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Rock falls in the Mont Blanc Massif in 2007 and 2008

Abstract Due to a lack of systematic observations, the intensity and volume of rock falls and rock avalanches in high mountain areas are still poorly known. Nevertheless, these phenomena could have burly consequences. To document present rock falls, a network of observers (guides, mountaineers, and hut wardens) was initiated in the Mont Blanc Massif in 2005 and became fully operational in 2007. This article presents data on the 66 rock falls ($100\ \mathrm{m}^3 \leq V \leq 50{,}000\ \mathrm{m}^3$) documented in 2007 ($n=41$) and 2008 ($n=25$). Most of the starting zones are located in warm permafrost areas, which are most sensitive to warming, and only four rock falls are clearly out of permafrost area. Different elements support permafrost degradation as one of the main triggering factors of present rock falls in high mountain areas.

Keywords Rock falls · Permafrost · High alpine environments · Mountains · Mont Blanc Massif

Introduction

In recent years, large rock avalanches, such as the Kolka–Karmadon event in the Caucasus in 2002 (Huggel et al. 2005), have affected high mountain areas in the world. In the Alps, those that have occurred on the Brenva glacier (Mont Blanc Massif in 1997; Deline 2001), the Punta Thurwieser (Ortles–Cevedale Massif in 2004; Sosio et al. 2008), or the Drus (Mont Blanc Massif in 2005; Ravanel and Deline 2008) are some of the most recent examples. A high number of rock falls have affected alpine rock walls during the hot summer 2003 that strongly increased the awareness of mountaineers, mountain guides, hut keepers, and the general public towards the connection between climate, permafrost, and slope stability in the Alps. These phenomena can have strong impacts on natural hazards, high mountain infrastructure stability, and landscape evolution (cf. Haeberli et al. 1997; Davies et al. 2001; Gruber and Haeberli 2007; Bommer et al. 2008).

The hypothesis of a relationship between these events and the current global warming through a degradation of the rock wall permafrost is supported by several evidences (Gruber and Haeberli 2007): (1) physical processes linking climate and collapses exist; (2) many collapses originates from permafrost areas; (3) cracks filled with ice are common in high mountain rock walls and, frequently, ice is exposed in fresh detachment scars, or seeping water can be observed, even in very dry conditions; (4) the intense rock fall activity of the 2003 summer heat wave points to permafrost degradation as the only plausible explanation (Gruber et al. 2004a); and (5) permafrost degradation has been measured and is consistent with atmospheric warming. The increase in mean annual air temperature in the Alps during the twentieth century exceeded 1.5°C above 2,500 m a.s.l., with an acceleration since the early 1980s (Casty et al. 2005). Because the frequency and volume of rock falls and rock avalanches remain poorly known, an observation system was initiated in the French–Italian research project *PERMAdataROC* (2006–2008; Deline et al. 2008a) and is continued in the *PermaNET* project (*Permafrost long-term monitoring network*; http://www.permanet-alpinespace.eu) since 2008. In particular, the identification and analysis of past and present rock falls in high alpine rock walls and the establishment of a corresponding database in support of further research are pursued to provide a better scientific basis in the assessment of climate change effects on rock wall stability.

This article presents an inventory and first synopsis of rock falls having a volume >100 m^3 in the Mont Blanc Massif during 2007 and 2008. Due to its high elevation—highest peaks exceed 4,000 m a.s.l.—and strong precipitations, there are about 100 glaciers in the massif and permafrost is generally present in steep bedrock above 2,800–3,000 m a.s.l. The risk that results from the combination of steep topography, dense infrastructure below or within rock walls, and large tourist fluxes adds direct practical relevance to those investigations.

Study area

The Mont Blanc Massif (Figs. 1 and 2), oriented SW–NE, has an area of approximately 350 km^2 and its highest point is at 4,810 m a.s.l. Bordered by the deep valley of Chamonix in the NW, the Val Veny in the E, and the Val Ferret in the SE, it is characterized by an extraordinary combination of peaks and ridges, with glaciers covering about 40% of its surface. Many of its granitic, fractured faces and summits stand well above 3,000 m a.s.l.: the drainage divide between Rhône and Pô basins forms a 35-km-long crest line which is continuously above 3,300 m and locally exceeds 4,000 m a.s.l.

