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INFLUENCE OF THE CONNECTIVITY WITH PERMAFROST ON THE DEBRIS-FLOW TRIGGERING IN HIGH-ALPINE ENVIRONMENT

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ABSTRACT

The study area is the Bonnard glacier which lies in the Anniviers Valley, Valais, Switzerland. Two glacial torrents originate from a source area that is composed of 60% of creeping permafrost which supplies loose material. Heavy rainfall events trigger debris flows on the steep slopes of the lower permafrost complex. Three scarps are visible, two of them from the last event in 2008. In scar n°1 the permafrost plays a key role in triggering debris flow by loading the streambed with unstable materials and creating an impervious layer due to the presence of ice and/or frozen ground. In scar n° 2 the triggering follows shallow landslide liquefaction with no signs of permafrost, though we know that it surrounds this area. There, we assume that the water circulation, influenced by frozen layer upstream is a key factor. Scar n°3 shows only superficial erosion that contributes to gully recharge. Four processes of debris-flow triggering related to permafrost can be highlighted: cohesion loss of sediments due to thaw in the matrix, cohesion reduction due to the constant creeping, spatio-temporal changes in water circulation and constant rejuvenation of sediment on the slope. For this site, the permafrost complex is a key factor for the triggering of debris flow, although we should take into consideration all other geomechanical processes that may occur in loose sediments.

Key words: *alpine debris flow, triggering, permafrost*

INTRODUCTION

Results from a case study of debris-flow events involving permafrost-related features provide new information regarding the relationship between debris-flow hazard and permafrost in an alpine environment.

In the European Alps, a series of debris flows at the end of the 1990's already highlighted the connection between permafrost (or so-called recently deglaciated area) and debris flow (Haeberli *et alii*, 1991; Harris & Gustafson, 1993; Rickenmann & Zimmermann, 1993). This sensitivity of the high-altitude environment is similar in other mountain ranges (e.g. Seinova, 1991; Palacios *et alii*, 1999, Seinova & Zolotarev, 2003). In the same period, with the accumulation of evidence on global warming many authors have predicted an increase in debris flows triggered by melting of previously frozen sediments (Zimmermann & Haeberli, 1992; Rebetez *et alii*, 1997).

Frozen soils have been the subject of several geotechnical studies aimed at understanding the micro-mechanisms leading to their deformation (e.g. Dysli, 1993; Harris *et alii*, 2003; Arenson & Palmer, 2005; Arenson & Springman, 2005). However, as noted by Dysli (2007), only a few studies concentrated on the processes during thaw. Owing to the logistical difficulties, most of these studies are done in the labs. To our knowledge, only a few are directly done in the field (Teysseire *et alii*, 2000; Springman & Teysseire, 2001).

This work shows how debris-flow triggering is connected to permafrost at a macro-scale manage-

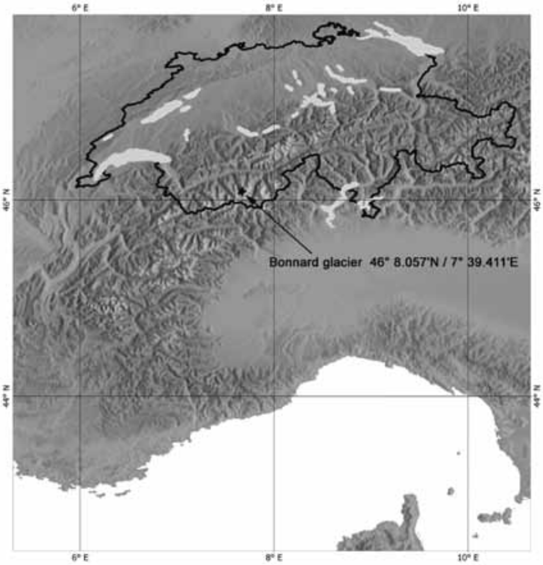

Fig. 1 - Location of the study area

able in the field. In presenting 4 chains of processes leading to debris flow formation, the studied site stands as an interesting outdoor laboratory. These 4 different ways of connecting permafrost to debris flow may be combined providing a glimpse of the complexity of the high-alpine environment as already noted by others (e.g. Haeberli, 1992). However, this work is not an exhaustive presentation of the possible connection between debris flow and permafrost, but it presents a first step toward a *functional analysis* at a macro-scale of alpine catchments suffering permafrost degradation.

