resolution: 10 cm		Gugla (10 scans) DEM resolution: 5 cm		Tsarmine (7 scans) DEM resolution: 20 cm	
	Date scan (dd.mm.yyyy)	Registration error σ (m)	Date scan (dd.mm.yyyy)	Registration error σ (m)	Date scan (dd.mm.yyyy)	Registration error σ (m)
2013			25.06.2013	±0.035		
					09.07.2013	±0.140
			10.07.2013	±0.032		
					06.08.2013	±0.045
			04.10.2013	±0.019		
2014	26.06.2014	±0.025	26.06.2014	±0.034		
					23.09.2014	±0.068
	09.10.2014	±0.030	09.10.2014	±0.023		
2015			08.06.2015	±0.025		
					29.06.2015	±0.181
	30.06.2015	±0.024	30.06.2015	±0.024		
					22.09.2015	±0.197
	06.10.2015	±0.018	06.10.2015	±0.029		
2016	29.06.2016	±0.028	29.06.2016	±0.028		
					01.07.2016	±0.174
	04.10.2016	±0.027	04.10.2016	±0.022		
					07.10.2016	±0.168

et al. (2016). Clear outliers were first permanently deleted from the point clouds. Then for each site, one point cloud was selected and treated as already registered and all the other point clouds were shifted and adjusted on this reference following several steps. First, changing surfaces (e.g. the rock glaciers, the fronts, the gullies) were temporarily removed from the unregistered point clouds in order to keep only assumed stable areas for the registration (Fig. 2). In a second step, a manual coarse registration using visually identified matching points was applied to roughly shift the unregistered point clouds towards the reference one. It was then possible to apply a multi station adjustment (MSA) algorithm for semi-automatic registration based on iterative closest point (ICP) techniques to precisely adjust the point clouds to the reference position (e.g. Zhang, 1994, Kenner et al., 2011, Carrivick et al., 2013). The quality of the registration procedures can be assessed and quantified using the standard deviation of error from the point residuals which is provided by the RiSCAN PRO® software. The values range respectively from ±0.018 m to ±0.035 m for Dirru and Gugla, and between ±0.045 m and ±0.200 m for Tsarmine, where the greater distance of acquisition compared to the other sites caused lower point cloud densities (see details in Table 1). Finally, an octree filter (Perroy et al., 2010) was applied in order to combine point data from different scan positions, and to obtain new point clouds with a distributed numbers of points per area. The processed point clouds were interpolated in ArcMap 10.3 in order to obtain DEMs. The high point density and the regular point distribution over the area of interest justified the use of a simple natural neighborhood algorithm for the interpolation (Scheidl et al., 2008). The respective resolutions of the TLS-derived DEM products are given in Table 1 and an example of DEM is shown for each site in Fig. 6. The created multi-temporal DEMs were then subtracted from each other to obtain DoDs for all the time intervals available, depending on the sites (Table 1 for the dates of the available DEMs). In the resulting DoDs, each cell is characterized by a value of surface elevation change between the two dates (t1 and t2). Simply multiplying the sum of surface elevation change over a chosen area ($\sum_{\Delta z}$) by the surface of one raster cell (d^2) (see for example Heckmann et al., 2012) allows volumetric budgets, i.e. volumes of surface elevation changes in given areas, to be calculated (Eq. (3))

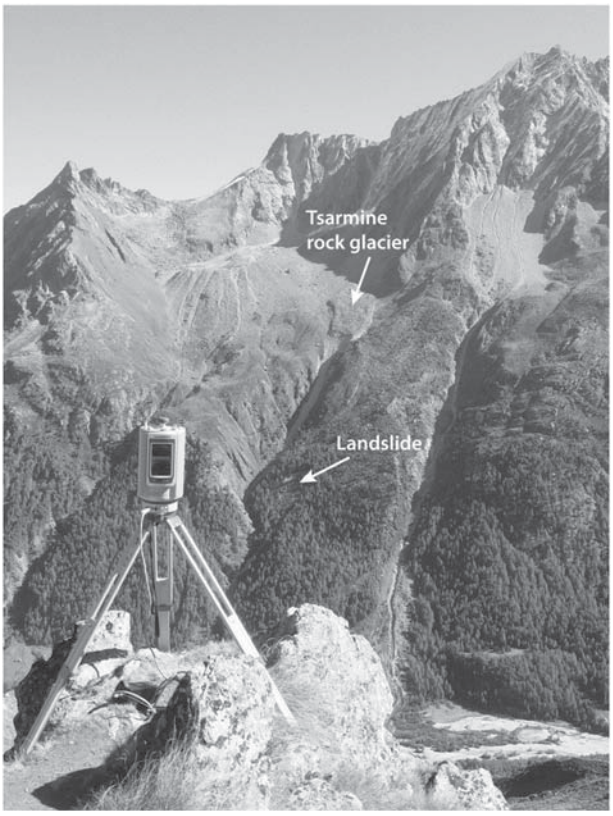

Fig. 5. TLS measurement with the Riegl VZ®-6000 at Tsarmine on October 7, 2016. The scan position (position 001 on Fig. 2) is located at an approximate distance of 3 km from the rock glacier.

$$\Delta V = d^2 * \sum\nolimits_{\Delta z} \qquad (3)$$

3.2. DoDs to infer sediment transfer dynamic

Both at the fronts and in the upper gullies, the values of surface changes are mainly related to actual sediment transport processes (sediment reworking and ground motion; Fig. 7). The DoDs created for different time intervals can therefore be visually analyzed as maps of sediment transfer (see Results), and the volumetric budgets calculated for both zones respectively (ΔV_F and ΔV_{UG}) can be interpreted as sediment budgets. The limits of each zone were drawn manually on the DEMs based on the visual interpretation of the DoDs and of aerial

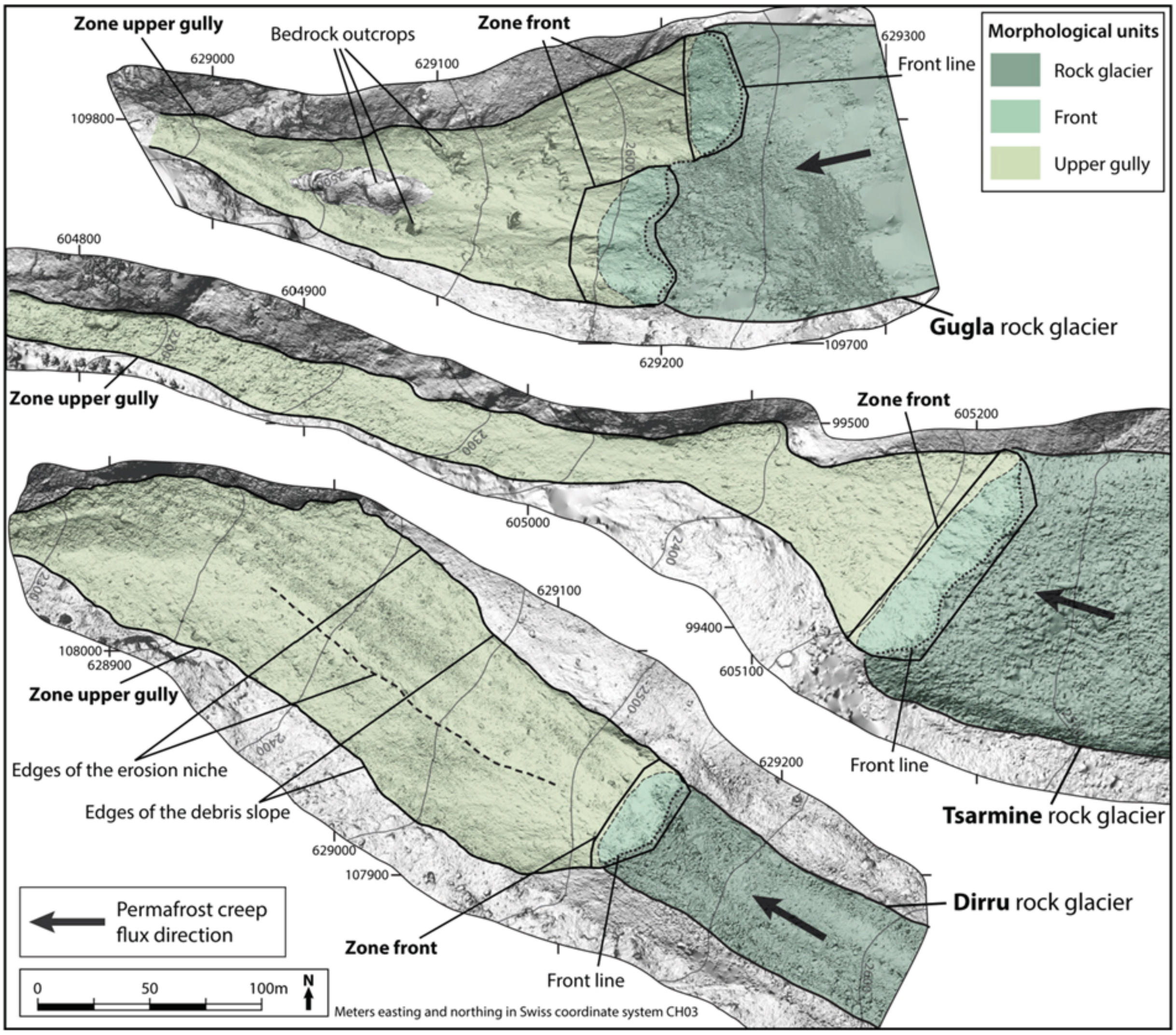

Fig. 6. Example of TLS-derived DEMs produced at Gugla (October 4, 2016), Tsarmine (October 7, 2016) and Dirru (October 4, 2016). At Gugla, the large smoothed surfaces visible on the rock glacier back are due to the uncomplete coverage of this area by the scans. The different morphological units (rock glacier tongue, front and upper gully) are differentiated by their colors while the limits of the fronts and the upper gullies as used for the sediment budget calculations are drawn in black.

images. Due to the rock glacier advance, the extent of the frontal areas varies over time making it difficult to delimitate. A fixed front zone has therefore been defined for each site, taking voluntarily a slightly larger area than the supposed "real" front in order to be sure to encompass all of it and any of its variation over time (see difference between the "zone front" and the "front" as a morphological unit in Fig. 6).

Calculating volumetric budgets allows assessing the sediment transfer dynamic of each zone separately. In order to quantify the sediment transfer activity between the fronts and the gullies, the volumetric changes due to sediment reworking (ΔV_{Fre}) needs to be isolated from the overall sediment budget of the fronts (ΔV_F). For that purpose, the mean surface elevation change resulting only from the rock glaciers movement ((3) in Fig. 7) was estimated at each site and for each time interval based on three main parameters (Fig. 8): the mean horizontal displacement (dxy), the mean vertical displacement (dz) and the fronts mean slope angle (α).