The Mont Blanc is mainly a granitic batholith (Fig. 1) formed during the Hercynian orogeny by granite intrusion in the gneissic basement (micaschists and gneiss). The Mont Blanc summit is on the contact of these two units. The granite changes from an intrusive position in gneiss in the SW to a tectonic contact in the NE. Tilted towards the NW, the massif is cut in panels by large subvertical Variscan, recurrent faults (north–south), and alpine faults (N40–N60°E) with mylonitized zones (shear zones). The Mont Blanc granite has a very coarse-grained texture, with facies varying from microgranite to porphyroidic granite. Multiple tectonic phases have broken up the rock with

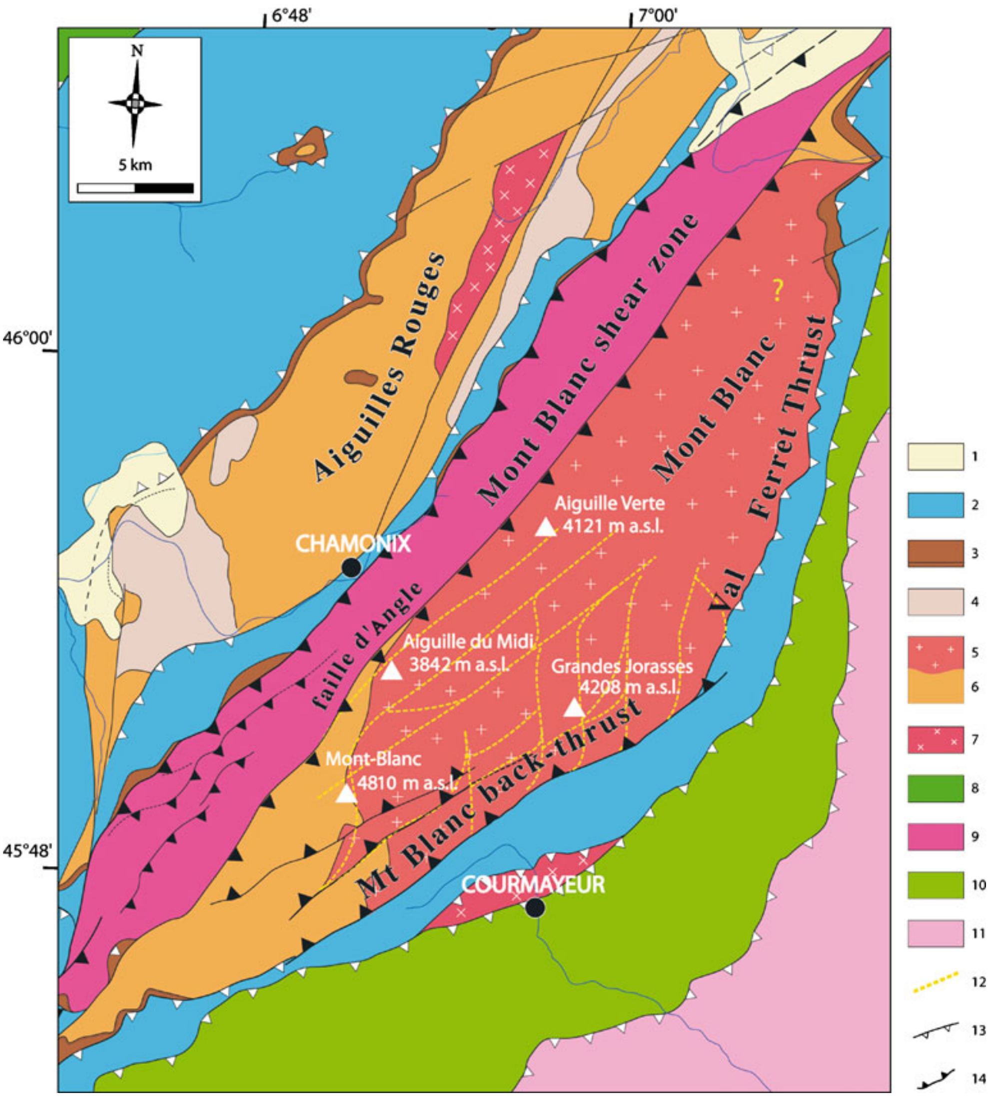


Fig. 1 Geological map of the Mont Blanc area (after Leloup et al. 2005 and Rolland et al. 2003, modified). *1* Quaternary, *2* Dauphinois and Helvetic Mesozoic sediments, *3* Triassic, *4* carboniferous, *5* Mont Blanc granite, *6* Variscan metamorphic rocks (gneiss), *7* undifferentiated granites, *8* Penninic klippe, *9* Mont Blanc shear zone (gneiss), *10* Versoyen + Valais, *11* internal zones, *12* mapped shear zone network, *13* thrust, *14* late reverse fault

multiple direction planes that may overlap. Finally, the combination of past and present glaciations, steep and fractured rock walls, and strong relative relief results in high-magnitude morphodynamics.