Traditionally in mountainous environments, streams are influenced by water and sediments. Thus, catchments may be divided into (Surell, 1841; Meunier, 1991):

1. a source area (or production area for water as well as for sediments);
2. a transient area (where erosion and deposition may occurs alternatively);
3. a deposition area (on the alluvial fan where the deposition is the preponderant process).

During our study it became clear that at this macro-scale we have to distinguish between two debris flow stages: an initial stage encompassing the onset of the movement phase to the preliminary flow under a debris-flow form and an advanced debris flow stage in which the characteristics derived from the initial stage have evolved during the flow downstream. The evolution concerns not only the volume (e.g. King, 1996) as it will be emphasized here, but also other intrinsic characteristics such as the grain size distribution and the relative mineralogical composition, which in turn may change the flow behaviour (Bardou *et alii*, 2007).

STUDY AREA

GENERAL SETTINGS

The study area is located in the Canton of Valais, Southwestern Switzerland (Figure 1). The catchments range in altitude between of 1660 and 3548 m^{asl}. It implies that low temperature (freezing) and snow play an important role in the water balance across the year. The area concerned is about 3 km^2 of which the source area represents ~1.7 km^2. Two torrents originate from there, the Pétérey in the North and the Tracuit's torrent in the South. Approximately 60% of the source area is composed by creeping permafrost. It is beyond of the scope of this paper to outline in detail these parts of the catchments and we will refer to it below as the permafrost complex or the Bonnard glacier.

The geology of the source area is located on the contact between the thrust sheets of the Dent Blanche and Tsaté systems (Pilloud & Sartori 1981). The granitic gneisses of the Dent Blanche covering the Bonnard glacier fall from the cliffs that surround Diablons summit. The outcrops directly around the glacier and moraine bastion are made of gabbros. The outcrops and the cliffs are fractured and produce a very large amount of blocks that rarely exceed 1 m in diameter. Scree fans completely encircle the glacial system as can be seen on Figure 4. The slopes below the source area are mainly formed by hanging till from the Zinal glacier and others slopes deposits.

The slope downstream from the source area is very steep (Figg. 4 and 6), exceeding 80% just after the initiation zone. Below 2500 m a.s.l., the slope fall to less than 40% occasionally inducing debris-flow deposition. In the last third of the long profile a rock cliff increases the slope before the gentle reduction on the alluvial fan (with a mean slope of ~18%).

PERMAFROST FEATURES

The permafrost zone of the Bonnard glacier is very complex, with a combination of feature including rock glacier, moraine, push moraine and covered glacier or at least shreds of a former glacial edifice (visible on the maps of XIX century). Indeed, massive ice was sometimes observed (Fig. 2).

This permafrost complex feeds the two torrents with loose material, but debris-flow frequency in each torrent differs notably. The displacement measurement made by differential global positioning system (DGPS) on more than 150 points on the whole area show that since 2006 the average displacements have been around 0.5 m/a.

EVENT HISTORY

The Pétérey, that originates from the north lobe of the complex outbreaks frequently. The etymology of this very active torrent itself gives us a first clue about this activity: indeed, in former dialect, Pétérey means quagmire. Considering events detected by dendrochronology analysis (Stoffel & Bollschweiler, 2009), a total of at least 15 major events have been recorded for the Pétérey (Fig. 3). People living near the torrent's bank speak of a mean of 1, with up to 3 debris flows per year. However the sensitivity of local inhabitants (Zinal has been inhabited year round only since 1961) increases with time as roughly depicted by the detection threshold on Figure 3. The building of the retention dam (since 1958) increased this threshold at the beginning, but has been less effective since 1980 due to less maintenance as a result of rising costs.

