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A NETWORK OF OBSERVERS IN THE MONT-BLANC MASSIF TO STUDY ROCKFALL FROM HIGH ALPINE ROCKWALLS

ABSTRACT: RAVANEL L. & DELINE P., *A network of observers in the Mont-Blanc massif to study rockfall from high Alpine rockwalls*. (IT ISSN 0391-9838, 2013).

The study of rockfall (volume > 100 m^3) in high mountain is essential to understand landscape evolution and to evaluate natural hazards. The number of rockfalls is presently rising in the Alps, while vulnerability is increasing at high elevation and in valleys. Due to the lack of systematic observations, frequency and volume of rockfalls, as well as their triggering factors remain poorly understood. Until today, most of the studies on rockfall carried out in high Alpine rockwalls were indeed devoted to individual events, while systematic surveys are needed to clarify the role of regional factors such as permafrost degradation. Here we present the network of observers (guides, hut keepers, mountaineers) which sets aside the documentation of all the rockfall events that occur in the central part of the Mont-Blanc massif. Operational since 2007, this network allowed identifying and documenting 251 rockfalls between 2007 and 2011. Checked and completed each year by extensive field work, data from the network are then analysed through a Geographic Information System to statistically characterise these rockfalls. The results of the first five years of survey indicate that permafrost degradation is the main rockfall triggering factor.

KEY WORDS: Rockfall, Permafrost, High Alpine rockwalls, Network of observers, GIS, Mont-Blanc massif.

INTRODUCTION

Due to their steep topography, high mountain areas are affected by significant gravity-related transfers of material such as rockfall (Fort & *alii*, 2009), which represents the sudden collapse of a rock mass from a steep rockwall with a volume exceeding 100 m^3. Rockfall is the most unexpected process because of its possible high speed and large rock volume, it may imprint profound changes to rock slopes, and it generates risks for populations and infrastructures (Haeberli & *alii*, 1997): destruction of infrastructures, damages on infrastructures and flows of people (tourists, workers) located along the rockfall path, and material and human risks on the valley floor through cascading effects.

In the last two decades, many rockfalls and rock avalanches affected high Alpine rockwalls throughout the World. Several mixed both rock and ice, with a volume exceeding 1×10^6 m^3: Mount Cook in New Zealand in 1991 (14×10^6 m^3; McSaveney, 2002), Kolka-Karmadon in the Caucasus in 2002 (100×10^6 m^3; Huggel & *alii*, 2005), Punta Thurwieser in Italy in 2004 (2.5×10^6 m^3; Pirulli, 2009), and Piz Cengalo in Switzerland in 2011 (3×10^6 m^3; Allen & Huggel, 2012). Other rockfalls with a smaller volume occurred at the Matterhorn in Switzerland in 2003 (1000 m^3), the Cima Una in Italy in 2007 (40,000 m^3; Coratza & De Waele, 2012), and the Drus (Ravanel & Deline, 2008) in the Mont-Blanc massif in France in 1997 (27,000 m^3), 2003 (6500 m^3), 2005 (250,000 m^3), and 2011 (15,000 then 43,000 m^3).

The failure mechanisms differ according to the topographic and structural configuration. However, rockfall generally occurs in hard rocks along pre-existing geological discontinuities. In high mountain areas, three major factors, possibly combined, were identified as rockfall triggers (Evans & Gardner, 1989): (i) glacial debuttressing following glacial retreat (Cossart & *alii*, 2008), (ii) seismic activity (Becker & Davenport, 2003), and (iii) permafrost degradation (Harris & *alii*, 2009), which corresponds to the warming up of the permafrost, ground (*i.e.*, substratum) that remains at or below 0°C for at least two years, thus generating physical changes of the potential interstitial ice (Gruber & Haeberli, 2007).

The characterisation of rockfall and the understanding of its evolution (in terms of frequency, volume and location) are prerequisites to any response of management. However, data on rockfall at high elevation are rare, with the danger to interpret non-representative data. It is thus necessary to systematically collect and process rockfall da-

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ta in order to better characterise this process (triggering conditions, frequency, volume), which occurrence is higher due to global warming (Evans & Clague, 1994; Ravanel & Deline, 2011). The aim of this article is to present a method that enables to acquire exhaustive data on current rockfalls in a high mountain area in order to get a representative database to investigate what triggers rockfall, and especially to clarify the role of the permafrost degradation. The inventory of annual rockfalls occurring within the Mont-Blanc massif was only made possible by a well-structured network of observers (Ravanel & *alii*, 2010).