Method

First, data were collected in 2005 through observations made by a small number of Italian and French mountain guides. Since 2007, the observer network is operational with about 30 French and Italian guides and additionally several hut keepers and rescue teams. The Swiss and SW sides of the massif are not surveyed. In addition, educational posters in huts and a website (http://edytem.univ-savoie.fr/eboulements) invite mountaineers to send their own observations. A form is filled for each observed rock fall or its deposit, with the characteristics of the event: date, location, weather and snow conditions, and volume. For each year, data on identified events have been verified and completed on the field by the beginning of autumn by one of the first authors to ensure a good homogeneity of the recorded data. Furthermore, for 2007, the number of rock falls that formed supraglacial deposits has also been checked using aerial photographs at 1:20,000, dated September 16, 2007. For the 2 years, this checking phase has not revealed rock falls that were not reported by the observer network, even in less frequented areas of the massif.

For each event, scar elevation, slope angle, and aspect of the affected slopes are calculated using GIS ArcGIS 9.2 and a 50-m digital elevation model (DEM; Fig. 3)—enhanced to 10 m for affected areas—for the French side of the Mont Blanc Massif and a 10-m DEM for the Italian side—no DEM at a higher resolution is available. If aspects values and slope geometry before failures have been as far as possible checked and corrected based on maps and orthophotos where necessary, slope angle values have to be taken with caution because of the small scale resolution. Deposits have been mapped on the field or from aerial photographs for 2007, even for the smallest rock falls which usually produce deposits of several hundreds of square meters. Their areas have been computed with the polygon tool of the *Bayo-IGN PhotoExplorer* software. The collapsed volumes and the maximum scar depths have been computed from the dimensions of the scars, surveyed on the field with a *Laser Technology TruPulse 200* laser rangefinder or, when impossible, from altitudes reported on scar photographs. Thus, the maximum depths are sometimes unknown, often given *a*

