Rapidly moving rock glaciers in Mattertal

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Abstract
This contribution provides preliminary results and discussion elements on the so-called destabilization of rock glaciers based essentially on the on-going study of five rock glaciers in the Mattertal. A unique explanation of the involved mechanisms is so far probably to exclude. Beside the role played by the internal structure of the rock glacier, a destabilization phase appears to be the result of the varying and combined influence of several factors related to the thermal state of the permafrost, to the topography of the terrain over which the geometrical changes of the rock glacier occur and to a possible local overloading in debris consecutive to the Little Ice Age advance of a glacier or to a landslide or rock fall activity. In the latter situation a mechanical surge is triggered and can take decades to reach the rock glacier front.

Keywords: Rapidly moving rock glacier, destabilization, kinematics, alpine permafrost, Mattertal

1 Introduction

Essentially based on a large set of satellite InSAR (synthetic aperture radar interferometry) scenes dating back to the years 1991 to 1999, various regional studies aiming to the detection and characterization of slope motion above the tree line in the Swiss Alps have allowed the identification of eleven rock glaciers moving at a unusual rate of 1 cm/day or more (Barboux *et al.*, this volume; Delaloye *et al.* 2007, 2008b, 2010b) and some others moving only slightly slower than this velocity. All the eleven rapidest rock glaciers are located in the Valais Alps, namely: Petit-Vélan in the Grand Saint-Bernard area (Delaloye and Morard 2011), Mont de l'Etoile in the Hérens valley, Tsaté in the Moiry valley (Lambiel 2011), Grüob and Furggwanghorn in the Turtmann valley (Roer *et al.* 2005), Jegi in the Saas valley and the five later (Grosse Grabe, Gugla, Dirru, Grabengufer and Gänder) on the orographic right side of the valley of Zermatt (Mattertal). They were previously called – perhaps inadequately because the responsible mechanisms were not known – surging or destabilized rock glaciers. At least two of them (Furggwanghorn and Grabengufer) increased their activity during the 2000 to 2010 decade. However, even if since the extinction of the ERS1-2 satellite tandem mission in 1999 there was until recently no possibility to update the InSAR based analysis for landforms moving at a rate of more than 1 to 2 m/year, the spatial distribution pattern of rapidly moving rock glaciers in the Swiss Alps does not appear to have significantly changed for the last decade.

Investigation has been initiated since a few years on rapidly moving rock glaciers in order to gain more precise knowledge about the possible causes of the destabilization processes (e.g. Roer *et al.* 2008). Our on-going study is focusing on the systematic determination of (i) the historical development, (ii) the current kinematics and (iii) the geometry of the destabilization phase of several of the rock glaciers in concern, as well as (iv) their internal structure. The study has a peculiar focus on the Mattertal region, where all the five rapidly moving rock glaciers located in are ending on a steep slope and supplying directly gullies and torrents in debris (Fig. 1). As a consequence, the significant quantities of debris delivered downstream by the rock glaciers may drastically change the debris-flow activity in the subjacent gullies and, at the end of the chain, modify locally the exposure of settlements and transportation systems to damages on alluvial fans in the valley bottom.

The five rapidly moving rock glaciers that have been identified on the right side of the Mattertal valley (Delaloye *et al.* 2008b) are west to north-west facing and all terminating around 2500 m a.s.l. (+/– 100 m) above or beneath the Europaweg hiking trail. First surveying activities started in 2007 and since 2009 the Geography Unit of University of Fribourg has been in charge of investigating, monitoring and analyzing these five very active landforms. Surface displacements are mainly surveyed by two to three annual GPS measurement campaigns, as well as, where necessary by permanent GPS or ground-based InSAR surveying. Webcams are used to observe the erosion phenomena at the snout of the rock glaciers, whereas their internal structure is evaluated by means of geophysical measurements. Additional photogrammetric analysis is being conducted with former terrestrial and aerial photographs in order to reconstruct the development of the crisis over the past decades.

The present contribution intends to overview the current results of the investigation on the crisis development and the current interannual kinematical behaviour of the so-called rapidly moving (or "destabilized") rock glaciers in the Mattertal valley. Horizontal surface velocities are also compared to the relative annual velocity change of the other monitored active rock glaciers in the Valais Alps, whose displacement rates are in the order of 0.1 to 2 m/year (Delaloye *et al.* 2010a; PERMOS 2010).