3.2.1. The mean horizontal (dxy) and vertical (dz) displacements of the rock glaciers

The mean horizontal (dxy) and vertical (dz) displacements of the rock glaciers were derived here from the mean 3D surface displacements measured at the front of each rock glacier using different techniques. At Dirru and Tsarmine, the terminal parts of the rock glacier tongues are included in the scans. It was possible to identify boulders (four at each site) located close to the front line in the TLS-derived DEMs and to track them with GIS techniques to infer their displacement. The mean surface 3D displacement was then obtained for each time interval by taking the average of displacement values calculated for the four identified boulders. At Gugla, the surface of the tongue is not sufficiently covered by the scans and it was not possible to track moving features on the DEMs. However, we used here a network of dGNSS points measured in the field at least twice a year and covering the whole rock glacier providing values of displacement for several boulders located near the front line (between 5 and 7) for dates coinciding approximately with our scanning campaigns (maximally a few days of difference). Given the strong differences in velocity observed between the southern part and the northern part of the Gugla rock glacier front, a value of 3D displacement was obtained respectively for each part of the frontal area and for each time interval by calculating the mean of the displacement values measured at the point locations. In order to take into account the velocity decrease at depth, the measured mean 3D surface displacement values were reduced by 25% at each site, which corresponds to a 50% linear reduction of the velocity from the surface down to the main shear horizon. The obtained values for the mean 3D displacement (dxyz) were also decomposed into mean

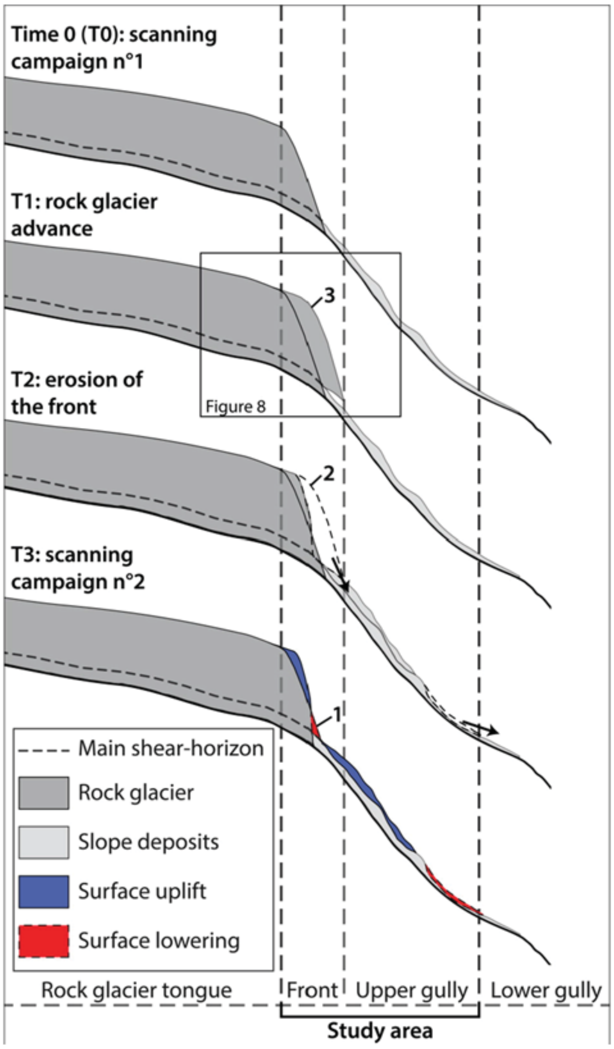

Fig. 7. Conceptual example of sediment transfer activity occurring between two scanning campaigns (T0 and T3). Interestingly, this example shows that surface lowering, i.e. erosion, is often underestimated in the overall budget of the front (1). To know the amount of sediment eroded from the front and transferred to the gully (2), it is thus necessary to estimate the approximate volume of sediments previously brought forward by the rock glacier motion (3).

horizontal (dxy) and vertical (dz) displacements, which were calculated for each site and for each time interval.

3.2.2. The mean slope angle (α) of the frontal areas

The mean slope angle of the front was obtained for each site and for each time interval by simple GIS spatial analysis of the TLS derived DEMs.

By combining these three parameters, a *mean surface elevation change* strictly due to the calculated advance of the rock glacier (ΔH) can be inferred using Eq. (4) (Fig. 8):

$$\Delta H = (\tan\alpha * dxy) - dz \quad (4)$$

By multiplying this value by the area of the front (obtained by multiplying the number of cells encompassed within the area ($\sum_c$) by the surface of one cell (d^2)), it is possible to estimate the mean volume change due to the advance of the rock glaciers (ΔV_{Fadv}).

$$\Delta V_{Fadv} = d^2 * \sum_c * \Delta H \quad (5)$$

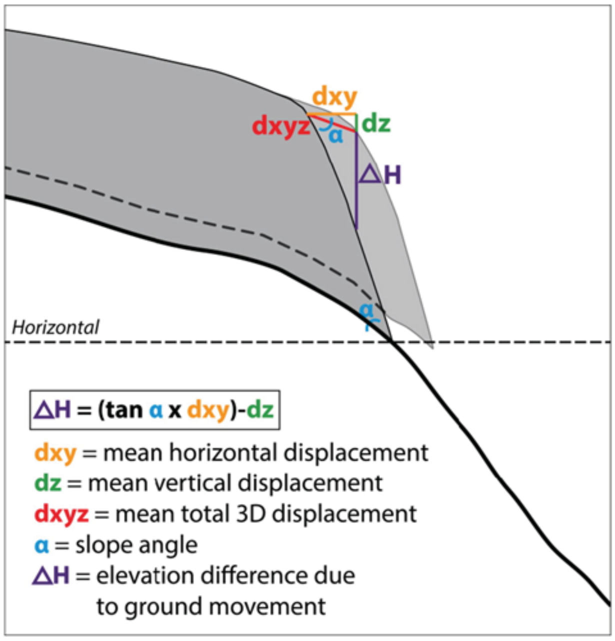

Fig. 8. Eq. (4) (in text) used to estimate the surface elevation change in the frontal area induced by the rock glacier advance.

ΔV_{Fre}, i.e. the volume of sediment eroded from the front, can then be obtained by subtracting the result of Eq. (5) (volume of advance of the rock glacier front) from Eq. (3) (general volumetric budget), as in Eq. (6):

$$\Delta V_{Fre} = \Delta V_F - \Delta V_{Fadv} = \left(d^2 * \sum_{\Delta z}\right) - \left(d^2 * \sum_c * \Delta H\right) = d^2 * \left(\sum_{\Delta z} - \left(\sum_c * \Delta H\right)\right) \quad (6)$$

Sediment budgets could thus be obtained respectively at the fronts and in the upper gullies (ΔV_F and ΔV_{UG}). In addition, erosion volumes and erosion rates at the front of each site respectively for every time interval (E_S) and for annual periods (autumn to autumn, E_A) were calculated. The results along with the main parameters used in the volume calculations are described in the Results section of this paper.

3.3. Data uncertainty

Uncertainties can issue from errors in the surface elevation changes data or from the interpretation of the calculated volumetric budgets as sediment budgets. If the latter could not be quantified and are further considered in the discussion part of this paper, uncertainties concerning the values of surface elevation changes were assessed here. First, errors can result from the data acquisition by the device itself. A simplified estimate of such error is usually directly provided by the manufacturer. For the RIEGL VZ-6000 used in this study, the ranging accuracy and precision are respectively about ±0.015 m and ±0.010 m (RIEGL Laser Measurement Systems, 2013). In addition, uncertainties can be induced by the data processing. Errors in the point cloud registration (see Table 1) are often used as an approximate of the errors of the DEMs (Micheletti et al., 2015). However, data filtering (i.e. the application of the octree filter) and interpolation also generates some errors (Fischer et al., 2016). To better represent all the processing errors, we assessed here the uncertainties directly from the created DoDs. For each site and for each time interval, supposed stable areas were selected from the DoDs (Fig. 2). The choice of the stable areas was difficult due to the presence of many other slope movements such as rockslides or solifluction lobes in the direct vicinity of the investigated rock glaciers (Figs. 2 and 5). The surfaces affected by slope instabilities were identified and delimited with the help of different data sources available, as for instance an inventory of slope movement based on SAR (Synthetic Aperture Radar) interferometry (see Delaloye et al., 2007a, 2007b; Barboux et al., 2014), dGNSS monitoring networks in the investigated areas which often encompass some non-moving control points in stable zones, and the visual interpretation of the terrain through aerial images and hillshaded DEMs. Along with the zones affected by slope instabilities, densely vegetated areas (bushes and forests) were excluded from the assumed stable areas. Statistics concerning elevation changes for the stable areas are given in Table 2. As expected for unchanged terrain, the mean (μ) elevation change is most of the time very close to zero and remain in a cm-range for Dirru and Gugla, and in a 3 cm-range for Tsarmine. The standard deviation (σ) of elevation changes over stable terrains gives an approximation of the error over the whole DoD for a confidence limit of 68% (Lane et al., 2003). To enhance the confidence in our elevation changes measurements, we multiplied these standard deviation values by a factor of 2 which statistically corresponds to a confidence limit of 95% (Brasington et al., 2003; Lane et al., 2003; Wheaton et al., 2010; Heckmann et al., 2012) and used them as a minimum Limit of Detection (LoD) to threshold the individual DoDs. By this mean, all changes inside this confidence interval (±2σ) are set to zero and are therefore not reflected in the volume calculations and in the interpretation of the results. In addition, an approximation of the maximal error that may affect the volumetric budgets can be calculated by multiplying the mean surface elevation change over the stable area (μ) respectively by the surface of the fronts (S_F) and the upper gullies (S_{UG}). The obtained values are statistically unlikely to be true but give a maximal range for the volumetric error (Table 2). They are typically larger for the gullies than for the fronts and are on average higher at Tsarmine due to the coarser resolution of the created DEMs. The values of maximal error range from almost 0 to more than 400 m^3 and vary strongly between time intervals.

4. Results

As DoDs could be interpreted in two different ways, the results are divided into two parts. First, the spatial patterns of surface elevation changes are presented qualitatively and in a second part the results from the quantitative analysis (sediment budgets) are given. In addition, as relatively strong differences characterize the three studied rock glaciers, the results are described separately for each site.