SETTING UP OF A NETWORK OF OBSERVERS IN THE MONT-BLANC MASSIF

The idea of a network of rockfall observers in the Mont-Blanc massif came up in 2005, after the heat wave of the summer 2003, characterised by a high number of rockfalls (Ravanel & *alii*, 2011), as elsewhere in the Alps (Schiermeier, 2003). The characteristics of this massif make it an ideal study site for rockfall in permafrost-affected area: rockwalls are high, steep and fractured so that numerous rockfalls occurred in the past (Ravanel & Deline, 2011).

The Mont-Blanc massif, a relevant site to study rockfalls

The Mont-Blanc massif (fig. 1) develops its 550 km^2 on the outer margin of the Western Alps. More than 20% of its surface area is covered by glaciers (Gardent & *alii*, 2012) and permafrost affects a large area (40-50%). On a geological point of view, almost all of the Mont-Blanc rocks are crystalline rocks (Von Raumer, 1999), the late-Hercynian grained granite of the Mont-Blanc being intrusive within the Hercynian metamorphic series. These rocks show evidence of a multiphase geological history, which generated shear zones and fractures (Bertini & *alii*, 1985). The large-scale deformation that affects the Mont-Blanc granite corresponds to faults and shear zones. Several tectonic directions are superimposed in the Mont-Blanc massif: Hercynian structures oriented mainly N-S to N25°E and Alpine structures oriented N45°E to N60°E.

Fractures and slope steepness make the Mont-Blanc massif conducive to mass movements (Deline, 2009). Therefore rock instability and the role of the permafrost degradation as triggering factor can be studied, especially considering that large rock avalanches occurred in the massif in the past. Indeed, a large rock avalanche occurred in AD 1717 on the Triolet glacier, involving a collapsed volume of *ca.* 8.5×10^6 m^3, which was dispersed over 2.9 km^2 (Deline & Kirkbride, 2009). More recently, the Brenva glacier experienced two major rock-avalanches (Deline, 2001), at the Grand Pilier d'Angle in 1920 (*ca*. 3×10^6 m^3) and the Eperon de la Brenva in 1997 (2×10^6 m^3). These cases suggest that rockfalls and rock avalanches account for major morphodynamics in the Mont-Blanc massif (Deline, 2009; Deline & *alii*, 2012).

2006-2007: setting up of the network

On the French side of Mont-Blanc massif, the first precisely documented rockfalls date from 2005. Some mountain guides and hut keepers, aware of our research, also reported a few scattered observations. The limited data however prohibited a statistical analysis due to their low representativeness.

In 2006, a dozen of guides from Chamonix were specifically educated/trained in the framework of the *PERMAdataROC* project (http://www.fondazionemontagnasicura.org/multimedia/permadataroc/start_fra.htm). These guides

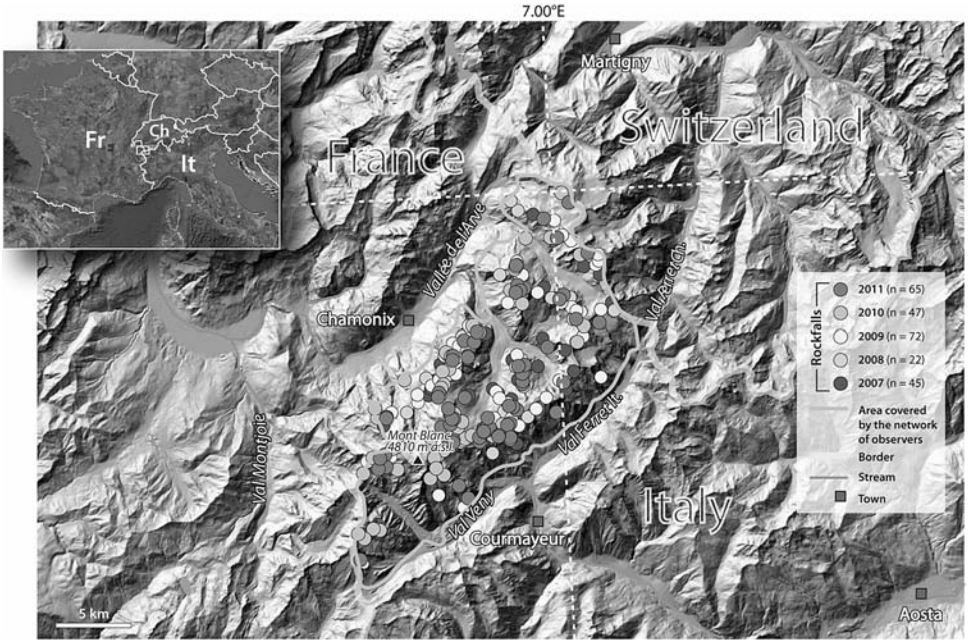


FIG. 1 - The Mont-Blanc massif and the distribution of the surveyed rockfalls (topography: ESRI DEM).

today still belong to the network of observers. Twelve rockfalls were documented, but completeness was not achieved as shown by field work during Fall 2006.