Fig. 2 - Massive ice observed at the Péterey's triggering zone

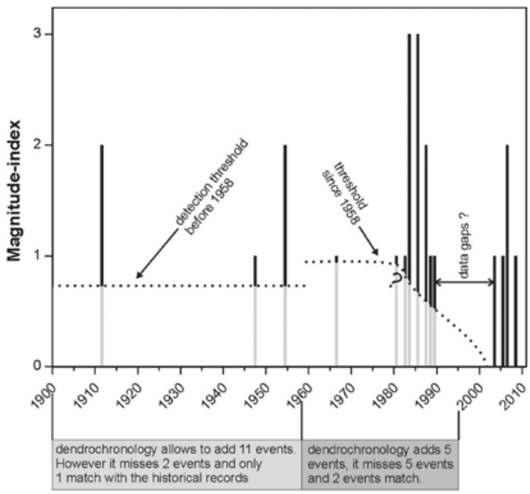

Fig. 3 - Historical chronic of events recorded for the Pétérey. The magnitude-index is derived form the level of damages or area covered by debris: 1 is for middle-sized event, 2 for rare and 3 for extreme (information about dendrochronology is from Stoffel & Bollschweiler, 2009)

Conversely, only 2 major events are reported for the Tracuit's torrent, probably due to the lack of historical data. However, these two debris flows originated from an area corresponding to the shallow landslide scar at the border of the permafrost complex, mainly formed here by what we think is a push moraine (Figure 4).

RESULTS OF FIELD OBSERVATIONS

PERMAFROST AREA & TRIGGERING POINTS

As shown by the geomorphological map (Fig. 4), the debris flow triggering zones are located in the lower part of the permafrost complex. However, all starting points present different features. The detailed map of this area (Fig. 5) illustrates these differences.

Scar n°1 delimits the terrain where Figure 2 is located. The ice near the surface is covered with unstable blocks with matrix elements at the base. Most recent "initial debris flows" seem to originate from this zone, lying at the end of one of the major mapped sub-channels (see below). Field evidence and older photographies do not exclude triggering from the other stream branch, but fresh tracks were not visible during our field campaigns.

Scar n° 2 represents the starting zone for two reported debris flows in Tracuit's torrent. Field observations made in the scar after the last event (in 2008) didn’t show any humidity or ice traces. The scoured depth was approximately 1.5 m, with an estimated 500 m^3 of material that started moving as a shallow landslide. The downstream channel presents fresh erosion marks. It is of interest to note that in 2009, even on this >35° slope, some material was already stored in the channel, which is a similar timescale to