4.1. Spatial characteristics of surface elevation changes

At each site the spatial distribution of surface elevation changes affecting the fronts was very heterogeneous and variable throughout the study period, reflecting the irregular nature of erosion in this sector. The zones of preferential erosion or aggradation observed at the fronts were thus less pronounced than in the upper gullies where relatively clear and consistent patterns emerged on the DoDs (Fig. 9). At Dirru, sediment aggradation was largely dominant on the debris slope subjacent to the front. Only small amounts of sediments were occasionally remobilized from the slope and transferred towards the lower gully. At Gugla, the patterns of surface changes were more variable in the upper gully. Strong sediment aggradation was recorded during some time intervals while sometimes substantial sediment reworking and removal was observed. Finally at Tsarmine, only sediment aggradation was recorded in the upper gully.

At Dirru, a preferential erosion area was strongly detectable in the central sector of the front during summer time intervals while it was less localized in time intervals covering the rest of the year (Fig. 9). On the debris slope underneath the front, accumulation predominated over the study period and showed a certain tendency towards the dispersion of the sediments on the slope. This accumulation-dominant behavior was particularly important in the former erosion niche (Fig. 6), while outside this niche, only some small sectors experienced a bit of accumulation, mostly near the front (Fig. 9). The accumulation areas on the debris slope were usually more important over winter time intervals (October to June). Erosion was detected downslope from the front but it mostly represented very limited areas and corresponded to low incision. Between October 2015 and June 2016 (Fig. 10), an increased remobilization of sediments occurred on the upper part of the debris slope causing an aggradation zone on the lower part of the slope.

The front of the Gugla rock glacier was mainly affected by erosion, especially in its southern part (Fig. 9). On the northern part of the front, one main erosion area was observed. Below the front, a sector ranging between approximatively 2600 m and 2540 m a.s.l. was commonly characterized by low sediment transfer activity. Depending on the time interval, some small erosion and accumulation zones appeared but involved apparently small volumes of sediments. Below 2540 m, substantial changes, i.e. either strong surface lowering or strong uplift

Table 2
Time intervals covered by the DoDs at each site and statistics computed over supposed stable areas: mean value (μ), standard deviation (σ) and the derived Limit of Detection (LoD). E_{Fmax} and E_{UGmax} represent respectively the maximum volumetric error calculated for the fronts and the gully by multiplying the mean elevation change (μ) with the surface of each zone (S_F and S_{UG}).

Site	Time interval (dd.mm.yyyy)	Statistics stable terrains (m)			S_F (ha)		S_{UG} (ha)	E_{Fmax} (m^3)		E_{UGmax} (m^3)
		μ	σ	$LoD = t\sigma\ (t = 2)$						
Dirru	26.06.2014-09.10.2014	-0.007	0.104	0.207	0,11		2,26	±8		±162
	09.10.2014-30.06.2015	0.010	0.092	0.185				±12		±232
	30.06.2015-06.10.2015	-0.004	0.082	0.165				±5		±91
	06.10.2015-29.06.2016	-0.005	0.085	0.169				±5		±104
	29.06.2016-04.10.2016	0.000	0.094	0.187				±0		±8
					North	*South*		*N*	*S*	
Gugla	25.06.2013-10.07.2013	-0.001	0.135	0.270	0,13	0,26	1,02	±1	±2	±7
	10.07.2013-04.10.2013	0.002	0.140	0.280				±4	±7	±29
	04.10.2013-26.06.2014	-0.003	0.196	0.392				±18	±36	±141
	26.06.2014-09.10.2014	-0.014	0.188	0.376				±5	±11	±43
	09.10.2014-08.06.2015	-0.002	0.153	0.306				±4	±8	±30
	08.06.2015-30.06.2015	-0.012	0.137	0.274				±1	±1	±4
	30.06.2015-06.10.2015	0.003	0.095	0.190				±20	±40	±160
	06.10.2015-29.06.2016	0.000	0.123	0.246				±1	±2	±7
	29.06.2016-04.10.2016	-0.016	0.115	0.229				±4	±7	±29
Tsarmine	09.07.2013-06.08.2013	-0.029	0.157	0.302	0,30		1,24	±28		±119
	06.08.2013-23.09.2014	0.019	0.170	0.341				±95		±401
	23.09.2014-29.06.2015	0.032	0.177	0.366				±74		±309
	29.06.2015-22.09.2015	-0.025	0.174	0.352				±32		±136
	22.09.2015-01.07.2016	0.011	0.141	0.283				±28		±419
	01.07.2016-07.10.2016	0.034	0.141	0.286				±95		±119

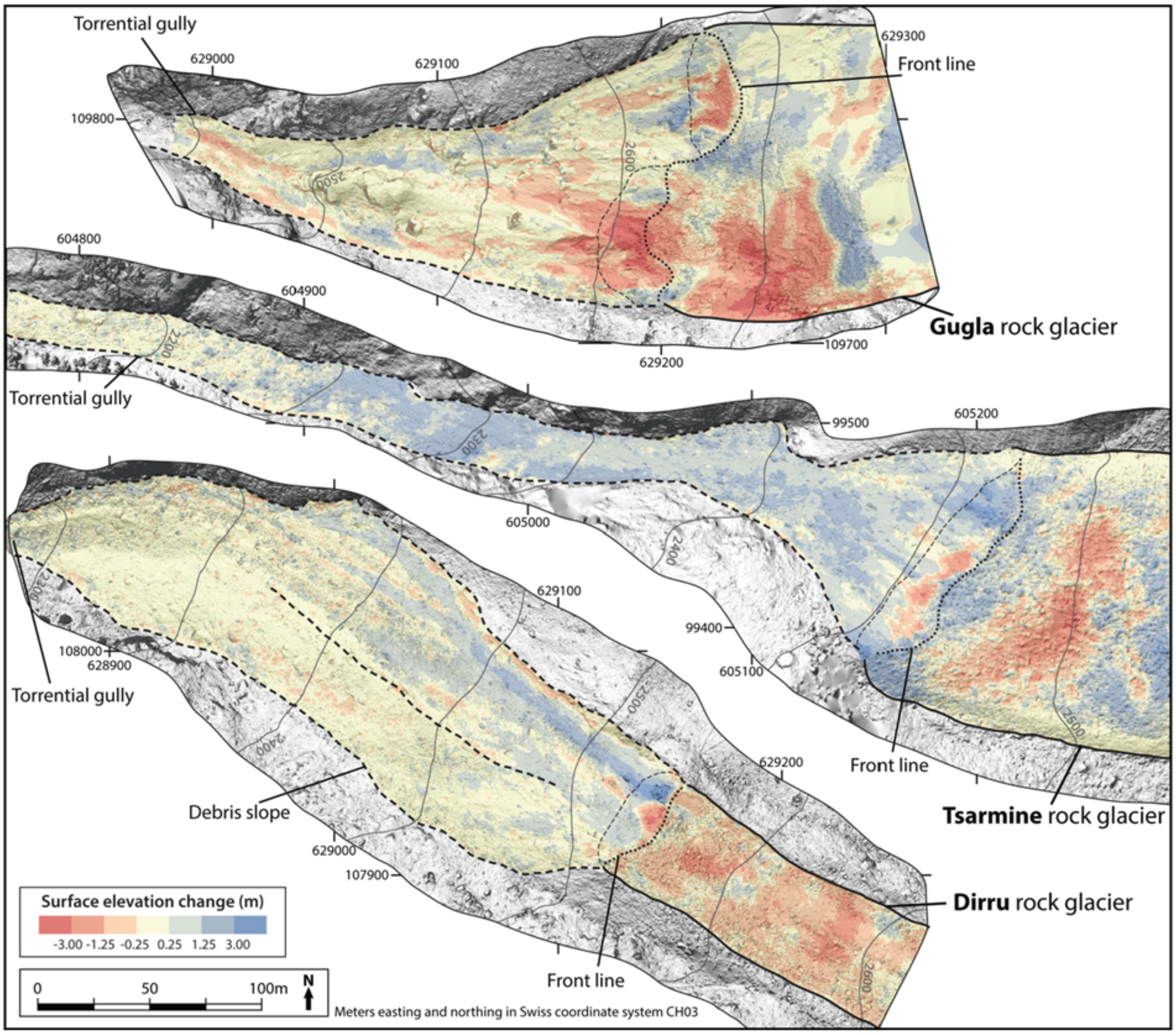

Fig. 9. Surface elevation changes recorded between the beginning of the measurements and the date of the last scan at Gugla (June 2013 to October 2016), Tsarmine (July 2013 to October 2016) and Dirru (June 2014 to October 2016).

(or both), often characterized a y-shaped sector separated in the middle by the main bedrock outcrop (Fig. 6). For instance, during the summer 2013 (between June and October), an important accumulation of rock debris was recorded (Fig. 11). Conversely, mostly erosion was observed in this sector during the summer 2014 (June to October) in relation to the occurrence of several debris flows events in July 2014 (Fig. 11). The strong variations in sediment transfer dynamics characterizing the upper gully underlined the fact that sediments were apparently frequently transported towards the lower gully during the study period.

At Tsarmine, the situation in terms of sediment fluxes and accumulation/erosion patterns was quite simple during the study period. Fig. 9 shows the cumulative surface changes between 2013 and 2016. Most of the maps produced for other time intervals exhibit the same patterns, even though often less pronounced because of the shorter time spans covered. An erosion zone was observed at the front, and more specifically on the southern side of the front. This zone was usually larger with more pronounced erosion on time interval covering summer periods than winter periods. On longer time intervals (covering one or several years as in Fig. 9 for instance), surface lowering was often well present in this area. In other sectors of the front, increase in elevation change was dominant. In the upper gully, only very little erosion was measured, and only in some of the different time intervals. An important accumulation area was observed in the upper gully, between approximately 2450 and 2250 m a.s.l. (see Fig. 9). This accumulation area extended gradually downslope during the study period. At lower altitudes (less than 2250 m), no erosion occurred and only very little accumulation was recorded. This accumulation corresponded mainly to very small and localized areas.

4.2. Sediment budgets

In general the orders of magnitude of the sediment transfer rates differ between the sites. Higher sediment erosion rates have been calculated at the front of the Gugla rock glacier in comparison to the two other sites (Fig. 12). In addition, the temporal variations of the erosion rate are different at each site.

Since 2014, the annual transfer rate (E_A) calculated between the front of the Dirru rock glacier and the underlying debris slope was about 1500 m^3/year (Table 3, Fig. 12). The volumes transferred were relatively constant over time even if a small decreasing trend seemed to characterize the study period (Fig. 12). Specific erosion rates (E_S) were also quite constant in time, even if slightly higher values characterized time intervals covering the period between July and September. For each time interval, the sediment budget of the upper gully is positive, indicating an accumulation-dominant behavior on the debris slope. Since June 2014, about 3500 m^3 of sediments have been stored in the upper gully (cumulative budget of the gully area).