The network was fully operational in 2007, focusing on the central part (57%) of the massif (Ravanel & *alii*, 2010). Due to the heavy workload, the Swiss (24% of the massif) and French SW (19%) sectors were set apart from the network. After few events observed during Winter and Spring 2007, 180 guides were invited to an information meeting in Chamonix in May 2007. The presentation of the *PERMA dataROC* project and its first results decided about 35 of the 45 guides who were present to be involved in the network of observers. Throughout the Summer 2007, a close relationship with the guides of the *Compagnie des Guides de Chamonix* helped to energize this network. On the Italian side, a second network was set up in collaboration with the *Fondation Montagne Sure* (FMS) in Courmayeur, which mobilised a dozen of guides; Italian data were collected by a geologist (also Alpine guide) and then transmitted to us. Finally, most of the hut keepers of the central part of the Mont-Blanc massif were visited in spring 2007 and got a presentation of our research. Hut keepers are observers of a high quality as permanently present in an area of the massif at least through the whole Summer. They have a perfect knowledge of their geographical sector and rock faces accessible from their hut. They also represent a relay of our work to all mountaineers. This last point is very important to get a network as operational as possible. We committed to include them in the network, through two elements. A poster (fig. 2) was displayed in the massif huts and in organisations such as the Chamonix section of the *Club Alpin Français* (CAF), the *Compagnie des Guides de Chamonix*, and the *Office de Haute Montagne* of Chamonix. It is an educational poster, as it exposes the main mechanisms involved in rock failures in high mountain and their triggers; it is also a poster with a scientific purpose, requesting the alpinists to send us their rockfall observations. A web page (http://edytem.univ-savoie.fr/eboulements) dealing with our work and related issues contains additional documents that are downloadable, to encourage anyone to send us his observations. Finally, in order to stimulate the integration of members of the *Peloton de Gendarmerie de Haute Montagne* (PGHM) of Chamonix, the *Ecole Nationale de Ski et d'Alpinisme* (ENSA) and the *Centre National d'Entraînement à l'Alpinisme et au Ski* (CNEAS) of the French national police of Chamonix in the network, geomorphology and geology courses are offered to them since 2007.

NETWORK OPERATION

Rockfall identification

All professionals mentioned above receive each year by email a rockfall notification form (fig. 3), and the link to our research webpage (where this form is downloadable), also mentioned on the poster, the notification form itself, and the web (mountaineering forums in particular). The form is intended to collect the most relevant/significant elements of each observation done by a professional or an amateur. It must provide information as complete and accurate as possible about the dimensions and conditions of the collapse while remaining as simple as possible to be easily filled on the field by the observer.

Several data series are to be filled: source area of the rockfall, location of the observation point, and conditions of the slope at the rupture zone. Photographs are solicited, together with other comments or details such as weather conditions during the day of the collapse and during the previous days, snow/ice conditions of the face where the collapse occurred, *etc.* (fig. 3).

The form may be completed and left in huts where blank sheets are generally available (filled forms are collected later on in the season when closing), or returned by e-mail (possibly *via* the webpage). Many observations are also transmitted directly by phone or during interviews.

Since 2007, the French network has collected data on both sides of the massif, reinforced in 2007 and 2008 by the Italian network. In 2009, this latter one could not be maintained but observations from Italian guides were however received/collected, often corroborating the observations from the French network. From 2009 to 2011, the network was maintained as part of the *PermaNET* project (http://www.permanet-alpinespace.eu/).