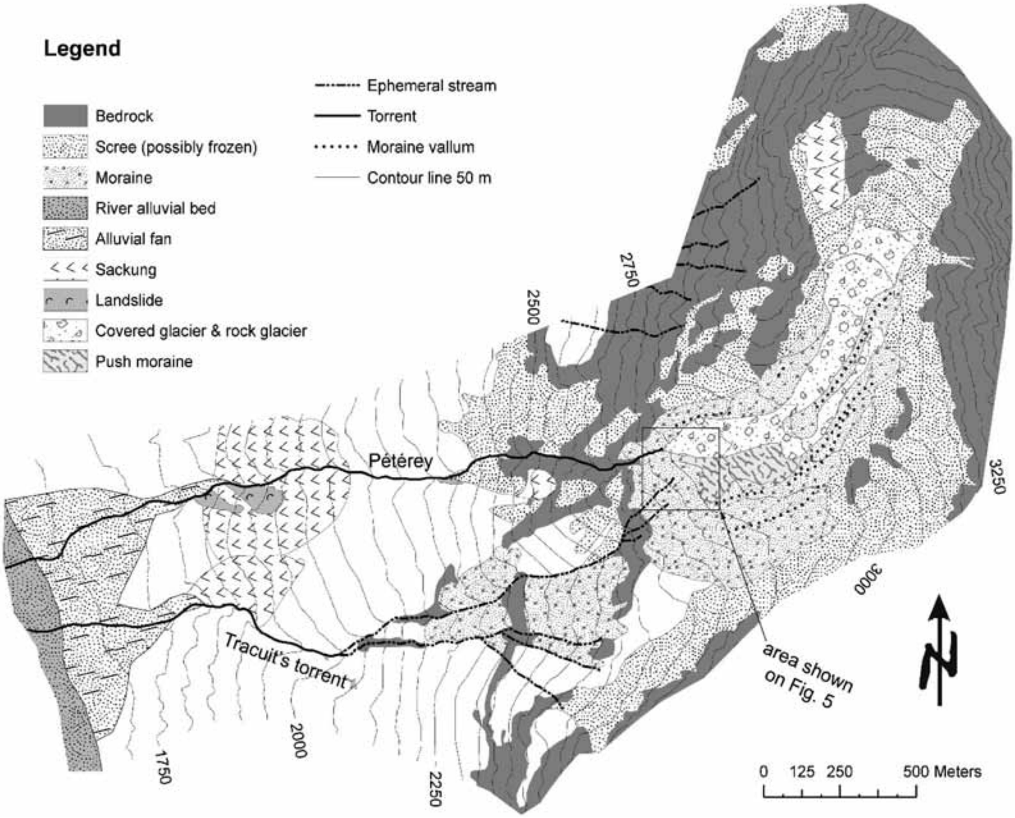

Fig. 4 - Simplified geomorphological map of the Bonnard glacier complex. Debris-flow triggering zones investigated are on the headwaters of the torrents (roughly on the 2800 m contour line)

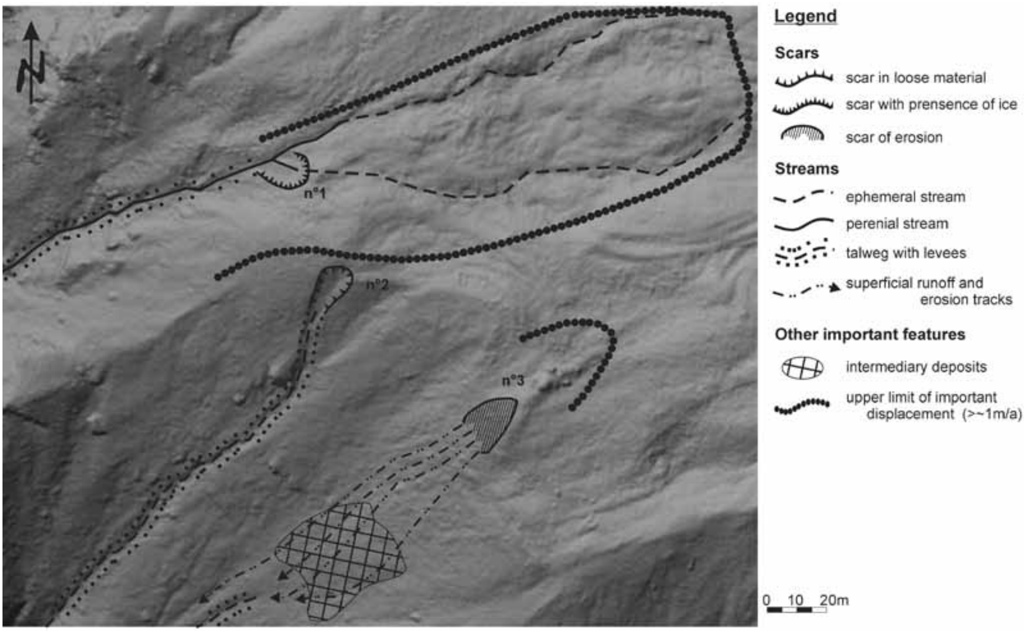

Fig. 5 - Map of the debris flow triggering zones as observed during field campaigns achieved between 2007 and 2009

one reported by Bovis & Jakob (1999) and far more rapid than one reported by Benda & Dunne (1997).