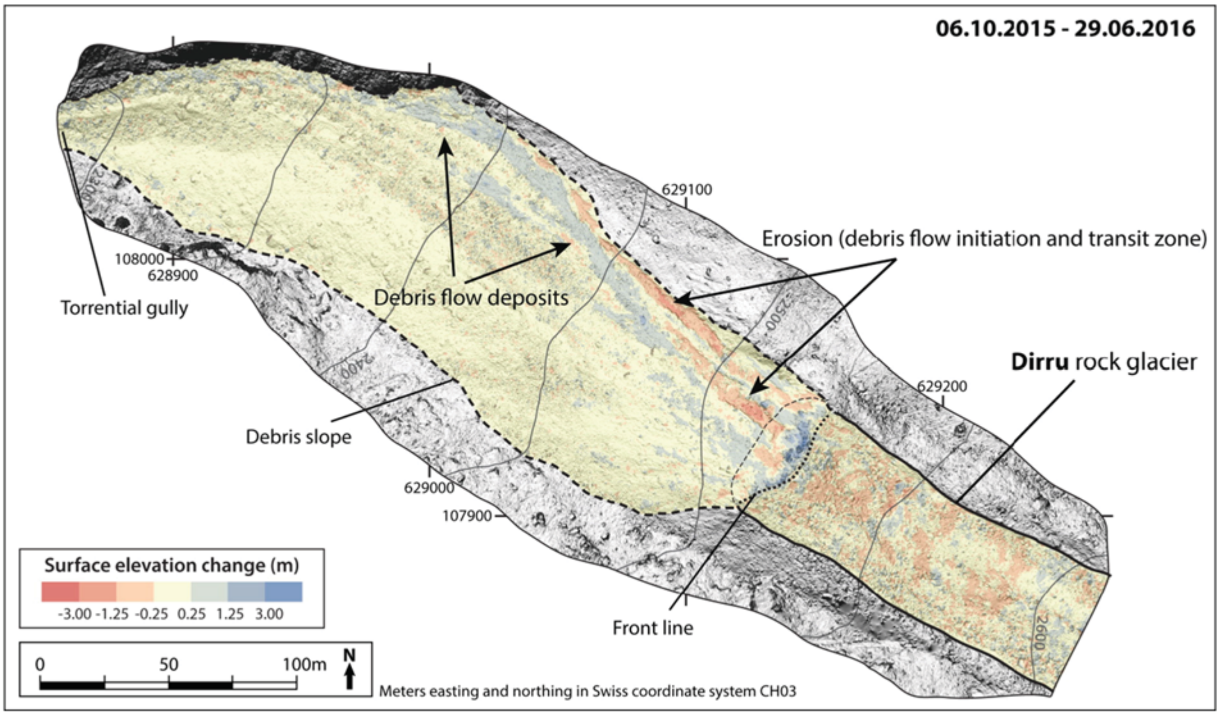

Fig. 10. Surface elevation changes (DoD) at Dirru for a period spanning from October 6, 2015 to June 29, 2016. The erosion and accumulation patterns on the debris slope (arrows) are evidences of a small debris flow which occurred on June 22, 2016.

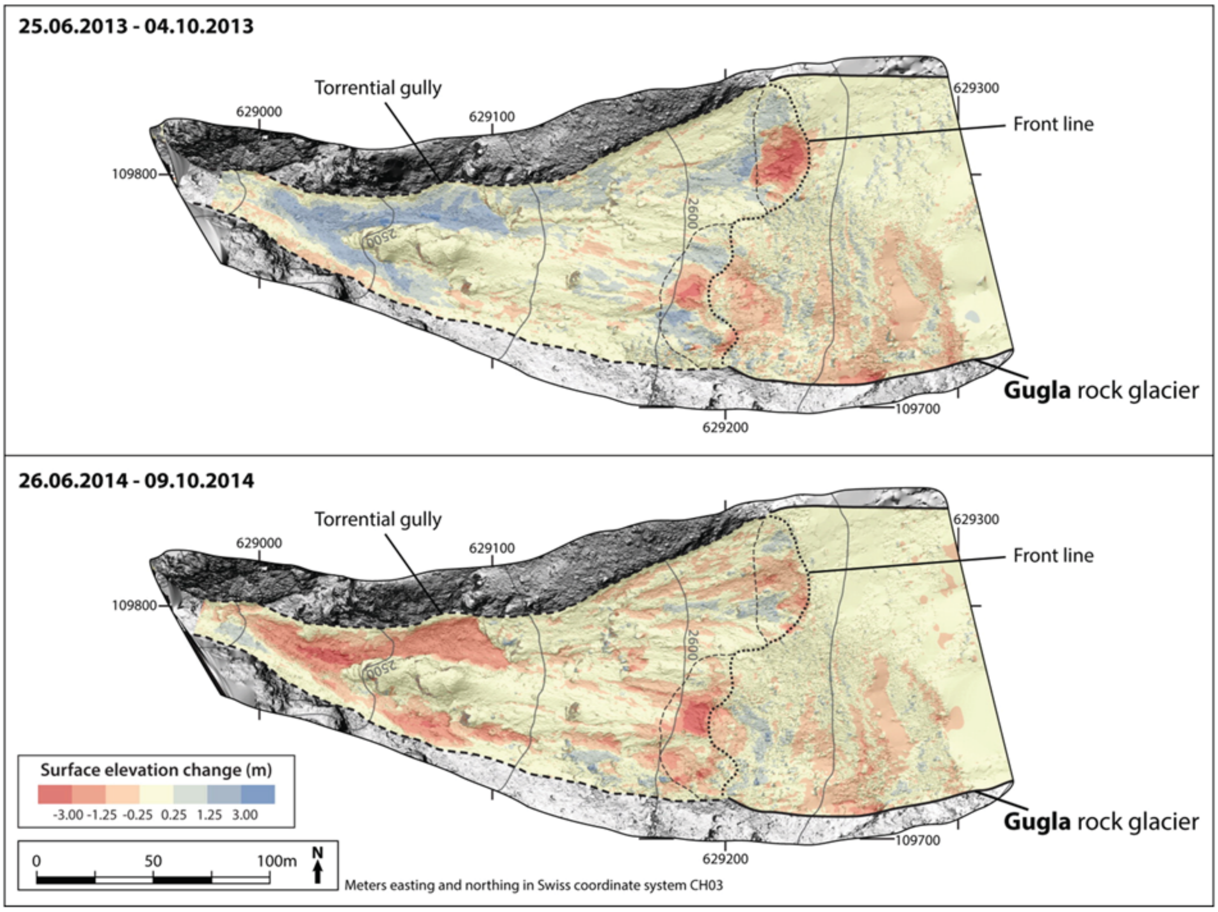

Fig. 11. Surface elevation changes recorded at Gugla for the summer 2013 (up) and 2014 (down) (specific dates in top left corners). A dominance of accumulation can be observed in the channel in 2013 (blue), while in 2014, the same area is characterized mainly by erosion (red).

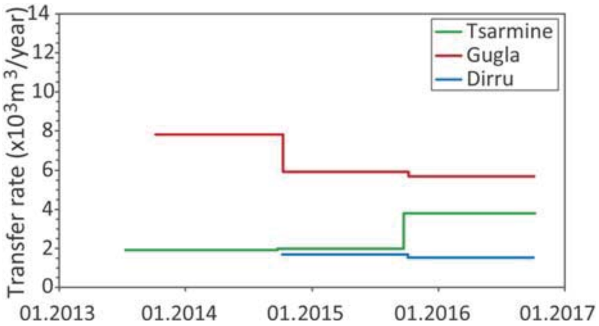

Fig. 12. Evolution of the annual sediment transfer rate between the fronts of the three studied rock glaciers and the respective connected debris slopes. The rates are calculated for yearly periods, from October to October.

At Gugla, values of annual sediment transfer rate between the front and the gully ranged roughly between 7800 m^3/year and 5600 m^3/year (Table 3), with a decreasing trend since 2013 (Fig. 12). The specific erosion rate at the front (E_S) was relatively variable in time, with generally higher erosion rates calculated between June and October. Two DoDs obtained for shorter time periods and covering the very beginning of the summer (June/July) were characterized by specific erosion rates of respectively 16,500 m^3/y (25.06.2013 to 10.07.2013) and 24,000 m^3/y (08.06.2015 to 30.06.2015) which correspond to the highest rates calculated. The sediment budget calculated in the gully showed also a strong variability, with periods characterized by a negative budget and periods of positive budget, measured for time intervals covering either summer or the period spanning from October to June. The volume of sediment stored in the upper gully fluctuated through the study period due to the recurrence of debris flow events and in October 2016, the level of aggradation was very similar to the one measured by the end of June 2013 (a few hundred cubic meters of difference).

At Tsarmine, the measured annual transfer rates at the front ranged between 1900 and 3800 m^3/year (Table 3). This range depicts important variations in the sediment transfer dynamic between the front and the gully during the study period. The erosion rate has been increasing since the start of the measurements in 2013 to reach a maximum in 2016 (Fig. 12). The specific erosion rate (E_S) at the front was also quite variable between the different time intervals and was systematically higher during summer periods. The cumulative budget for the whole study period (2013–2016) showed a constant increase of the volume of sediment stored in the upper gully. About 11,000 m^3 accumulated between July 2013 and October 2016.

4.3. Spatio-temporal variations

At all the sites, the calculated specific erosion rates of the fronts were higher during the interval spanning from July to October. On the DoDs, more significant erosion zones were observed at the fronts for the summer periods as well. However, an important part of the winter time intervals is characterized by the snow-covered period. It corresponds to a long time period in which erosion only occurs during short phases, i.e. before the ground freezing and after the snowmelt started (Kummert et al., 2017). The erosion rates calculated for these time intervals are therefore reflecting the mean activity over the whole period and are not representative of the real erosion activity which can occur shortly before and after the winter ground freezing. At Gugla, two time intervals cover short time periods at the very beginning of the summer (respectively from the 25th of June to the 10th of July 2013, and from the 08th to the 30th of June 2015, Table 1). The values of specific erosion rates for these two intervals are the highest measured and suggest that erosion was higher in the early summer, shortly after the snowmelt occurred on the whole catchment area. The erosion rate may be even more important during intense snowmelt phases in the catchment area upslope from the rock glaciers, as it has been observed for instance at Gugla between the 10th and the 26th of June 2013 when up to 10,000 m^3 were eroded from the front and the upper gully (see video at http://www.youtube.com/watch?v=0k8OYEvHD_Y). At Dirru and Tsarmine, the fronts are usually depicting gain in surface elevation over winter time intervals. This also reflects the fact that when the scans are performed in the beginning of the summer (June or July), the part of the front which advanced during the winter was not yet completely eroded. This accumulation is therefore mainly due to the advance of the rock glaciers.