Observation checking and role of the fieldwork

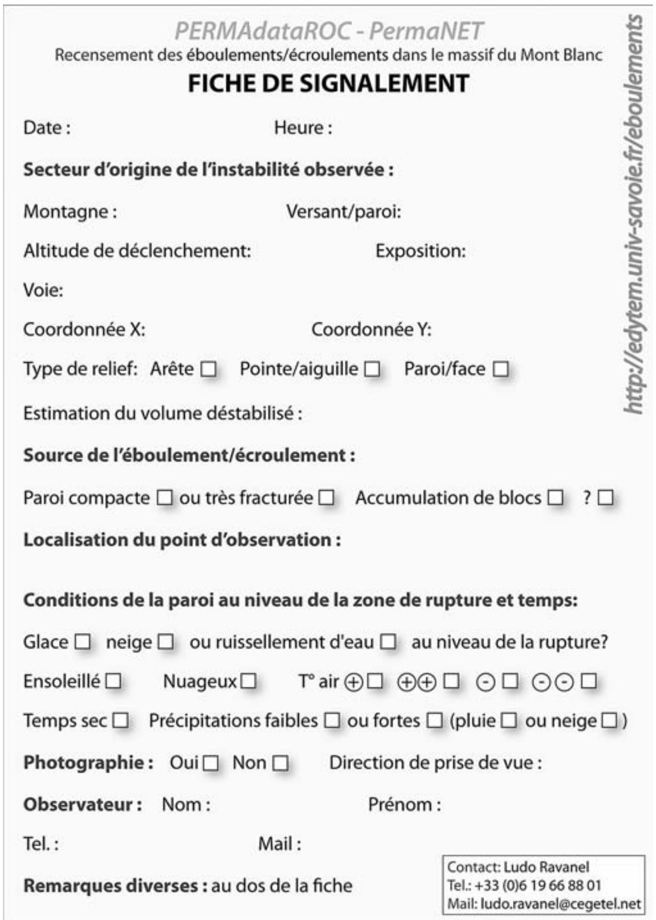
The network guarantees a very good representativeness of the data obtained but cannot ensure a perfect completeness of the inventory. After each fall event, an extensive fieldwork is thus routinely carried out to verify the observations from the network and/or to complete them with further data. Also, in poorly frequented areas, fieldwork is carried out at locations that were not reported by the network but identified by correlative deposit. Such field campaigns lasted 15 days in 2007, half less in 2008 due to early heavy snowfalls at low elevation, more than 20 in 2009 (partly to fill the gaps of 2008), and 10-15 days in 2010 and 2011.

The first type of additional elements is derived from field observations. In general, it corresponds to items, which have not been or incorrectly filled in by the observers on the notification forms. Only local weather and water/snow/ice conditions of the detachment zone at the time of the collapse cannot be adequately post-informed. In addition, the data contained in the forms (or directly given) are checked when possible (precise location, elevation and volume in particular).

Field campaigns are also opportunities to make additional observations on recent deposits (*i.e.*, linked to rockfalls of the year), which might have not been reported through the network, to complete the inventory and make it as exhaustive as possible, except for 2008 when some events could have remained unidentified.

In 2007, during the first year with a fully operational network, a verification of its quality has been achieved from the analysis of aerial photographs. Almost 37% of

FIG. 2 - Poster (A1 format) displayed in the Mont-Blanc massif huts and mountain organisations.



PERMAdataROC - PermaNET

Recensement des éboulements/écroulements dans le massif du Mont Blanc

FICHE DE SIGNALEMENT

Date : Heure :

Secteur d'origine de l'instabilité observée :

Montagne : Versant/paroi:

Altitude de déclenchement: Exposition:

Voie:

Coordonnée X: Coordonnée Y:

Type de relief: Arête ☐ Pointe/aiguille ☐ Paroi/face ☐

Estimation du volume déstabilisé :

Source de l'éboulement/écroulement :

Paroi compacte ☐ ou très fracturée ☐ Accumulation de blocs ☐ ? ☐

Localisation du point d'observation :

Conditions de la paroi au niveau de la zone de rupture et temps:

Glace ☐ neige ☐ ou ruissellement d'eau ☐ au niveau de la rupture?

Ensoleillé ☐ Nuageux ☐ T° air ⊕☐ ⊕⊕ ☐ ⊝ ☐ ⊝⊝ ☐

Temps sec ☐ Précipitations faibles ☐ ou fortes ☐ (pluie ☐ ou neige ☐)

Photographie : Oui ☐ Non ☐ Direction de prise de vue :

Observateur : Nom : Prénom :

Tel. : Mail :

Remarques diverses : au dos de la fiche

Contact: Ludo Ravanel
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http://edytem.univ-savoie.fr/eboulements

FIG. 3 - Rockfall notification form.

the surface of the massif (62% of the study area) have been checked on the aerial photographs taken at the end of the summer. The objective was to check if the number of recent deposits present on the photographs corresponded to the number of collapses identified by the network of observers (fig. 4). Within the whole area covered by the photographs, only two small-volume deposits were not taken into account with the 45 ground observed rockfalls, what is a fairly good validation of the method.

Annual reactivation of the network

Since 2007, the network of observers is reactivated annually: each spring, articles regarding the ongoing research and the network are posted on the main mountaineering forums, an email is sent to all French Alpine guides through the mailing lists of the *Syndicat National des Guides de Montagne* and the *Compagnie des Guides de Chamonix*, and most of the hut keepers are met.