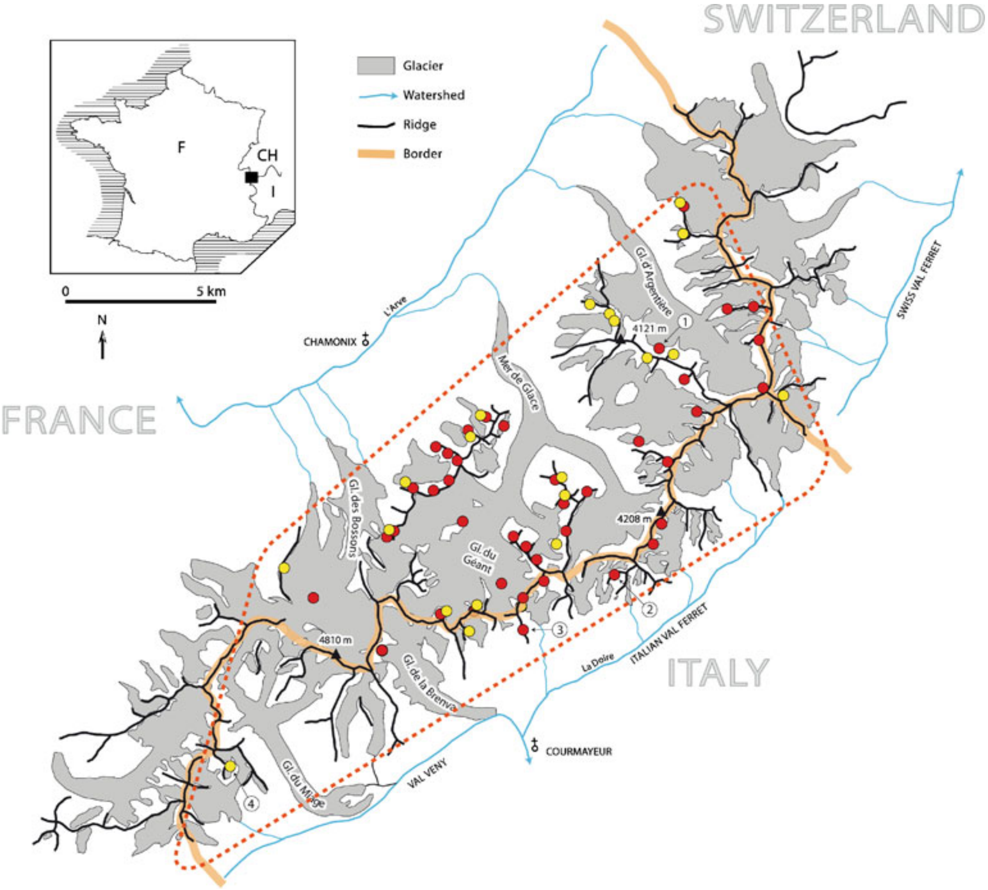


Fig. 2 Rock falls occurred in the Mont Blanc Massif in 2007 (*red*) and 2008 (*yellow*). *Dashed red line* surveyed zone; *1* Droite, *2* Tour des Grandes Jorasses, *3* Dent de Jethoula, *4* Tré-la-Tête

minima, and the uncertainty on volumes may reach 25%. The possible presence of permafrost is estimated from an approximate model of the mean annual ground surface temperatures (MAGST) of the massif, carried out using an energy balance model (TEBAL; see Gruber et al. 2004b). MAGST values are not presented because rock wall surface temperatures are modeled for the period 1982–2002 based on meteorological data from Corvatsch and Jungfraujoch stations (Switzerland) and not from the Aiguille du Midi station (where air temperature is the only data measured, since only February 2007); only a qualitative index of the probability of

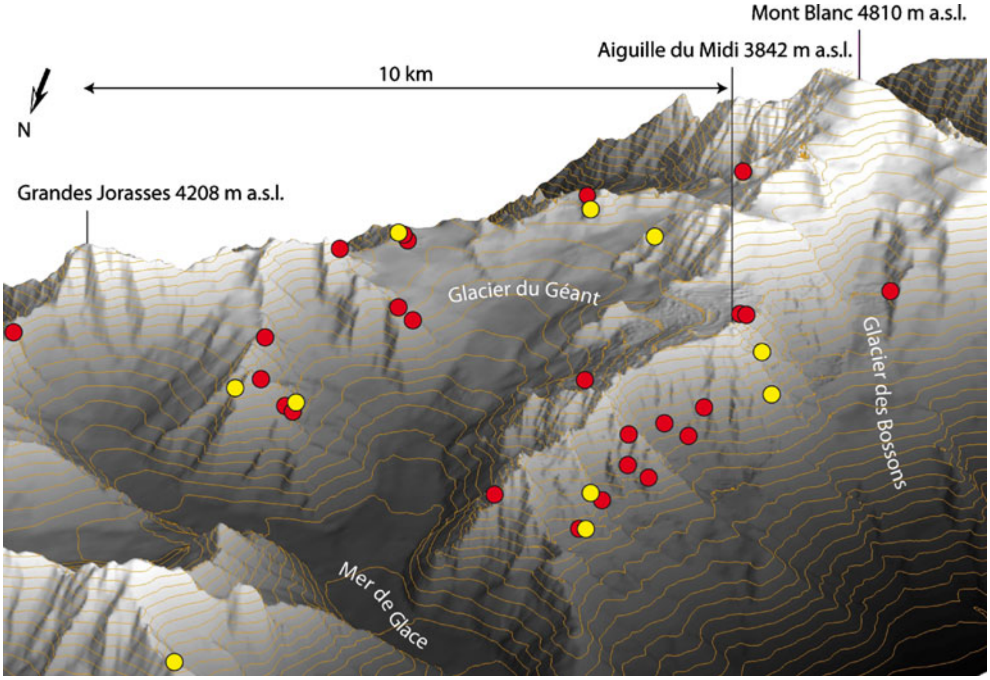


Fig. 3 A part of the 50-m DEM used for the study (enhanced to 10 m in the areas affected by rock falls). *Circles* rock falls in 2007 (*red*) and 2008 (*yellow*)