The observed patterns of erosion and accumulation show the presence of a sediment storage zone in the upper gully at each study site. This is confirmed by the sediment budget calculated for the gullies. However, in each site this storage area appears to behave differently. Fig. 13 shows the evolution of the amount of sediment stored in the upper gully for the three sites in comparison with the original state, which corresponds to the first LiDAR scan. At Tsarmine, the accumulation was gradual in time. No mobilization of sediments from this storage zone was measured or observed in the DoDs. In this case, the erosion

Table 3
Main results obtained from the volume calculations using LiDAR DEMs differencing for each successive time interval.

Site	Time interval (dd.mm.yyyy)	Days (n)	Front										Gully	
			ΔV_F (m^3)	dxyz (m)		α (deg)		ΔV_{Fadv} (m^3)	ΔV_{Fre} (m^3)	Cumulative budget (m^3)	E_S (m^3/year)	E_A (m^3/year)	ΔV_{UG} (m^3)	Cumulative budget (m^3)
Dirru	26.06.2014–09.10.2014	105	−206	1.77		43.2		631	−837	−837	−2909		515	515
	09.10.2014–30.06.2015	264	399	3.76		43		1388	−990	−1827	−1368		1390	1905
	30.06.2015–06.10.2015	98	−18	1.56		43.3		633	−652	−2479	−2428	−1656	457	2362
	06.10.2015–29.06.2016	267	280	3.15		45.1		1291	−1011	−3490	−1382		803	3165
	29.06.2016–04.10.2016	97	82	1.32		43.2		561	−479	−3969	−1803	−1494	259	3424
Gugla				N	S	N	S							
	25.06.2013–04.10.2013	101	−1367	1.10	4.00	45.3	43.7	1620	−2988	−2988	−10,797		2863	2863
	04.10.2013–26.06.2014	265	−671	2.48	6.76	43.5	43.5	3247	−3918	−6906	−5396		1108	3971
	26.06.2014–09.10.2014	105	−2101	1.21	3.20	43.7	43.5	1886	−3987	−10,893	−13,859	−7798	−4453	−482
	09.10.2014–30.06.2015	264	312	2.52	5.17	44	43	3732	−3420	−14,313	−4729		−564	−1045
	30.06.2015–06.10.2015	98	−627	1.20	2.54	46	44	1809	−2436	−16,749	−9073	−5904	506	−540
	06.10.2015–29.06.2016	267	6	2.47	4.01	52	48	4523	−4517	−21,266	−6175		−289	−829
	29.06.2016–04.10.2016	97	820	1.15	2.66	48.3	45.7	1964	−1144	−22,410	−4305	−5676	714	−115
Tsarmine	09.07.2013–23.09.2014	441	173	2.99		43.3		2454	−2281	−2281	−1888	−1888	2918	2918
	23.09.2014–29.06.2015	279	1500	2.62		44.6		2601	−1100	−3381	−1440		1963	4854
	29.06.2015–22.09.2015	85	−516	0.97		43.6		329	−853	−4234	−3664	−1958	596	5450
	22.09.2015–01.07.2016	283	1949	3.28		46.8		3200	−1251	−5485	−1614		3347	8798
	01.07.2016–07.10.2016	98	−752	1.37		43.8		1932	−2684	−8169	−9997	−3770	2241	11,038

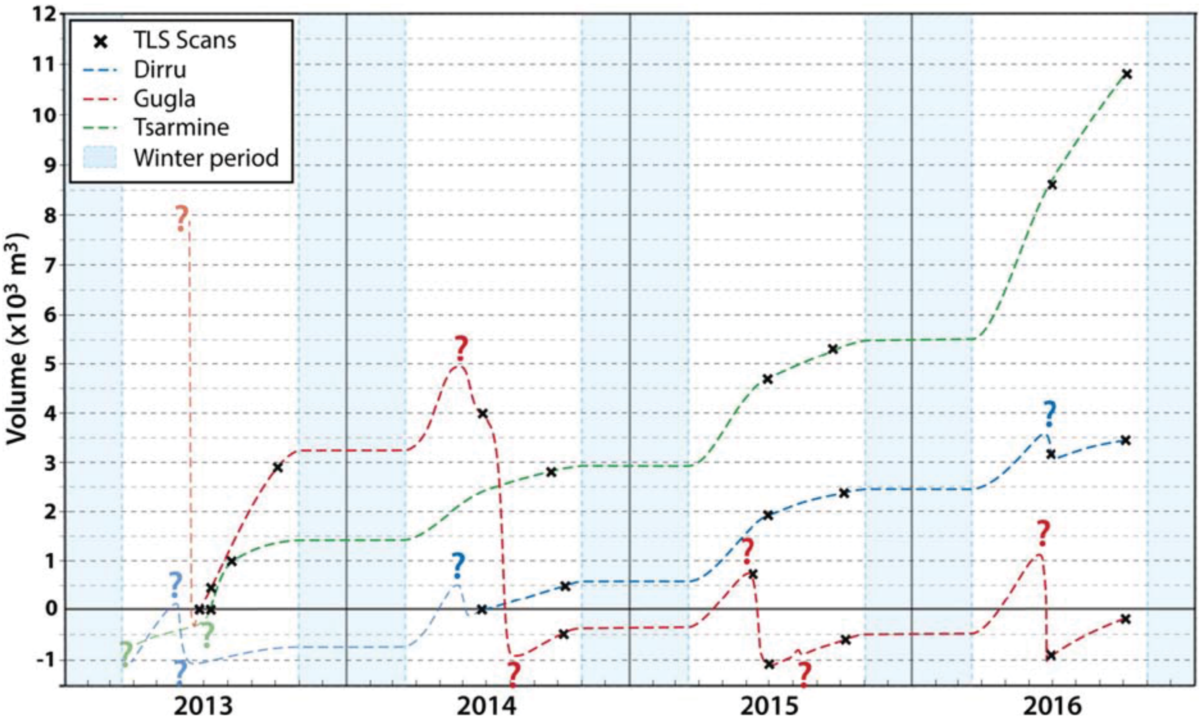

Fig. 13. Evolution of the amount of sediment stored in the upper gully for each site in relation to the original state which corresponds to the date of the first TLS scan, respectively June 26, 2014 at Dirru, June 25, 2013 at Gugla and July 09, 2013 at Tsarmine. The black X correspond to the measured values and therefore to the TLS campaigns, while the shapes of the curves between the black X are a best guess of what happened based on observations of webcam images (Kummert et al., 2017). The question marks are added to suggest that there are a lot of uncertainties about the filling rate of the gullies between two scans.

affecting the front led to the concentration of the sediments within the upper gully. Interestingly, the increasing steepness of the curve in Fig. 13 illustrates the increase in the erosion rate characterizing the front of the Tsarmine rock glacier from 2013 to 2016. At Dirru, the erosion of the front also contributed to increase the volume stored in the upper gully. The storage area is nonetheless morphologically different than for Tsarmine as the sediments are not concentrated in a narrow channel but spread on a debris slope. At Dirru, partial sediment reworking was observed on the debris slope, for example between October 2015 and June 2016. This was due to the occurrence of a small debris flow which was initiated close to the front on the 22th of June 2016. The material eroded by the latter was for the most part deposited a little bit downward on the slope and in the Geisstriftbach torrent (Fig. 10). It seemed however that only a very small amount of sediment exited the system during this event (maximally one hundred cubic meters). At Dirru, some larger events were observed in June 2013 (before the measurements started). They induced a transfer of sediments further down in the Geisstriftbach torrent. All these reworking events affected the erosion niche on the northern side of the debris slope, where the connectivity with the main torrent is more efficient. Finally at Gugla, there was a concentration of sediment in the channel, similarly to what was observed at Tsarmine. However the results showed that the reworking of these sediments stored in the upper gully and their transfer further downward was quite frequent during the investigated period. Indeed, negative sediment budgets were measured in the upper gully for several time intervals covering both winter and summer time periods. Fig. 13 illustrates quite well this dynamic. At Gugla, the upper gully was characterized by an alternate occurrence of sediment buildup periods and erosion/emptying periods, depending on the timing of the occurrence of debris flow events which tended to empty the gully. In addition, the volumes involved in this alternate activity have been decreasing since the beginning of the measurements in June 2013, showing a decreasing trend in the sediment transfer magnitude. However, a long time period characterized by an aggradation-dominant behavior could eventually occur and enhance substantially the sediment availability in the upper gully, as it was for instance the case later, in 2017.

5. Discussion

5.1. Controls on the sediment transfer rate

The results show differences in sediment transfer rate between the three sites (Fig. 12). These differences can be attributed to different factors which act as controls on the sediment transfer rates between the fronts and the underlying gullies/debris slopes. First, the morphology and the size of the frontal area impacts the potential amount of sediment eroded from the front. For example, the tongue of the Dirru rock glacier has an approximately two times smaller width than the two other sites (respectively 50 m at Dirru and about 100 m both at Gugla and Tsarmine). Therefore, the section of the rock glacier advancing and then being eroded (frontal area) is smaller and explains the generally smaller erosion rates calculated. In addition, the velocity of the rock glacier influences the amount of sediment which is brought forward and set available each year. For instance, the frontal sections of Gugla and Tsarmine rock glaciers have similar dimensions, however, the creep velocities measured at Gugla are higher than the ones measured at Tsarmine and partly explains the higher sediment transfer rates obtained for Gugla. Fig. 14 shows for each site the evolution of the frontal erosion rates compared to the evolution of the surface velocities measured by differential GNSS at the fronts. The relation between these two variables is quite clear and confirms the hypothesis that, as the positions of the front lines are approximately stable in time, higher creep velocity rates favor higher sediment transfer rates. This effect is particularly visible in Gugla (southern front) and Tsarmine where relatively important changes in creep velocity are correlated to respectively a decrease and an increase in sediment transfer rate from the rock glacier into the upper gully (Fig. 14). At Dirru, the slight decrease in surface velocity measured since 2015 seems to be related to a corresponding slight decrease in sediment transfer activity. Finally, the erosion