Other actions are implemented for professionals as for amateurs and onlookers: the network and its objectives were introduced to the public at large through local radio stations and newspapers, and through numerous scientific and public meetings. Articles/notes/short notes in mountaineering journals complete the communication about the network (*e.g.*, Ravanel, 2008, 2010, 2012).

GIS AND EXTRACTION OF THE ROCKFALL PARAMETERS

Within this research, we used *ESRI* ArcGIS software as Geographic Information System. The border position of the Mont-Blanc constrained to mosaic different Digital Elevation Models (DEM): 10-m-DEM from the Valle d'Aosta Region for Italy and 50-m-DEM from the IGN for France. Swiss territory is partly covered by these two DEMs but does not belong to the area covered by the network. In rockfall-most-prone areas of the massif, the DEM resolution was improved to about 10 m by digitising contour lines and spot elevations on the IGN 1:25000 map (fig. 5). Slope angle, aspect and elevation of the source area of each rockfall were extracted from the mosaicked DEM.

Finally, the possible presence of permafrost was determined from the TEBAL model of distribution of the mean annual ground surface temperature (Gruber & *alii*, 2004).

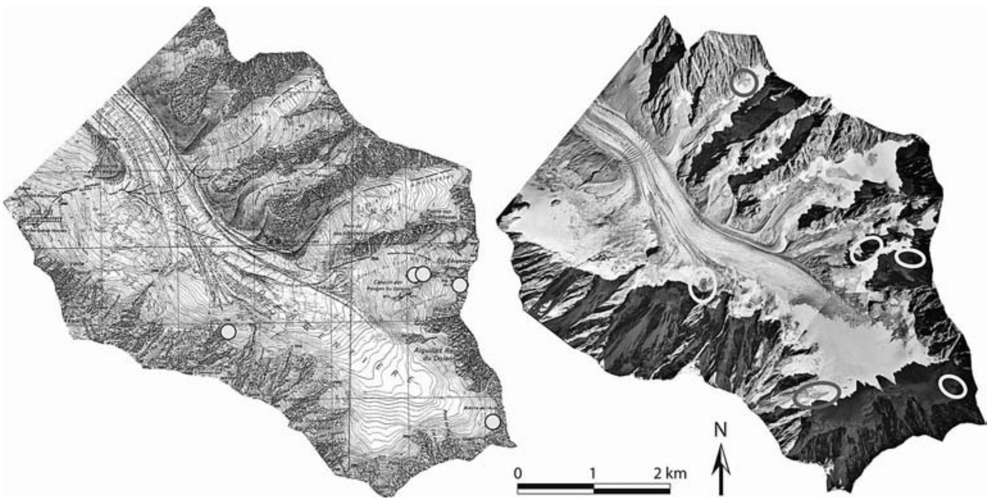

FIG. 4 - Verification of the completeness of the inventory of the 2007 rockfalls in the Argentière Glacier basin by recognition of supraglacial rockfall deposits on aerial photographs from the 16th September 2007. Left (IGN topographic map): location of observed rockfalls from the ground, by network observers. Right (photo LGGE): location of recognised rockfall (white) and snow/ice avalanche (black) deposits on aerial photographs.