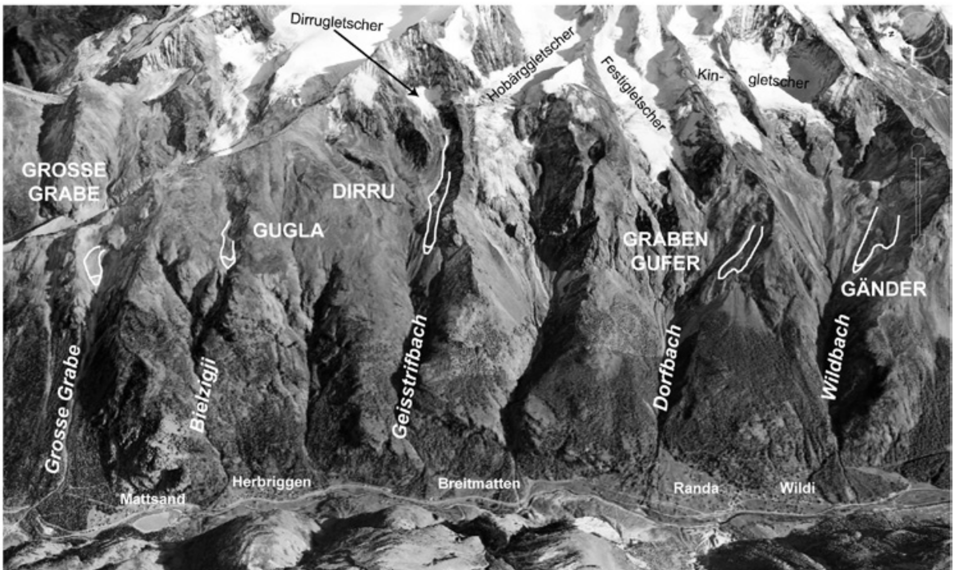

Fig. 1. Location of the five rapidly moving rock glaciers in the Mattertal valley. Settlements and torrent names are also indicated.

2 Main results

2.1 Grosse Grabe

The Grosse Grabe rock glacier extends from 2750 down to 2400 m a.s.l. upstream the Grosse Grabe torrent (Figs. 1–2). The landform is about 120 m wide and more than 500 m long. Its thickness is not known but seems not to exceed 30 m for most of the rock glacier. A topographical step separates by 2650 m a.s.l. the 30 to 35° steep terminal tongue from the gently inclined upper part of the rock glaciers. A distinct levee is visible along most of the right side of the rock glacier tongue indicating a former larger thickness of the landform, whereas the left margin is difficult to determine with precision. The pattern of the surface flow field is characterized by maximal horizontal velocities close to the front (> 5 m/year in 2008/09) (Fig. 3). The middle and steepest part of the rock glacier moves much more slowly (< 0.5 m/year), whereas the upper less inclined part encounters again a more rapid surface displacement rate (0.6–0.9 m/year) (Fig. 3). The Grosse Grabe rock glacier appears to have ruptured in two parts above and below the step where the slope becomes steeper. In 2010/11 the maximal surface velocity in the terminal section dropped down to 1.2 m/year indicating that the destabilization process could be terminated or close to be so.

The past development of the rock glacier crisis is still under investigation, but the onset appears so far to have occurred before the 1990s. The role of a possible partial overloading of the rock glacier due to former major rock fall events from a lateral headwall is being evaluated.