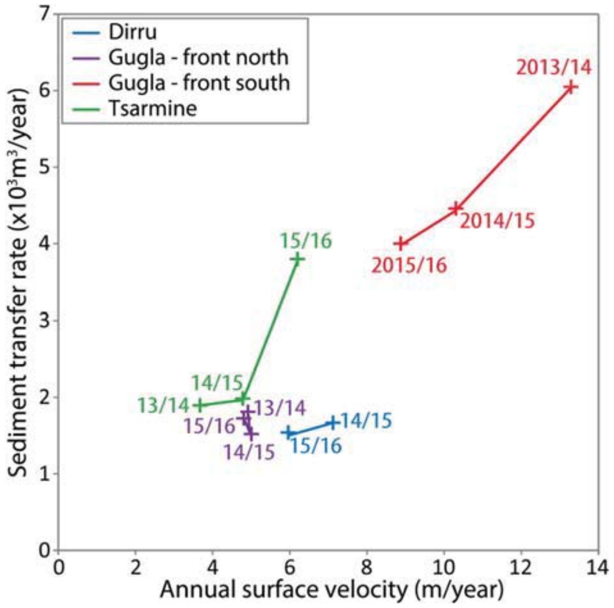

Fig. 14. Comparison between the annual transfer rate and the velocity rate for each studied rock glacier. The rates (both transfer rates and velocity rates) are calculated for one year periods (October to October).

susceptibility of the sediments lying at the front, as well as water availability in the gully can vary both in time and/or between the sites and can influence the erosion rates (see Kummert et al., 2017). For example, Gugla is characterized by a substantially larger catchment area upslope from the rock glacier than the two other sites. During intense snowmelt or repeated rainfall events, greater runoff discharge can be observed in the gully, increasing the magnitude of erosion events (Kummert et al., 2017). In addition, at Dirru the development of the main erosion niche in the mid-1990s was apparently associated with the occurrence of intense torrential transfer events (Raymond Pralong et al., Unpublished), and might have been related to a change in water availability enhancing regressive erosion.

5.2. Significance of the transfer rate for torrential activity

Sediment transfer rates ranging between 1000 and 7800 m^3/y were calculated. We can assume that similar orders of magnitude apply for rock glaciers characterized by comparable sizes, dynamics and topographical configurations. Once lying in the channel, the sediments are potentially available for torrential transport, and therefore for the development of debris flows. If we follow the volumetric classification of debris flows proposed by Jakob (2005) in the case of British Columbia (Canada), the orders of magnitude for annual sediment supply by the rock glaciers calculated here are sufficient, if mobilized within one event, to produce medium sizes debris flows (class 3 in Jakob, 2005). According to Jakob (2005), such debris flow size is enough to destroy buildings, damage concrete bridge piers and block or damage highways and railways. In addition, the sediment input from the rock glacier may be continuous over several years or decades as long as the level of activity of the latter remains constant. If no remobilization events occur, the sediment supply from the rock glacier front can lead in a few years to the progressive storage of larger amounts of rock debris in the gully, which are then potentially available for the triggering of larger magnitude debris flows, as long as enough water is available. For example, at Gugla the sediment supply by the rock glacier contributed to the triggering of repeated debris flow events emptying the upper gully between 2012 and 2016 (Fig. 13). The decrease of the sediment transfer rate since 2013 associated with the high frequency of events constitute explanatory factors for the lower magnitude of the debris flow events which occurred in 2015 and 2016. The largest events occurred between the 13th and the 18th June 2013 at Gugla, shortly before the start of the TLS surveys (Oggier et al., 2016). The amount of sediment transferred during these repeated events were therefore not quantified but exceeded the ones measured ever since and were most likely involving sediments that have accumulated in the upper gully for several consecutive years. At Dirru, the dispersion of the sediments on the slope seems to currently lower the overall magnitude of debris flow events. These events were in addition less frequent than in Gugla due to factors such as water availability and topography (slope), which are at least as important as the presence of sediments in the gullies to explain the debris flow susceptibility of the catchments (Kummert et al., 2017). It is important to note that the presence of a rapidly moving rock glacier connected to a torrential channel does not necessarily imply frequent occurrence of debris flow events. The best example is the case of Tsarmine, where only very small-size debris flows were observed in the past decades (maximally up to a few hundred cubic meters) despite the substantial sediment availability in the upper gully (11,000 m^3 accumulated in only 4 years). The sediment input from the rock glacier only participates to the buildup of the important sediment storage area in the upper gully, and factors such as the small size of the catchment area inducing a relatively low water availability or the relatively coarse sediment size has so far prevented large debris flows from being triggered.

5.3. Comparison with other studies

Many studies (e.g. Barsch, 1977; Humlum, 2000; Gärtner-Roer and Nyenhuis, 2010) propose estimations of the sediment transfer rates of rock glaciers. However, the results are usually expressed in tons per years and take into account the whole mass of the rock glaciers rather than the transfer occurring at the front or at a given section of the landform. They are therefore not comparable to our approach. As already mentioned, very few studies focusing on the quantification of sediment transfer at the front of active rock glaciers exist. In one of the few examples, Micheletti et al. (2017) presented results of volumetric changes at the front of the Tsarmine rock glacier. They compared volumes calculated with a conventional method using DoDs, similarly to the one applied here, to volumes directly extracted from TLS point clouds. However, Micheletti et al. (2017) did not calculate sediment transfer rates nor sediment budgets but only volumes of accumulation and erosion on the whole area, including the front and the gully. Furthermore, no specific methodology to estimate the volumetric inputs from the rock glacier advance is proposed. It is therefore not possible to directly relate their results to the ones presented here.

Lugon and Stoffel (2010) calculated sediment transfer rates between a rock glacier front and a torrential channel for different time periods by multiplying the annual surface velocity with the surface width and depth of the rock glacier front. Their method did not consider the velocity decrease at depth and was based on the assumption that the volume brought forward annually by the motion of the rock glacier corresponds to the volume eroded and transported each year towards the gully. They calculated annual transfer rates ranging between 300 and 400 m^3/y at the front of a rock glacier characterized by a surface velocity varying between 30 and 40 cm/y. These values are about ten times lower that the ones we calculated at our sites and can be explained by the surface velocity, which is also approximately ten times lower. As a comparison, a similar approach adapted to take into account the velocity decrease at depth (Fig. 15) was applied for all the rock glaciers located in the west-oriented side of the Mattertal valley, including Dirru and Gugla (Delaloye et al., Unpublished), as well as at Tsarmine. The values of annual sediment transfer obtained with this alternate simplified method (method 2) are shown in Table 4, where they are compared to the values of annual erosion rates (E_A) presented in this paper. The two methods estimated sediment transfer rates of the same magnitude. The results presented in this paper indicate however that the erosion

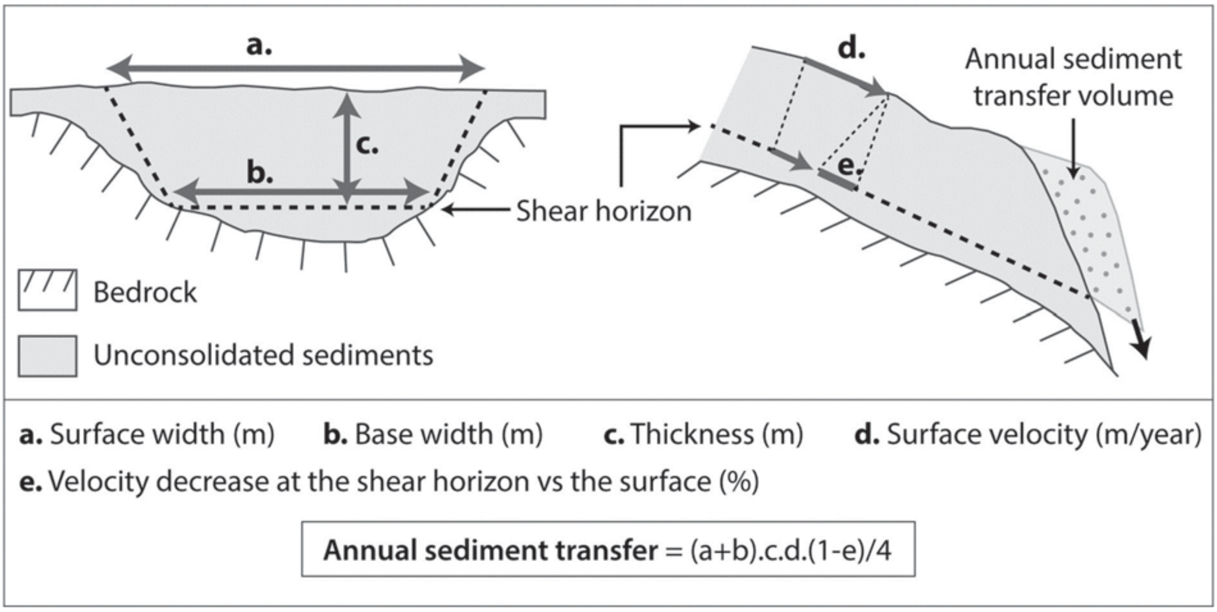

Fig. 15. Schematic view of a rock glacier with the different dimensions (a. to e.) used in method 2 to estimate the annual sediment input at the front of active rock glaciers. In this method, it is assumed that all the sediments brought forward by the rock glacier advance are eroded and transferred towards the gully. The annual sediment input corresponds thus to the annual erosion rate at the front.

of the front does not only follow the variations of movement of the rock glacier, but depends also on external factors such as the weather conditions. Therefore, even though the front line position seems stable at a decadal scale, the erosion of the front is characterized by inter-annual and seasonal variations that are not captured by the second approach. The comparative table shows nevertheless that method 2 can be helpful to get first quantitative approximations of the sediment transfer activity at the front of active rock glaciers connected to torrential gullies.

5.4. Remaining uncertainties over the data

The presented results display certain variability in the sediment transfer rates and budget values. The correspondence between volumes eroded from the fronts and aggradation rates in the upper gullies is also not perfectly balanced. If this can illustrate the transfer of sediments towards the lower gullies and the valley bottoms, it can also reflect uncertainties and errors in our estimations. At Tsarmine and Dirru for instance, there is almost no remobilization of sediments out of the scanned area. The budgets calculated at the fronts should then be balanced by the volume changes obtained for the upper gullies for each time period and for both sites. However, results show in most cases slightly unbalanced total budgets, generally positive at Tsarmine and negative at Dirru. These unbalanced budgets point out remaining uncertainties which are both numerous and difficult to estimate. These uncertainties are discussed hereafter.

Table 4
Data comparison between sediment transfer rates calculated with the methodology described and applied in this study, and an alternative method (method 2) adapted from Lugon and Stoffel (2010) and used by Delaloye et al. (Unpublished).