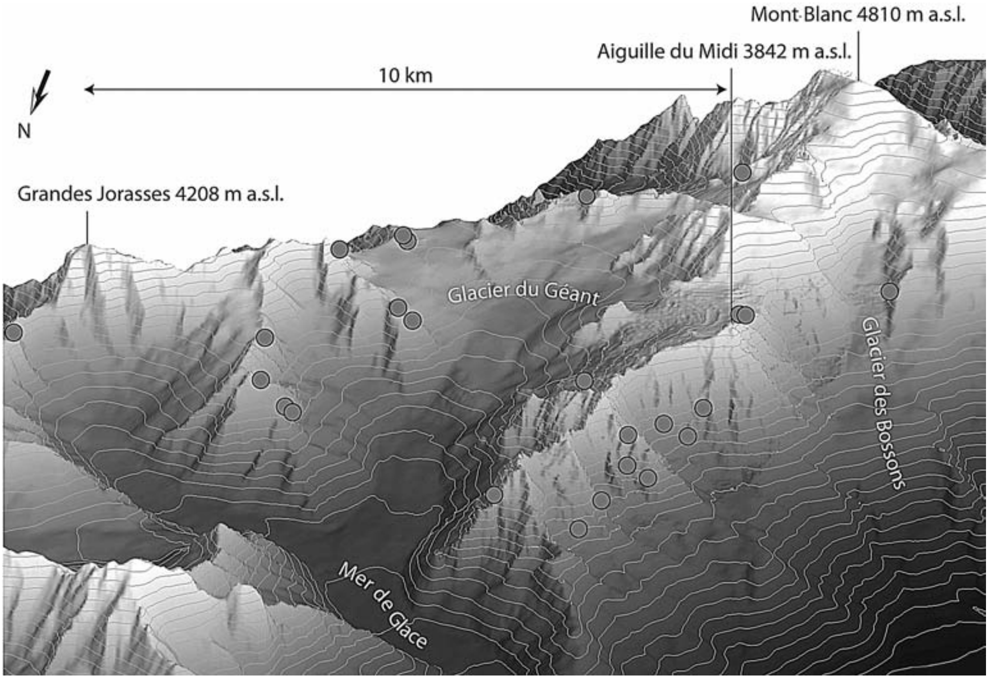

FIG. 5 - IGN 50-m-DEM enhanced to 10 m for areas affected by rockfalls (Ravanel & *alii*, 2010 modified). Points: 2007 rockfalls. Contour interval is 100 m.

FIVE YEARS OF OBSERVATION AND PRELIMINARY ANALYSIS

251 documented rockfalls

Since 2007, the network of observers surveys the occurrence of rockfalls in the central area of the massif, with sediment volumes ranging from 100 to 43,000 m^3. In 2007, 45 rockfalls (Ravanel & *alii*, 2010) occurred from January to late September, with only three events outside the Modelled Permafrost Area (MPA). In 2008, 22 rockfalls (Mortara & *alii*, 2009; Ravanel & *alii*, 2010) were reported between June and September, the last one of these was the largest (33,000 m^3); only one rockfall occurred outside the MPA. In 2009, 72 rockfalls (Ravanel & Deline, 2010) were recorded between April and October but mainly in August, with mostly small volumes (up to 7000 m^3); only two of them occurred outside the MPA. In 2010, a few rockfalls occurred between late May and June; most of the 47 rockfalls involving a maximal volume of 15,000 m^3 occurred in July (unpublished data); only 3 occurred outside the MPA. In 2011, the first rockfall event was recorded in June; rockfall activity was very intense in August and September, the largest rockfall being the last one (late October 2011); among the 65 rockfalls with a maximal volume of 43,000 m^3, only 3 occurred outside the MPA (unpublished data).

Permafrost degradation as the main triggering factor

The average rockwall elevation in the Mont-Blanc massif is around 3000 m a.s.l., whereas the average elevation of the 2007-2011 rockfall scars is much higher (3325 m). Although rockwalls are very common below 3000 m a.s.l., very few collapses were observed there. These elements indicate that the main triggering factor(s) is(are) not ubiquitous, being altitude dependant. The most affected altitudinal belt is in the range 3200-3600 m a.s.l., an area also described as «warm» permafrost (> –2°C), associated with fast degradation (Noetzli & *alii*, 2003). Moreover, the hotter the summer, the higher the scar elevation of rockfall events; there is also a sharp contrast in the scar elevation between north and south faces, which is also consistent with permafrost distribution and evolution (Noetzli & *alii*, 2007; Noetzli & Gruber, 2009). Finally, rockfall activity is more frequent at topography particularly affected by permafrost degradation such as pillars, spurs and ridges (Noetzli & *alii*, 2007).

In addition to these observations, permafrost degradation appears to be the most likely rockfall triggering factor for the following reasons: (i) other cryospheric factors, like glacial debuttressing and evolution of ice/snow cover on rockwalls, may only explain a little part of the rockfalls (*e.g.*, Ravanel & Deline, 2011); (ii) almost all of the recorded rockfalls (98%) occurred in a context of possible or likely permafrost according to the permafrost modelling; (iii) rockfall primarily occur during summer time, which is also prone to permafrost degradation; (iv) massive permafrost ice was observed in at least 40 scars since 2007.

CONCLUDING REMARKS

Developed since 2005, the network of rockfall observers in the central part of the Mont-Blanc massif makes possible to survey for the first time the instability of steep rockwalls in a high-mountain area with a very high completeness. Fully operational since 2007, this network mainly consists in mountain professionals aware of the geomorphological evolution of the high Alpine environment and of the necessity of collecting data on rockfalls. Coupled with an extensive fieldwork after each fall event (in order to check and complete data), the network has allowed the survey 251 collapses over the period 2007-2011. Data analysis in GIS highlights the likely driving role of the permafrost degradation in rockfall triggering.