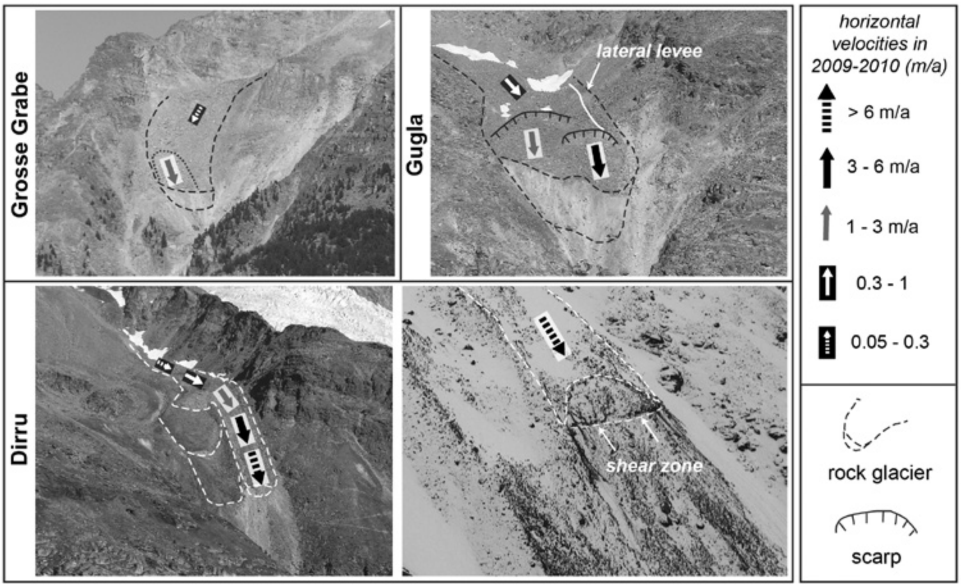

Fig. 2. Geomorphological elements and horizontal velocities of the Grosse Grabe, Gugla and Dirru rock glaciers.

2.2 Gugla

Located above the Bielzigji torrent in a small perched valley between the Breithorn and Gugla summits, the Gugla (also called Breithorn) rock glacier is about 130 m wide, 600 m long and up to 40 m thick in its terminal part. The tongue of a second rock glacier is partly connected to the uppermost section of the Gugla rock glacier. Most of the rock glacier is less than 20° inclined, whereas its terminal part is steeper. Only the terminal part is moving rapidly (roughly the last 100–150 m). The annual surface velocity has increased continuously from 2.8 m/year in 2007/08 to more than 5 m/year in 2010/11 (Fig. 3). At the time of writing this paper (June 2012), the annual velocity is already reaching 7 m/year. Prominent transverse scars are developing where the topography becomes steeper about 150 m above the front (Fig. 2). Winter images taken by a webcam pointing to the rock glacier snout permit to identify the occurrence of at least three superimposed shear horizons at the front, what suggests that the displacement rate is decreasing significantly with depth.

In the upper part of the rock glacier a lateral levee is clearly visible on the left side. Moving currently downwards in conformity with the rock glacier flow (here about 1 m/year), the levee is interpreted as the witness of a possible ancient crisis phase of the entire rock glacier that took place before the 1930s when the levee was already visible on oblique photographs taken by swisstopo.

A rapid movement of 2 to 3 m/year of the rock glacier tongue was already occurring around 1995 as attested by InSAR data, and is supposed to have been more or less so until 2007/08. The increase of the displacement rate after 2008/09 differs singularly from the mean

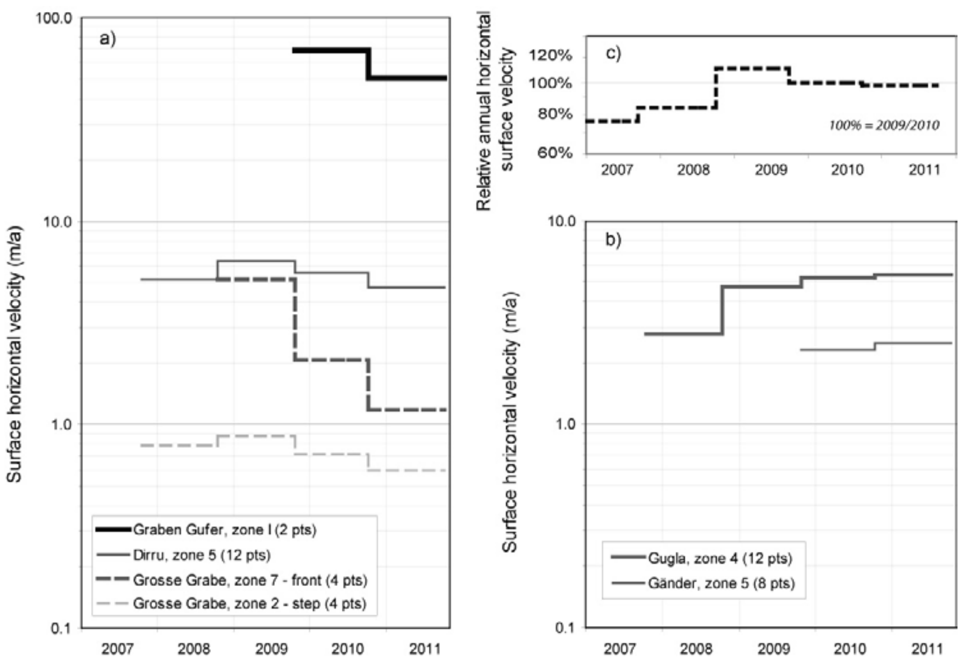

Fig. 3. a–b) Annual surface horizontal velocities in the most rapid (often terminal) parts of rapidly moving rock glaciers in the Mattertal; c) relative annual velocity change of active rock glaciers in the Valais Alps (n = 18) (© PERMOS, UniFR, UniL).