	Time interval (dd.mm.yyyy)	Transfer rate (E_A) (m^3/y)	Transfer rate method 2 (m^3/y)
Dirru	09.10.2014-06.10.2015	-1642	-1811
	06.10.2015-04.10.2016	-1494	-1520
Gugla	04.10.2013-09.10.2014	-7798	-6860
	09.10.2014-06.10.2015	-5904	-5599
	06.10.2015-04.10.2016	-5676	-4986
Tsarmine	23.09.2014-22.09.2015	-1958	-2823
	22.09.2015-07.10.2016	-3770	-3656

Despite our efforts to limit the impact of DEMs errors in our volume calculations, some uncertainties linked to the data processing can still be present. In addition, uncertainties can arise from the interpretation of the calculated volumetric budget as sediment budgets. As mentioned, in our cases the values of surface changes are mostly reflecting sediment transfer activity; either sediment reworking through aggradation and erosion, or the movement of the rock glacier which participates to transport sediments downward. However, other processes might influence the values of surface changes within the DoDs and therefore be reflected in our sediment budget values. At the front, the ice content within the advancing sections of the rock glaciers may vary spatially and impact calculated volumetric budgets. In addition, the melt of permafrost ice which in some cases occupies a larger volume than the overall porosity can also affect values of surface elevation changes at the fronts. This effect could for instance explain part of the unbalanced overall sediment budget calculated at Dirru, where relatively high ice content is expected. In the upper gullies, occasional and localized snowmelt-induced surface changes may also be present in some of the DoDs, for instance at Gugla where the narrowness and the steepness of the gully sometimes allow some small snow patches to remain present until end of June. These processes could however not be quantified. Their impact on the values of volumetric budget is expected to be small but they need to be kept in mind while analyzing the results.

Finally, errors can also derive from the calculations of the volume gain from the rock glacier advance (ΔV_{Fadv}). In our calculations we used the mean 3D velocities measured at 3 to 4 points located close to the fronts to estimate the rock glaciers movements. The spatial representativeness of this mean value is possibly not ideal. As already mentioned, we reduced this mean value by a factor of 25% to better represent the velocity decrease at depth. By doing so we assume that the velocity at the shear horizon is about half the one measured at the surface, and that the velocity decrease in depth is linear. These two assumptions represent simplifications of the reality and therefore can lead to uncertainties. It might however counterbalance the effect of the melt of interstitial ice on volume changes, especially at Gugla and Tsarmine where the ice content is expected to be low. In addition, the same amount of sediment could occupy different volumes in the upper gully and at the front. In the rock glacier body, a part of the volume corresponds to ice which is not present in the sediments lying in the gully. On the other hand, the sediments might be more compacted in the rock glacier body than in the gully due to the compressive action of the permafrost creep process. Moreover, fine material occupies often an important part of the front surface but is generally less visible in the gully where it can be leached. These differences can also explain unbalanced values of total budgets even if no sediments were transferred outside the scanned areas. This is most likely he case at Tsarmine, where fine sediments occupy a relatively large portion of the front surface but are almost non-visible in the upper gully.

All these remaining sources of uncertainties were not quantified. Therefore, the absolute values of volume changes presented here should not be interpreted as true values but more as best approximations. Additionally, as the same methodology has been applied for each time interval and at each site, one can argue that relative changes in erosion and transfer within one site or differences recorded between the sites are representative of real geomorphological differences in sediment transfer activity. More than the single absolute values, orders of magnitude and both temporal variations within one site and differences between the sites are the main elements that are emphasized and discussed in this paper.

6. Conclusion

TLS derived DoDs have shown good applicability to map and quantify sediment fluxes between the front of rapidly moving rock glaciers and gullies. However, uncertainties remain present due to the post-processing of the LiDAR data and the difficulty to estimate the volume changes due to the rock glacier movements. These sources of uncertainties seem unfortunately difficult to overcome. However, more advanced procedures of TLS post-processing routines as well as better local knowledge about the depth of the main shear horizon, the velocity decrease at depth or the internal structure (e.g. porosity, ice content) could improve our estimations. Given the remaining uncertainties, the quantitative results presented here should be analyzed as orders of magnitude more than as absolute values. They however allow numerous conclusions to be drawn. The fronts of the investigated rock glaciers act as substantial sediment inputs to the underlying torrential channels. Sediment transfer rates measured between the fronts and the torrential gullies range from about 1500 m^3/y at Dirru to more than 7800 m^3/y measured in 2013–2014 at Gugla. In most cases, these transfer rates participate to the buildup of important accumulation areas in the upper sectors of the gullies or on the slopes situated just underneath the fronts, as shown by the DoDs. Once stored on the slopes, the sediments may then be remobilized within debris flow events of various sizes, depending on the sediment availability but also on the concordance of other controlling factors such as topography and water availability (Kummert et al., 2017). In addition to these factors, the annual sediment transfer rate between the rock glacier fronts and the torrential channels is mainly controlled by the sizes of the frontal areas and the creep velocity rates. A clear relation between the motion rates of the rock glaciers and the sediment transfer rates calculated at their fronts could be highlighted here. We can therefore affirm that a substantial sediment transfer activity must characterize rock glaciers lending similar topographical and kinematical configurations as the ones studied here. The values presented here are thus only representatives for rapidly moving rock glaciers. In the case of slow moving rock glaciers, values of sediment transfer rates are expected to be much lower. However, in the current context of climate change, the potential acceleration of such steep and connected rock glaciers could increase sediment transfer rates and enhance the sediment availability within the headwaters of high alpines watersheds. The identification of the cases corresponding to this configuration should therefore be a priority for future work.

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References

Abermann, A., Fisher, A., Lambrecht, A., Geist, T., 2010. On the potential of very high-resolution repeat DEMs in glacial and periglacial environments. Cryosphere 4, 53–65.

Arenson, L., Hoelzle, M., Springman, S., 2002. Borehole deformation measurements and internal structure of some rock glaciers in Switzerland. Permafr. Periglac. Process. 13, 117–135.

Avian, M., Kellerer-Pirklbauer, A., Bauer, A., 2009. LiDAR for monitoring mass movements in permafrost environments at the cirque Hinteres Langtal, Austria, between 2000 and 2008. Nat. Hazards Earth Syst. Sci. 9, 1078–1094.

Barboux, C., Delaloye, R., Lambiel, C., 2014. Inventorying slope movements in an Alpine environment using DInSAR. Earth Surf. Process. Landf. 39, 2087–2099.

Barsch, D., 1977. Nature and importance of mass-wasting by rock glaciers in alpine permafrost environment. Earth Surf. Process. 2, 231–245.

Barsch, D., Caine, N., 1984. The nature of mountain geomorphology. Mt. Res. Dev. 4, 287–298.

Bauer, A., Paar, G., Kaufmann, V., 2003. Terrestrial laser scanning for rock glacier monitoring. In: Phillips, M., Springman, S.M., Arenson, L.U. (Eds.), Permafrost, Proceedings of the Eighth International Conference on Permafrost, 21–25 July 2003, Zurich, Switzerland. vol. 1. A.A. Balkema, Lisse, pp. 55–60.

Bennett, G.L., Molnar, P., Eisenbeiss, H., McArdell, B.W., 2012. Erosional power in the Swiss Alps: characterization of slope failure in the Illgraben. Earth Surf. Process. Landf. 37 (15), 1627–1640.

Bodin, X., Trombotto, D., 2015. Evaluation of a terrestrial photogrammetry method to assess rock glacier dynamics. A study case in the Argentinean andes of Mendoza. In: Jasiewicz, J., Zwolinski, Zb, Mitasova, H., Hengl, T. (Eds.), Geomorphometry for Geosciences. Adam Mickiewicz University in Poznan - Institute of Geoecology and Geoinformation, International Society for Geomorphometry, Poznan, pp. 189–192.

Bracken, L.J., Turnbull, L., Wainwright, J., Bogaart, P., 2015. Sediment connectivity: a framework for understanding sediment transfer at multiple scales. Earth Surf. Process. Landf. 40, 177–188.

Brasington, J., Rumsby, B.T., McVey, R.A., 2000. Monitoring and modelling morphological change in a braided gravel-bed river using high resolution GPS-based survey. Earth Surf. Process. Landf. 25 (9), 973–990.

Brasington, J., Langham, J., Rumsby, B., 2003. Methodological sensitivity of morphometric estimates of coarse fluvial sediment transport. Geomorphology 53, 299–316.

Buchli, T., Merz, K., Zhou, X., Kinzelbach, W., Springman, S.M., 2013. Characterization and monitoring of the Furggwanghorn rock glacier, Turtmann Valley, Switzerland: results from 2010 to 2012. Vadose Zone J. 12, 15.

Caine, N., 1974. The geomorphic processes of the alpine environment. In: Ives, J.D., Barry, R.G. (Eds.), Arctic and Alpine Environments. Methuen, London, pp. 721–748.

Carrivick, J.L., Geilhausen, M., Warburton, J., Dickson, N.E., Carver, S.J., Evans, A.J., Brown, L.E., 2013. Contemporary geomorphological activity throughout the proglacial area of an alpine catchment. Geomorphology 188, 83–95.

Cavalli, M., Goldin, B., Comiti, F., Brardinoni, F., Marchi, L., 2017. Assessment of erosion and deposition in steep mountain basins by differencing sequential digital terrain models. Geomorphology 291, 4–16.

Daanen, R.P., Grosse, G., Darrow, M.M., Hamilton, T.D., Jones, B.M., 2012. Rapid movement of frozen debris-lobes: implications for permafrost degradation and slope instability in the south-central Brooks Range, Alaska. Nat. Hazards Earth Syst. Sci. 12, 1521–1537.

Delaloye, R., Lambiel, C., Lugon, R., Raetzo, H., Strozzi, T., 2007a. ERS InSAR for detecting slope movement in a periglacial mountain environment (western Valais Alps, Switzerland). Proceedings of HMRSC-IX, Grazer Schriften der Geographie und Raumforschung 43, pp. 113–120.

Delaloye, R., Lambiel, C., Lugon, R., Raetzo, H., Strozzi, T., 2007b. Typical ERS InSAR signature of slope movement in a periglacial mountain environment (Swiss Alps). Proceedings of ESA ENVISAT Symposium, 2007, Montreux, Switzerland.

Delaloye, R., Perruchoud, E., Avian, M., Kaufmann, V., Bodin, X., Hausmann, H., Ikeda, A., Kääb, A., Kellerer-Pirklbauer, A., Krainer, K., Lambiel, C., Mihajlovic, D., Staub, B., Roer, I., Thibert, E., 2008. Recent interannual variations of rock glacier creep in the European Alps. In: Kane, D.L., Hinkel, K.M. (Eds.), Proceedings of the 9th International Conference on Permafrost, June 29–July 3, 2008, Fairbanks, Alaska. vol. 1. Institute of Northern Engineering, University of Alaska Fairbanks, pp. 343–348.