The objective to establish and maintain the network was realistic taking into account several factors: (i) the high number of Alpine guides and hut keepers working in the massif, with whom a close relationship was established through the integration of the first author in Chamonix, especially as a member of the *Compagnie des Guides de Chamonix*; (ii) the high frequentation of the massif by alpinists; (iii) a very good accessibility of the massif for the fieldwork checking procedure; (iv) fundings by projects (*PERMAdataROC*, *PermaNET*) involving French and Italian partners from both sides of the massif; (v) the network is part of a more general research project about the relationship between permafrost degradation and rockfall, which also includes terrestrial laser scanning surveys on selected rockwalls repeated every year, and photograph comparisons to reconstruct the evolution since the 19th century of some well-documented rockwalls of the massif (Ravanel & Deline, 2008, 2011).

The network has shown its capacity both quantitatively and qualitatively, but it continues to seek for a strong commitment to manage and perpetuate it. Volunteer-based, this network of guides and hut keepers requires a very close relationship with these observers and a continued revitalisation. Otherwise completeness sought would quickly become a chimera.

REFERENCES

ALLEN S.K. & HUGGEL C. (2012) - *Recent high mountain rockfalls and warm daily temperature extremes*. Geophysical Research Abstracts, 14, 9886.

BECKER A. & DAVENPORT C.A. (2003) - *Rockfalls triggered by the ad 1356 Basle Earthquake*. Terra Nova, 15, 258-264.

BERTINI G., MARCUCCI M., NEVINI R., PASSERINI P. & SGUAZZONI G. (1985) - *Patterns of faulting in the Mont Blanc granite*. Tectonophysics, 111, 65-106.

CORATZA P. & DE WAELE J. (2012) - *Geomorphosites and natural hazards: teaching the importance of geomorphology in society*. Geoheritage, 4-3, 195-203.

COSSART E., BRAUCHER R., FORT M., BOURLÈS D.L. & CARCAILLET J. (2008) - *Slope instability in relation to glacial debuttressing in alpine areas (Upper Durance catchment, south-eastern France): evidence from field data and ^{10}Be cosmic ray exposure ages*. Geomorphology, 95, 3-26.

DELINE P. (2001) - *Recent Brenva rock avalanches (Valley of Aosta): new chapter in an old story?* Geografia Fisica e Dinamica Quaternaria, 5, 55-63.

DELINE P. (2009) - *Interactions between rock avalanches and glaciers in the Mont-Blanc massif during the late Holocene*. Quaternary Science Reviews, 28, 1070-1083.

DELINE P. & Kirkbride M.P. (2009) - *Rock avalanches on a glacier and morainic complex in Haut-Val-Ferret (Mont-Blanc Massif, Italy)*. Geomorphology, 103, 80-92.

DELINE P., GARDENT M., MAGNIN F. & RAVANEL L. (2012) - *The morphodynamics of the Mont-Blanc massif in a changing cryosphère: a comprehensive review*. Geografiska Annaler: Series A, Physical Geography, 94, 265-283.

EVANS S.G. & CLAGUE J.J. (1994) - *Recent climatic change and catastrophic geomorphic processes in mountain environments*. Geomorphology, 10, 107-128.

EVANS S.G. & GARDNER J.S. (1989) - *Risques de catastrophes naturelles dans la Cordillière canadienne*. In: Fulton R.J. (Ed.), Le Quaternaire du Canada et du Groenland, 1, 756-767.

FORT M., COSSART E., DELINE P., DZIKOWSKI M., NICOUD G., RAVANEL L., SCHOENEICH P. & WASSMER P. (2009) - *Geomorphic impacts of large and rapid mass movements: a review*. Géomorphologie: relief, processus, environnement, 1, 47-64.

GARDENT M., RABATEL A., DEDIEU J.P., DELINE P. & SCHOENEICH P. (2012) - *Analysis of the glacier retreat in the French Alps since the 1960s based on the new glacier inventory*. Geophysical Research Abstracts, 14, 8984.

GRUBER S. & HAEBERLI W. (2007) - *Permafrost in steep bedrock slopes and its temperature-related destabilization following climate change*. Journal of Geophysical Research, 112, F02S18.

GRUBER S., HOELZLE M. & HAEBERLI W. (2004) - *Rock-wall temperatures in the Alps: modelling their topographic distribution and regional differences*. Permafrost and Periglacial Processes, 15, 299-307.

HAEBERLI W., WEGMANN M. & VONDER-MÜHLL D. (1997) - *Slope stability problems related to glacier shrinkage and permafrost degradation in the Alps*. Eclogae Geologicae Helvetiae, 90, 407-414.