behavior of the other monitored active rock glaciers in the Valais Alps, which appears to be primarily a delayed response of permafrost creep to temperature change at the surface (Delaloye *et al.* 2008a, 2010a). Conversely to Grosse Grabe, one can consider the Gugla rock glacier as entering currently into a stronger destabilization phase (Fig. 3).

The cause of the former destabilization phase is not known. There was then obviously no significant increase of the sediment load on the rock glacier. The current crisis started at latest in 1995, but perhaps already a long time before. The recent development of the rock glacier destabilization is so far restricted to the steeper terminal section of the landform. The on-going increase of the rock glacier destabilization appears to be consecutive to a combined effect of the topography, the geometry of the landform (which is larger and thicker below the topography step) and increased permafrost temperatures for the last two decades.

2.3 Dirru

The Dirru rock glacier is a more than 1 km long landform originating from the outer margins of the historical forefield of a small glacier located in a cirque at the bottom of the western face of the Dirruhorn. The rock glacier is flowing along the northern side of the crest named Dirrugrat (Fig. 1), whose erosion is partly supplying the landform with debris. Several generations of the rock glacier are superimposed. The current active rock glacier ends laterally over the gully of the Geisstriftbach torrent.

Morphologically it is important to note the concavity of the cross-section in the uppermost third of the rock glacier and the occurrence of a significant lateral levee on the right side of the landform. In the central part of the rock glacier the cross-section is convex and there is obviously here a huge accumulation of debris. The rapidly moving (destabilized) section of the rock glacier extends downwards and concerns a 60 m wide and at least 400 m long terminal section. Geophysics and geomorphic analysis – a single shear zone is clearly visible on the images taken in winter by a fixed webcam (Fig. 2) – permit to estimate the thickness of the destabilized frozen material to about 20 m. Contrary to Grosse Grabe or Gugla no obvious rupture zone is perceptible. The velocities are about 5 to 7 m/year with maximal activity in 2008/09 and have slightly decreased the next two years (Fig. 3a), as did many other active rock glaciers in the Valais Alps (Fig. 3c).

The destabilization of the frontal part was started progressively during the 1970s and 1980s. The origin of the destabilization of the Dirru seems however to be quite older. The main hypothesis can go back to the Little Ice Age (LIA) when the Dirru glacier partly overrode the rooting zone of the rock glacier and could have leaded to its mechanical destabilization. The compressive "wave" of the sediments may then have propagated downstream slowly on a quite flat area during the 20th century before reaching the terminal steeper section, that in turn began to move more rapidly for the last 30 years or so. The current kinematical behaviour of the rock glaciers appears so far to be mainly driven by changes of the temperature state of the permafrost.

2.4 Graben Gufer

The Grabengufer rock glacier is about 600 m long and 100 m wide. It is located in steep cirque dominated by highly fractured rocky slopes mainly taking part to a huge active deep-seated landslide. The rock glacier tongue terminates about 2400 m a.s.l. on a very steep slope section where it dominates the Grabengufer gully, a large couloir collecting most of the material produced by the rapid erosion of the rock glacier front. The Grabengufer gully is reaching the Dorfbach torrent at around 1800 m a.s.l.