Delaloye, R., Lambiel, C., Gärtner-Roer, I., 2010. Overview of rock glacier kinematics research in the Swiss Alps. Seasonal rythm, interannual variations and trends over several decades. Geogr. Helv. 65 (2), 135–145.

Delaloye, R., Morard, S., Barboux, C., Abbet, D., Gruber, V., Riedo, M., Gachet, S., 2013. Rapidly moving rock glaciers in Mattertal. In: Graf, C. (Ed.), Mattertal – ein Tal in Bewegung. Publikation zur Jahrestagung der Schweizerischen Geomorphologischen

Gesellschaft 29. Juni–1. Juli 2011, St. Niklaus, Switzerland. Eidg. Forschungsanstalt WSL, Birmensdorf, pp. 113–124.
Delaloye, R., Abbet, D., Barboux, C., Braillard, L., Kummert, M., Morard, S. Unpublished. Blockgletscher und Hangrutschungen in Permafrostgebieten. Projekt "Mattertal" (2009–2013), Gemeinde St.-Niklaus und Randa, Abschlussbericht 2013.
Dietrich, W.E., Dunne, T., 1978. Sediment budget for a small catchment in mountainous terrain. Z. Geomorphol. 29 (supplement issue), 191–206.
Fischer, M., Huss, M., Kummert, M., Hoelzle, M., 2016. Application and validation of long range terrestrial laser scanning to monitor the mass balance of very small glaciers in the Swiss Alps. Cryosphere 10, 1279–1295.
Frauenfelder, R., Haeberli, W., Hoelzle, M., 2003. Rockglacier occurence and related terrain parameters in a study area of the eastern Swiss Alps. In: Phillips, M., Springman, S., Arenson, L. (Eds.), Proceedings of the 8th International Conference on Permafrost, Zurich 21–25 July 2003, pp. 253–258.
Fryirs, C., 2013. (Dis)connectivity in catchment sediment cascades: a fresh look at the sediment delivery problem. Earth Surf. Process. Landf. 38, 30–46.
Gärtner-Roer, I., 2012. Sediment transfer rates of two active rockglaciers in the Swiss Alps. Geomorphology 167–168, 45–50.
Gärtner-Roer, I., Nyenhuis, M., 2010. Volume estimation, kinematics and sediment transfer rates of active rockglaciers in the Turtmann Valley, Switzerland. In: Otto, J.C., Dikau, R. (Eds.), Landform – Structure, Evolution, Process Control, Lecture Notes in Earth Sciences. 115, pp. 185–198 (Berlin, Heidelberg).
Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J., Stoffel, M., 2014. 21st century climate change in the European Alps – a review. Sci. Total Environ. 493, 1138–1151.
Haeberli, W., Hallet, B., Arenson, L., Elconin, R., Humlum, O., Kääb, A., Kaufmann, V., Ladanyi, B., Matsuoka, N., Springman, S., Vonder Mühll, D., 2006. Permafrost creep and rock glacier dynamics. Permafr. Periglac. Process. 17, 189–214.
Heckmann, T., Bimböse, M., Krautblatter, M., Haas, F., Becht, M., Morche, D., 2012. From geotechnical analysis to quantification and modelling using LiDAR data: a study on rockfall in the Reintal catchment, Bavarian Alps, Germany. Earth Surf. Process. Landf. 37, 119–133.
Humlum, O., 2000. The geomorphic significance of rock glaciers: estimates of rock glacier debris volumes and headwall recession rates in West Greenland. Geomorphology 35, 41–67.
Ikeda, A., Matsuoka, N., Kääb, A., 2008. Fast deformation of perennially frozen debris in a warm rock glacier in the Swiss Alps: an effect of liquid water. J. Geophys. Res. 113, F01021.
Jakob, M., 2005. A size classification for debris flows. Eng. Geol. 79, 151–161.
Kääb, A., Reichmuth, T., 2005. Advance mechanisms of rock glaciers. Permafr. Periglac. Process. 16 (2), 187–193.
Kääb, A., Frauenfelder, R., Roer, I., 2007. On the response of rockglacier creep to surface temprature increase. Glob. Planet. Chang. 56, 172–187.
Kääb, A., Strozzi, T., Sorg, A., Stoffel, M., 2016. Variations in rockglacier speed in the Tien Shan and their significance. In: Günther, F., Morgenstern, A. (Eds.), XI. International Conference on Permafrost – Book of Abstracts, 20–24 June 2016, Potsdam, Germany. Bibliothek Wissenschaftspark Albert Einstein.
Kaufmann, V., Ladstädter, R., Kienast, G., 2007. 10 years of monitoring of the Doesen rock glacier (Ankogel group, Austria) – a review of the research activities for the time period 1995–2005. In: Petrovic, D. (Ed.), Proceedings of the 5th Mountain Cartography Workshop, Bohinj, Slovenia, 29 March–April 2006, pp. 129–144.
Kenner, R., Phillips, M., Danioth, C., Denier, C., Thee, P., Zgraggen, A., 2011. Investigation of rock and ice loss in a recently deglaciated mountain rock wall using terrestrial laser scanning: Gemsstock, Swiss Alps. Cold Reg. Sci. Technol. 67, 157–164.
Kenner, R., Bühler, Y., Delaloye, R., Ginzler, C., Phillips, M., 2013. Monitoring of alpine mass movements combining laser scanning with digital airborne photogrammetry. Geomorphology 206, 492–504.
Krysiecki, J.M., Garcia, S., Schoeneich, P., Echelard, T., Bodin, X., Evans, A., in prep. D'un possible surge à la fin du 19ème siècle aux dynamiques actuelles: essai d'évaluation des vitesses moyennes de surface du glacier rocheux du Dérochoir sur 115 ans via la présence d'un chemin muletier.
Kummert, M., Delaloye, R., 2015. Quantifying sediment transfer between the front of an active alpine rock glacier and a torrential gully. In: Jasiewicz, J., Zwolinski, Zb, Mitasova, H., Hengl, T. (Eds.), Geomorphometry for Geosciences. Adam Mickiewicz University in Poznan - Institute of Geoecology and Geoinformation, International Society for Geomorphometry, Poznan, pp. 193–196.
Kummert, M., Delaloye, R., Braillard, L., 2017. Erosion and sediment transfer at the front of rapidly moving rock glaciers: observations from the western Swiss Alps. Permafr. Periglac. Process. 29, 21–33.
Lane, S.N., Richards, K.S., Chandler, J.H., 1994. Developments in monitoring and modelling small-scale river bed topography. Earth Surf. Process. Landf. 19, 349–368.
Lane, S.N., Westaway, R.M., Murray Hicks, D., 2003. Estimation of erosion and deposition volumes in a large, gravel-bed, braided river using synoptic remote sensing. Earth Surf. Process. Landf. 28 (3), 249–271.
Lugon, R., Stoffel, M., 2010. Rock glacier dynamics and magnitude-frequency relations of debris flows in a high-elevation watershed: Ritigraben, Swiss Alps. Glob. Planet. Chang. 73, 202–210.
Micheletti, N., Chandler, J.H., Lane, S.N., 2015. Investigating decadal-scale geomorphic dynamics in an alpine mountain setting. J. Geophys. Res. Earth Surf. 120, 2155–2175.
Micheletti, N., Tonini, M., Lane, S.N., 2017. Geomorphological activity at a rock glacier front detected with a 3D density-based clustering algorithm. Geomorphology 278, 287–297.
Oggier, N., Graf, C., Delaloye, R., Burkard, A., 2016. Integral protection concept "Bielzug" - Integrales Schutzkonzept Bielzug. Conference Proceedings, INTERPRAEVENT 2016, pp. 525–534.
PERMOS, 2016. Permafrost in Switzerland 2010/2011 to 2013/2014. In: Noetzli, J., Luethi, R., Staub, B. (Eds.), Glaciological Report (Permafrost) No. 12–15 of the Cryospheric Commission of the Swiss Academy of Sciences (85 pp.).
Perroy, R.L., Bookhagen, B., Asner, G.P., Chadwick, O.A., 2010. Comparison of gully erosion estimates using airborne and ground-based LiDAR on Santa Cruz Island, California. Geomorphology 118, 288–300.
Raymond Pralong, M., Graf, C., Rickenmann, D. Unpublished. Bericht Murgangauslösende Faktoren und Prozesse im Mattertal, Projekt Hydralp, Swiss Federal Research Institute WSL, 2017.
RIEGL Laser Measurement Systems, 2013. Preliminary Data Sheet, 07.05.2013; Riegl VZ-6000 – 3D Ultra Long Range Terrestrial Laser Scanner With Online Waveform Processing. RIEGL Laser Measurement Systems, Horn, Austria.
Roer, I., Haeberli, W., Avian, M., Kaufmann, V., Delaloye, R., Lambiel, C., Kääb, A., 2008. Observations and considerations on destabilizing active rock glaciers in the European Alps. In: Kane, D.L., Hinkel, K.M. (Eds.), Proceedings of the 9th International Conference on Permafrost, June 29–July 3, 2008, Fairbanks, Alaska. vol. 2. Institute of Northern Engineering, University of Alaska Fairbanks, pp. 1505–1510.
Scheidl, C., Rickenmann, D., Chiari, M., 2008. The use of airborne LiDAR data for the analysis of debris flow events in Switzerland. Nat. Hazards Earth Syst. Sci. 8, 1113–1127.
Sorg, A., Kääb, A., Roesch, A., Bigler, C., Stoffel, M., 2015. Contrasting responses of Central Asian rock glaciers to global warming. Sci. Rep. 5 (8228) (6 pp.).
Theule, J.I., Liébault, F., Laigle, D., Jaboyedoff, M., 2012. Sediment budget monitoring of debris-flow and bedload transport in the Manival Torrent, SE France. Nat. Hazards Earth Syst. Sci. 12, 731–749.
Wahrhaftig, C., Cox, A., 1959. Rock glaciers in the Alaska range. Geol. Soc. Am. Bull. 70 (4), 383–436.
Walling, D.E., 1983. The sediment delivery problem. J. Hydrol. 65, 209–237.
Wheaton, J.M., Brasington, J., Darby, S.E., Sear, D.A., 2010. Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. Earth Surf. Process. Landf. 35, 135–156.
Williams, R.D., 2012. Section 2.3.2: DEMs of difference. In: Cook, S.J., Clarke, L.E., Nield, J.M. (Eds.), Geomorphological Techniques (Online Edition). British Society for Geomorphology, London, UK (ISSN: 2047-0371).
Zhang, Z., 1994. Iterative point matching for registration of free-form curves. Int. J. Comput. Vis. 13, 119–152.