HARRIS C., ARENSON L.U., CHRISTIANSEN H.H., ETZELMÜLLER B., FRAUENFELDER R., GRUBER S., HAEBERLI W., HAUCK C., HÖLZLE M., HUMLUM O., ISAKSEN K., KÄÄB A., KERN-LÜTSCHG M.A., LEHNING M., MATSUOKA N., MURTON J., NÖTZLI J., PHILLIPS M., ROSS N., SEPPÄLÄ M., SPRINGMAN S.M. & VONDER MÜHLL D. (2009) - *Permafrost and climate in Europe: monitoring and modelling thermal, geomorphological and geotechnical responses*. Earth-Science Review, 92, 117-171.

HUGGEL C., ZGRAGGEN-OSWALD S., HAEBERLI W., KÄÄB A., POLKVOJ A., GALUSHKIN I. & EVANS S.G. (2005) - *The 2002 rock/ice avalanche at Kolka/Karmadon, Russian Caucasus: assessment of extraordinary avalanche formation and mobility, and application of QuickBird satellite imagery*. Natural Hazards and Earth System Sciences, 5, 173-187.

MCSAVENEY M.J. (2002) - *Recent rockfalls and rock avalanches in Mount Cook National Park, New Zealand*. Reviews in Engineering Geology, 15, 35-69.

MORTARA G., ALBERTO W., BERTOGLIO V., DELINE P., RAVANEL L. & RAVELLO M. (2009) - *Les écroulements rocheux dans les massifs du Mont-Blanc et du Grand-Paradis (Alpes occidentales) en 2008*. Revue Valdôtaine d'Histoire Naturelle, 63, 5-22.

NOETZLI J. & GRUBER S. (2009) - *Transient thermal effects in Alpine permafrost*. The Cryosphere, 3, 85-99.

NOETZLI J., HOELZLE M. & HAEBERLI W. (2003) - *Mountain permafrost and recent Alpine rock-fall events: a GIS-based approach to determine critical factors.* Proceeding of the 8th International Conference on Permafrost. Swets & Zeitlinger, Lisse, Zürich, Switzerland, 827-832.

NOETZLI J., GRUBER S., KOHL T., SALZMANN N. & HAEBERLI W. (2007) - *Three-dimensional distribution and evolution of permafrost temperatures in idealized high mountain topography*. Journal of Geophysical Research, 112, F02S13.

PIRULLI M. (2009) - *The Thurwieser rock avalanche (Italian Alps): description and dynamic analysis*. Engineering Geology, 109, 80-92.

RAVANEL L. (2008) - *Les écroulements rocheux*. Revue du SNGM, 71, 30-35.

RAVANEL L. (2010) - *Evolution des parois de haute montagne alpine dans le contexte actuel de réchauffement climatique; le cas de la face Ouest des Drus*. Cimes - Revue du GHM, 2009, 26-35.

RAVANEL L. (2012) - *Qu'est-ce qui fait s'écrouler les Drus?* La Montagne et Alpinisme, 2012-1, 22-25.

RAVANEL L. & DELINE P. (2008) - *La face ouest des Drus (massif du Mont-Blanc): évolution de l'instabilité d'une paroi rocheuse dans la haute montagne alpine depuis la fin du Petit Age Glaciaire*. Géomorphologie: relief, processus, environnement, 4, 261-272.

RAVANEL L. & DELINE P. (2010) - *A study of the rockfalls occurred in 2009 in the Mont-Blanc massif*. Proceedings of the Symposium Rock Slope Stability 2010, Paris, France, 11 p.

RAVANEL L. & DELINE P. (2011) - *Climate influence on rockfalls in high-Alpine steep rockwalls: the North side of the Aiguilles de Chamonix (Mont-Blanc massif) since the end of the Little Ice Age*. The Holocene, 21, 357-365.

RAVANEL L., ALLIGNOL F., DELINE P., GRUBER S. & RAVELLO M. (2010) - *Rock falls in the Mont-Blanc Massif in 2007 and 2008*. Landslides, 7, 493-501.

RAVANEL L., ALLIGNOL F., DELINE P. & BRUNO G. (2011) - *Les écroulements rocheux dans le massif du Mont-Blanc pendant l'été caniculaire de 2003*. Géovisions, 36, 245-261.

SCHIERMEIER Q. (2003) - *Alpine thaw breaks ice over permafrost's role*. Nature, 424, 712.

VON RAUMER J.-F. (1999) - *Les massifs du Mont-Blanc et des Aiguilles-Rouges, un aperçu géologique*. Le Règne Minéral, H.S.5, 13-17.

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