Small initial debris flows also started from zone n°3. This source area presents a diffuse erosion pattern linked to thin superficial runoff (small rills) without evidences of water supply from the upstream permafrost complex. A part of the material that originates from scar n°3 has already been deposited downstream as scree (on slope >35°). Further downstream, at ~2630 m a.s.l., other fresh intermediate deposits (levees and complete snout) could be seen after the 2008 survey on a slope between 30-33°.

During the summer of 2007, in scar n°1 we performed a tracer test in water running along the upper part of the cover material. The estimated transit velocity of 4'000 m/d is ~10 times slower than what can be expected for free surface runoff and ~1000 times faster than in a very porous material. Calculated values are representative of fractured aquifers and these magnitudes are semi-quantitative proxies for describing subsurface hydrological processes. They are very rapid in this area (north lobe), which contrasts with the absence of surface water in the south lobe of the complex.

OTHERS PARAMETERS INFLUENCING THE FINAL MAGNITUDE OF DEBRIS FLOW

As shown simplified in Figure 4, in addition to the permafrost complex, other processes may contribute to the final debris-flow volume (detailed mapping performed in the study). These processes include shallow and deep-seated landslides (e.g. Baur *et alii*, 1992; Iverson *et alii*, 1997; Jakob *et alii*, 1997; Reid *et alii*, 2003), and slope of the reach, which influences deposition (proportionally to the debris-flow magnitude). These processes can contribute to recharging the gully, which in turn balances the probability of occurrence of large debris flows (Jakob *et alii*, 2005).

If we consider the cumulative volume of the 2008 debris flow that occurs in the Pétérey one could see that the initial volume of debris directly linked to the permafrost area is only 17% of the total volume (Fig. 6). It should be noted that this ratio is only representative for this particular event, which is, according to the debris-flow history, a middle-sized event (magnitude-index of 1 on Fig. 3). For other magnitudes or in other environments this ratio may change (e.g. King, 1996; Johnson *et alii*, 2008).

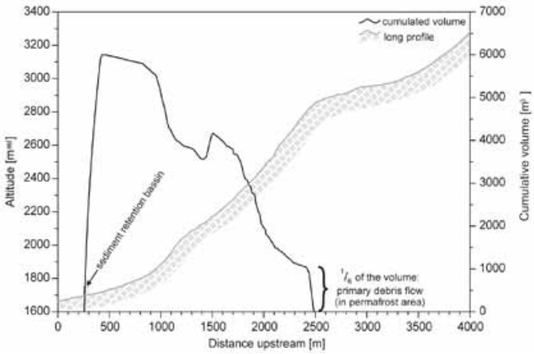

Fig. 6 - Cumulative volume of the 2008 debris flow as surveyed in the field. The major part of the deposition occurs in a sediment trap

During the same rainfall event, a ~1'500 m^3 debris flow occurred in the Tracuit's torrent. Evidence shows that the main source area is scar n°2 (Fig. 5). Here, the initial debris flow represents 25% of the whole volume.

DISCUSSION

SCAR N°1

In scar n°1 (Fig. 5), permafrost plays a key role in the triggering of debris flows. However, this role is defined by several mechanisms. First, due to the slope (38-40°) and the constant movement induced by Bonnard glacier complex, sediments of all sizes are at the limit of equilibrium. Individual elements are available for mass wasting and in close connection with the thalweg's torrent. Unstable material on these slopes may be regarded as very likely to develop debris flow (Rickenmann, 1999). After resurgence of water, bed erosion thickness itself can be greater than 5 m in this environment (Kronfellner-Kraus, 1984; Rickenmann & Zimmermann, 1993).

Second the presence of ice (lens or shreds from former the glacier) and/or frozen soil tend to facilitate the concentration of water as observed in other permafrost complexes (e.g. Krainer & Mostler, 2002). From the strict point of view of debris-flow triggering, sudden water supply is sufficient to mobilize sediments, due to drag forces and/or increase of pore pressure in the soil (Anderson & Sitar, 1995; Reid *et alii*, 1997). However in the case of Pétérey, due to the nature of the deposits, pore pressure increase should dissipate rapidly after the onset of movement. It is difficult to determine whether the pore pressure increase is a preponderant process or not. In addition, thin layers of similar material lying on bedrock in a non permafrost area could experience initial debris flow of the same magnitude.

