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

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ABSTRACT

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.

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).

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).

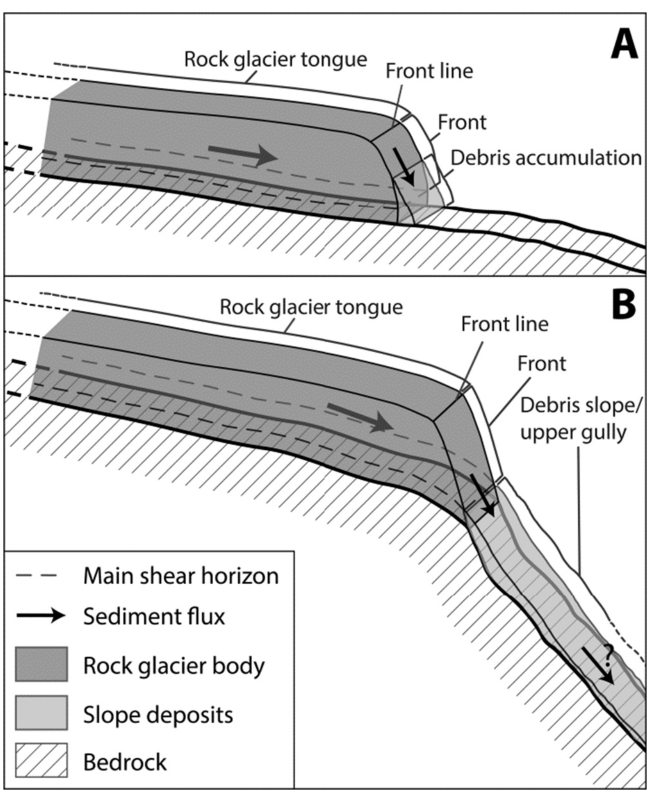

Fig. 1. Two types of connectivity between an active rock glacier and the downward slope. A – No connectivity: the sediments are stored at the foot of the front and will be overridden by the advancing rock glacier; B – efficient connectivity: the sediments are leaving the rock glacier system. In this 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).

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