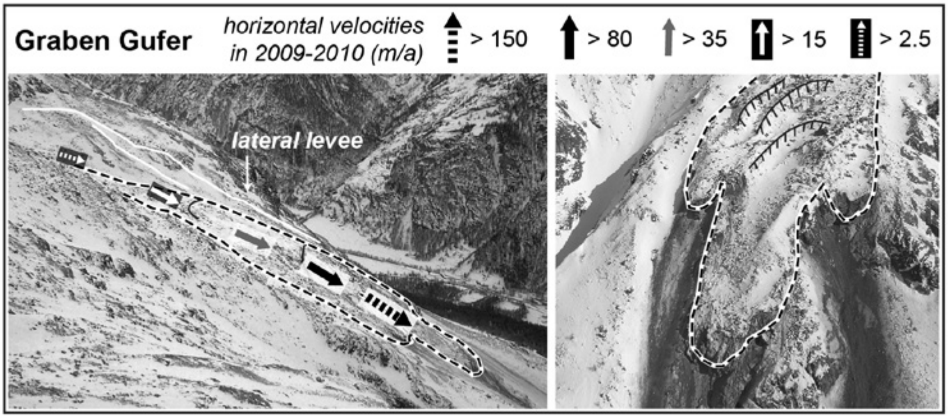

Fig. 4. Geomorphological elements and horizontal velocities of the Grabengufer rock glacier.

The Grabengufer rock glacier has encountered recently a complete destabilization and exceptionally high displacement rates. The maximal activity was recorded between July 2009 (start of the in situ monitoring) and February 2010 with surface velocity ranging between about 10 to 40 cm/day. After the paroxysmal phase and without regarding the seasonal fluctuations that are regularly occurring, the flow rate of the Grabengufer rock glacier has decreased gradually (Fig. 3a). A partial collapse of the landform as the Bérard rock glacier did in 2006 in the southern French Alps (Krysiecki *et al.* 2008) was not excluded in 2009, but did not occur. A quasi continuous rock fall activity and debris flow events have triggered from the rock glacier snout (Bühler and Graf, this volume and Graf *et al.*, this volume). The frontal erosion of the rock glacier is almost equivalent to the rock glacier displacement rate making the position of the front since 2009 roughly unchanged. Recurrent direct observation of the rock glacier internal frozen structure at the eroding front did not show so far the presence of significant massive ice layer within the rock glacier but only debris sealed by interstitial ice. Geophysical investigation carried out in 2009 (electrical resistivity tomography, ground-penetrating radar) has shown beneath 15 m depth the occurrence of a (probably still frozen) layer with high water content.

Historical knowledge from local inhabitants, aerial photographs and more recent InSAR data (Delaloye *et al.* 2010a) have permitted to partly reconstruct the timing and causes of the current destabilization phase, that can be summarized as follows:

- i On an oblique aerial photo in 1930, the Grabengufer rock glacier cirque looks like an undefined accumulation of blocky materials and no active front is clearly identifiable.
- ii A first destabilization occurred around 1940. On a vertical aerial photo in 1941, where unfortunately only the front of the rock glacier is visible, active debris-flow channels were clearly perceptible from the rock glacier toward the Grüngarten area, south of the Grabengufer gully. At that time, several dams were built at the rock glacier front and downwards with the principal aim to conduct the debris flows back into the Dorfbach torrent. On the left side of the rock glacier a lateral levee indicates a larger width (20–30 m) of the landform during the 1940 crisis in comparison to the current one (Fig. 4).
- iii Between 1950 and 1980, the rock glacier appears to have been again almost normally active. In 1967, a large transversal crevasse is visible at the surface of the rock glacier as a morphological reminiscence of the previous destabilization phase. This feature was still visible on 1977 and 1982 aerial photographs.

iv According to the analysis of aerial photographs the current crisis started between 1982 and 1988 with the following simplified development: (1) progressive overloading of the rooting zone of the rock glacier due to landslide and rock fall activity from the head areas; (2) build up of a compressive wave starting from the rooting zone of the rock glacier; (3) between 1995 and 2001 propagation of the compressive wave to the median part of the rock glacier, that began to strongly deform (development of new ridges and scarps); (4) progressive acceleration of the frontal part up to 5 m/year between 2001 and 2005; (5) increased destabilization of the frontal part due to its location on a steep convex slope; (6) destabilization of the entire of the landform (situation in 2009), partly pulled down by the rapid advance of the rock glacier tongue.

The development of the current crisis appears to be the result of a succession of dynamical reactions over 25 years and can be qualified as a mechanical surge process starting from the rooting zone of the rock glacier. There is no detailed information available for the previous crisis by 1940, but the basic process seems not to have been significantly different.