SCAR N° 2

In this zone, the triggering mechanism is similar to a shallow landslide liquefaction classically reported as a factor in debris flow formation (e.g. Sassa, 1984; Fleming *et alii*, 1989; Iverson *et alii*, 1997). Altough we have no evidence of permafrost in this scar, we know it surrounds the zone. A possible direct effect of permafrost on the onset of movement may be due to the decrease in apparent cohesion with melting of ice particles (Arenson & Springman, 2005).

By combining information about connectivity and the sediment dynamics on a long profile, we show the importance of the permafrost complex relative to other mass wasting processes. Figure 7 shows that only a very short part of the stream is connected to the permafrost complex. Intuitively, with regard to other downstream sediment feeding mechanisms, the part of the debris flow material possibly linked with permafrost should represent only a part of the whole volume.

An indirect effect of permafrost may be changes in the near surface flow paths upstream of the scar. Several authors have noted that these processes may lead to triggering (Palacios *et alii*, 1999; Chiarle *et alii*, 2007). In our case, no moisture is observed in the scar, and compared with tests performed in similar environments by Teysseire *et alii* (2000) it is unlikely that the rainfall can percolate deep into the ground, thus intermittent water supplies must come from upstream. Indeed, the 1st July 2008 rainfall was not sufficient to saturate the soil at 1.5 m depth, as observed. Thus here, the permafrost has influenced the water supply but not the geotechnical characteristics.

SCAR N° 3

The material starting to move from scar n°3 within the area that has undergone important displacement (≥1 m/a) in the south lobe of the complex. There, the thrust from the upstream creeping permafrost continuously rejuvenates the sediments in the slope, keeping it naturally at the limit of the friction angle. This colluvial material may be the primary source of sediments transfer (Montgomery & Buffington, 1997), which in turn may concentrate to form debris flows. This could be similar to the hydrologicaltriggering type described by Meunier (1991). Based on the current observations, it is impossible to quantify the proportion of material originating directly from this scar as an initial debris flow with the proportion of material eroded along the path that contributed to the final total debris flows volume deposited on the fan. The onset of particle movement due to the development of drag forces can be derived from the work of many authors, although not explicitly described as a triggering phenomenon (e.g. Julien, 1998; Takken & Govers, 2000; Egashira *et alii*, 2001). For now it is not clear if this source represents a small part of the volume for each debris flow, or if it contributes to gully recharge, leading to more intense future debris flows.

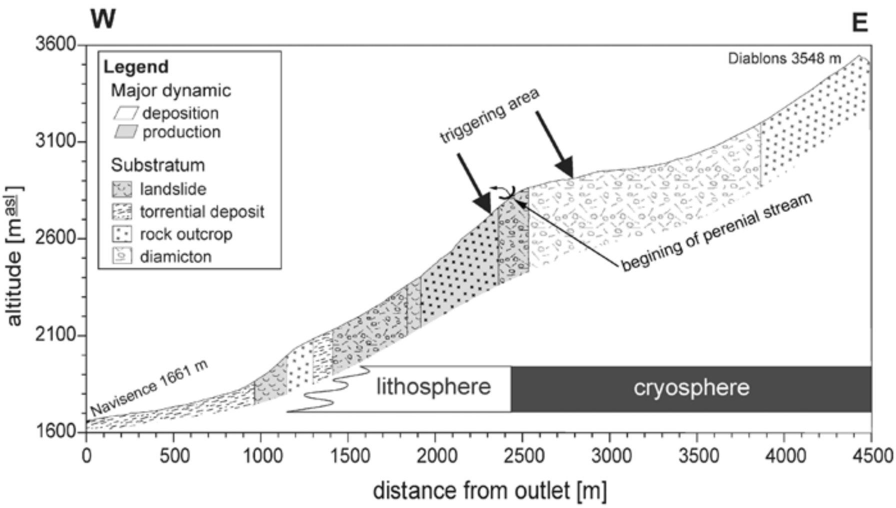

Fig. 7 - Long profile wrapped with: the major dynamic (white or gray background); quality of the substratum (patterns); extension of the permafrost complex. There is no information about material depth, vertical separation are there only for graphic purpose