2.5 Gänder

Gänder is the last rapidly moving rock glacier being under investigation and only little information is currently available. The rock glacier is about 900 m long, 100 to 120 m wide, and the front is about 20 m high. The terminal rock glacier tongue moves parallel to the Gänder gully and consecutively does not feed it with large quantities of debris (Fig. 5). A transversal scarp has developed in the median part of the rock glacier where the slope becomes steeper. The velocity ranges from about 1.0 m/year above the scarp to 2.5 m/year in average downwards (Fig. 3b). Beside the steep slope topography a possible cause of the destabilization may be the excess of material lying in the median section of the rock glacier formerly pushed down by the glacier that developed in the rooting zone during the Little Ice Age.

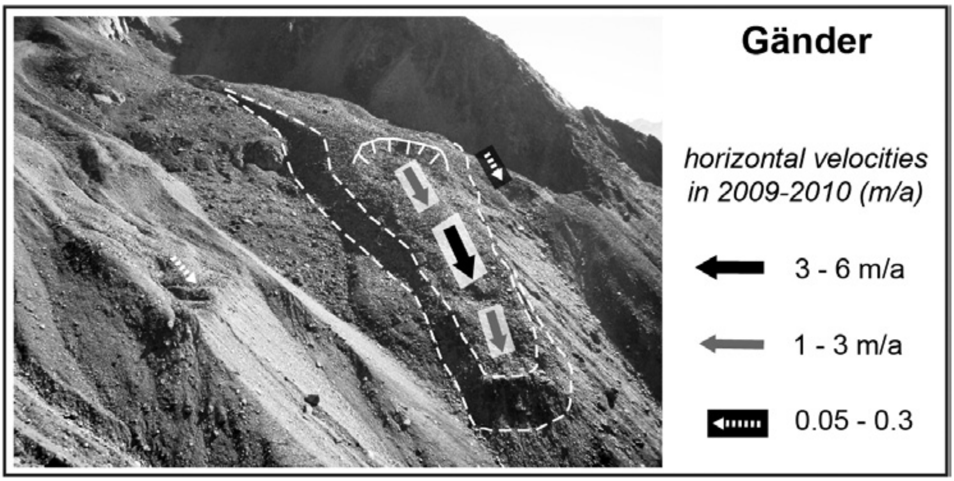

Fig. 5. Morphology and horizontal velocities of the Gänder rock glacier.

3 Discussion

The main causes of rock glacier destabilization are discussed hereafter. The preliminary results in Mattertal as well as other works carried out on rapidly moving rock glaciers (e.g. Delaloye and Morard 2011; Lambiel 2011) obviously show that several factors can lead to the triggering of a destabilization phase. These factors could be separated in three main categories: thermal, geometrical/topographical, mechanical. In addition the internal composition and structure of the rock glacier also play an influent role but is not expected to change significantly over time. A single or combine influence of these different elements over different time scales is likely expected to initiate the destabilization phase.

3.1 Thermal causes

In response to severe increase in air temperature that occurred during the 1980s and the permanence of warmer air temperature since that time, the permafrost temperature – at least in the uppermost 20 to 30 m – can be estimated to have warmed about 0.5 to 1°C for the last three decades. A change in the thermal conditions of the permafrost as it has occurred has at least two consequences (Roer *et al.* 2008), that both lead to the potentially increased activity of rock glaciers. The first one is the responding change of the rheological properties of ice, a warmer ice being more ductile than a colder one. The second one is the potential increase of unfrozen pore water, which diminishes the friction inside the rock glacier (Ikeda *et al.* 2008; Lambiel 2011). Hydrological effects are expected to be more pronounced within the permafrost body at the shear horizons or at its basis where an additional input of unfrozen water may contribute to the initiation of the slide-like mass wasting (Roer *et al.* 2008). Lab experiment by Davies *et al.* (2001) also showed that the stability of a frozen slope can be reduced with temperature rising close to the freezing point. In consequence, the creep of perennially frozen material close to 0 °C is significantly more sensitive to temperature changes than the creep of colder material (e.g. Kääb *et al.* 2007), a situation that is current in the alpine discontinuous permafrost zone. Regarding the probable permafrost warming of the last three decades, one has to consider that every alpine rock glaciers may have nowadays a different dynamical behavior than it was before. The onset of the destabilization of the Tsaté (Lambiel 2011; Scapozza and Lambiel, this volume) and Petit-Vélan (Delaloye and Morard 2011) rock glaciers, that occurred around 1990, appears to be a direct response to the change of the permafrost thermal state. In the case of rock glaciers in Mattertal, this onset appear most often be related to other mechanical and geometrical factors.