VOLUME ENTRAINED ON THE DOWNSTREAM REACHES

As soon as the debris flow becomes channelized, depending on the type of substratum, erosion (i.e. volume addition) continues to occur. This channel incision (e.g. Kronfellner-Kraus, 1984; Zimmermann, 1990) may be supplemented by connected mass movements (e.g. Johnson & Rodine, 1984) to form a landslidetriggering type (Meunier, 1991). Among the different methods of debris-flow volume assessment, Hungr *et alii* (1984) propose summing these two additional volumes at the reach scale to estimate the final volume.

It must be remembered here that Figure 6 is only valid for the event of the 1st of July 2008. This initial volume of 17% does not stand as a rule for torrents in general. Moreover, it may be different for other environment or hydrometeorological situations as noticed by other authors who find that the initial released volume contributes up to 92% of the total (Johnson *et alii*, 2008).

The results presented in Figure 6 are consistent with the work of other authors, but as stressed by Benda *et alii* (2005), it is important to link the depicted figure there with the probability of occurrence. Here, the linkage could be done only in a qualitative way. Indeed, the addition of volume to the initial debris flow triggered from the permafrost area is a strongly stochastic process (Benda & Dunne, 1997; May & Gresswell, 2003; Bardou & Jaboyedoff, 2008). The volume involved in the formation of initial debris flow in the permafrost area is constrained by local geometry (vicinity of scar n° 1). The geomorphological estimations in Pétérey show that the initial volume of initial debris-flow volume may be expanded by a factor 3 to 4, while the downstream (advanced) debris-flow volume may be increased by a factor 6 to 10 (mainly due to the presence of active landslides, in the last third of the torrent see map Fig. 4).

The magnitude of additional downstream volume entrainment can be linked with the magnitude of the initial debris-flow volume and the ratio of the initial volume to the whole volume deposited on the alluvial fan is likely to be the same or less, except for dramatic processes involved in general destabilization of the permafrost complex, such as Kolka-Karamadon catastrophe's kind (e.g. Haeberli *et alii*, 2004).

CONCLUSION

The compilation of post-event observations, geomorphological mapping and DGPS monitoring allow us to distinguish four processes of debris-flow triggering related to permafrost:

1. cohesion loss of sediment formerly cemented by ice and/or frozen matrix (case of scar n° 1);
2. cohesion reduction due to the constant movement induced by dynamics of the above permafrost complex;
3. spatio-temporal changes in water circulation, leading to sudden variations in water supply (case of scars n° 1 and 2);
4. constant rejuvenation of sediment accumulated on slope due to the thrust of creeping permafrost, keeping it at the limit of equilibrium (case of scar n° 3).

In addition, we must take into consideration all other geomechanical processes, non-permafrost related, that may occur in loose sediments hanging on steep slopes (due to increases in internal pore pressure).

In the present case study, the Bonnard glacier permafrost complex appears to be a key factor in the formation of initial debris flows. The recorded events and observations made since 2006 demonstrate that all events originate from this area. Notwithstanding, we could not exclude debris flows originating from other catchments parts below the altitude of the permafrost belt, the volume of initial debris flow can nevertheless be seen as a "detonator" for more intense advanced events.

To conclude, the debris-flow hazard for the downstream communities should only be analysed in a global framework as the permafrost related volume represents only a fraction of the total volume. The event magnitude is thus closely dependent on:

1. the local interaction between the cryospheric and lithospheric features (i.e. geometry, constituents, stream connection type);
2. the rate of deformation of the permafrost complex;
3. the connectivity of the downstream non-permafrost mass wasting phenomenon.

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