Within the last decade the monitoring and study of the kinematics of rock glaciers has been carried out more intensively (Haeberli *et al.* 2006; Roer *et al.* 2005; Kääb *et al.* 2007; Delaloye *et al.* 2008a, 2010a). One of the main results is that the surface displacement rate of active alpine rock glaciers – typically in the order of 0.1 to 2 m/year – displays a rather synchronous behaviour and responds sensitively with some delay to interannual surface temperature changes. The kinematical behaviour of the Dirru rock glacier, as the Petit-Vélan rock glacier (Delaloye and Morard 2011), is well fitting with those of other monitored active rock glaciers in the Valais Alps (Fig. 3c), what indicates that the dynamics of these rock glaciers is still thermally controlled.

3.2 Geometrical/topographical causes

One has to consider that geometry (morphology) of an active rock glacier is constantly changing over time and in connection with the topographical settings influences the rock glacier creep rate. The topography of the ground surface over which a rock glacier is developing is a major parameter for destabilization. On the one hand, a steeper slope angle favors higher shear stress and, on the other hand, convex bedrock topography favors the development of an extensive flow pattern and thus a local thinning of the rock glacier. These two aspects are encountered for all rapidly moving rock glaciers in the Mattertal: a convex topography with a steep terminal section. Moreover the Grosse Grabe, Gugla, Grabengufer and Gänder rock glacier have split or tend to split (transverse scarp development) on convex slope sections. It is identically the case of the Petit Vélan rock glacier, where the rapidly moving frontal part ruptured on an abrupt change of the bedrock slope angle (Delaloye and Morard 2011).

3.3 Mechanical causes by external factors

External factors could also initiate or reinforce the destabilization process. For instance a glacier advance during the little Ice Age was able to push pre-existing frozen sediments downstream and rearrange the pattern of the former debris accumulation (Reynard *et al.* 2003) and thus the dynamics of the entire rock glacier. Such a process seems to have occurred on the Dirru and Gänder rock glaciers and contributed to the current destabilization phase. Landslide, rock avalanche or rock falls may also partly overload a rock glacier with debris, initiating a destabilization phase. Such a development is obviously responsible for the destabilization of the Grabengufer rock glacier and perhaps also for the Grosse Grabe rock glacier. In any case, if the overloading (by a glacier or by sediments) is occurring in the rooting zone, a longer time is then necessary for the induced compressive wave to reach eventually the terminal part of the rock glacier to produce its destabilization. Twenty-five years were necessary to achieve this “mechanical surge” on the Grabengufer rock glacier and – if so – more than one century in the case of the Dirru rock glacier.

4 Conclusion

The current state of our investigation shows that the five rock glaciers analyzed in the Mattertal provide almost five different temporal and geometrical developments of the destabilization process. Whereas for instance the crisis of the Dirru rock glacier appears to be the final mechanical stage consecutive to the glacier invasion of its rooting zone during the Little Ice Age, the exceptional crisis of the Grabengufer was already preceded by a former, even larger crisis that began around 1940. The Grosse Grabe rock glacier has split in two distinct parts, whereas the other rock glaciers did not.

A unique explanation of the involved mechanisms for the unusual kinematics of these rock glaciers is so far probably to exclude. If the destabilization of the rock glaciers is certainly facilitated by the increase of permafrost temperature for the last two or three decades, it is also the result of the combined influence of different factors as the topography of the rock glacier bed over which the geometrical changes of the rock glacier morphology have occurred with time and the possible overloading of a rock glacier part consecutive to the Little Ice Age advance of a glacier or to a landslide or rock fall activity. Despite velocities from several m/year and so far the destabilization “level” remains unchanged the kinematics of a rapidly moving rock glacier appears to be still thermally controlled (e.g. Dirru). Indeed the relative interannual fluctuations are similar and synchronous to those of other active rock glaciers (e.g. Delaloye and Morard 2011 for the Petit-Vélan rock glacier).

The current paper has been intended to provide preliminary results and discussion elements on the so-called destabilization of rock glaciers. The end of the current project in 2013 is expected to give the opportunity of disposing of more elaborated results and of providing the basis for an in-depth discussion of some of the processes responsible for the destabilization of alpine rock glaciers and resulting consequences for underlying torrents.

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