Table 1 Characteristics of the 45 rock falls of 2007 in the Mont Blanc Massif

Site	Date	Location (extended Lambert II coordinate system)	Elevation of the scar centre (m a.s.l.)	Slope (°)	Rock type		Aspect (°)	Deposit area (m^2)	Collapsed volume (m^3)	Max. scar depth (m)	Permafrost occurrence			Ice seen in the scar
					Granite	Gneiss					Unlikely	Possible	Likely	
Dent de Jethoula	R 01/08	*X* 0958.096 *Y* 2103.945	2,810	65	×		180	>60,000	15,000	>10	×			No
Tour des Grandes Jorasses	R 30/09	*X* 0960.968 *Y* 2106.695	3,830	70	×		160	20,000	10,000	>4			×	Yes
Droites	F 06/09	*X* 0960.895 *Y* 2114.435	3,360	69	×		30	20,000	7,000	>6			×	Yes
Aiguille Passon	F 31/08	*X* 0960.105 *Y* 2119.294	3,060	43	×		15	4,500	5,000	2 to 3			×	?
Aiguilles Marbrées	F 12/09	*X* 0957.370 *Y* 2104.984	3,430	58	×		240	10,000	4,000	<2			×	?
Lex Blanche	R 01/08	*X* 0947.223 *Y* 2097.516	3,500	53		×	90	700	3,500	~6			×	Yes?
Rognon inf. du Plan	F 17/01	*X* 0954.830 *Y* 2108.538	3,310	77	×		220	450	3,000	~7		×		?
Brêche des Périades	F 12/09	*X* 0958.758 *Y* 2107.888	3,400	48	×		310	2,500	2,500	3 to 4			×	?
Aiguilles Marbrées	R 20/09	*X* 0957.323 *Y* 2105.093	3,430	62	×		290	?	2,500	~4			×	Yes
Pointes des Hirondelles	F 04/08	*X* 0961.940 *Y* 2107.913	3,410	57	×		150	20,000	2,000	?			×	?
Aiguilles du Tacul	F 12/09	*X* 0958.677 *Y* 2108.761	3,280	43	×		180	6,000	2,000	<2		×		?
Arête des Grands Mulets	R 07/07	*X* 0951.168 *Y* 2105.665	3,270	60		×	65	3,000	1,500	?			×	?
Aiguille du Peigne	F 30/08	*X* 0953.964 *Y* 2109.958	2,860	59	×		35	20,000	1,500	~4			×	No
Petites Aiguilles Rouges du Dolent	F 06/09	*X* 0964.161 *Y* 2115.395	3,450	64	×		350	2,000	1,500	?			×	?
Arête des Grands Mulets	F 25/05	*X* 0951.168 *Y* 2105.665	3,270	60		×	65	2,500	1,200	?			×	?
Aiguille du Tacul	F 12/09	*X* 0958.375 *Y* 2108.914	3,010	57	×		325	4,000	1,200	2 to 3		×		?
Rognon des Grands Charmoz	F 30/08	*X* 0954.716 *Y* 2110.956	2,700	63	×		340	5,000	1,000	2 to 3	×			No
Eperon de la Brenva	F 21/09	*X* 0953.133 *Y* 2102.975	3,560	43	×		150	9,000	1,000	?			×	Yes
Aiguille du Midi	F 21/07	*X* 0953.855 *Y* 2108.800	2,940	50	×		320	4,000	900	~ 5			×	Yes
Aiguille des Pélerins	F 30/08	*X* 0954.225 *Y* 2109.855	2,960	65	×		10	17,000	800	<2			×	?
Aiguille à Bochard	F 07/09	*X* 0957.738 *Y* 2115.763	3,010	60		×	350	2,000	800	<2		×		No
Arête des Grands Mulets	F 22/04	*X* 0951.168 *Y* 2105.665	3,270	60		×	65	2,000	700	?			×	?
Rognon du Dolent	F 06/09	*X* 0963.620 *Y* 2115.548	3,280	46	×		315	5,000	600	?		×		?
La Noire	F 12/09	*X* 0957.048 *Y* 2106.918	3,200	43	×		180	2,500	600	<2		×		?
Arête Freshfield	R 19/06	*X* 0955.083 *Y* 2103.898	3,610	56	×		70	3,000	448	4			×	Yes
Arête Freshfield	F 28/08	*X* 0955.083 *Y* 2103.898	3,610	56	×		70	1,000						Yes
Col sup. de la Noire	F 12/09	*X* 0957.752 *Y* 2106.352	3,470	54	×		260	600	200	<2			×	?
Arête inf. des Cosmiques	R 16/07	*X* 0952.990 *Y* 2107.169	3,600	39	×		140	100	180	2 to 3			×	Yes
Dent du Géant	F 29/06	*X* 0958.094 *Y* 2105.878	3,650	55	×		260	500	150	<2			×	Yes?
Pointe Isabelle	F 29/06	*X* 0962.473 *Y* 2112.373	3,270	57	×		315	800	150	<2			×	?
Pointes des Hirondelles	F 04/08	*X* 0962.033 *Y* 2108.013	3,250	58	×		40	800	150	?			×	?
La Noire	F 12/09	*X* 0957.256 *Y* 2106.822	3,340	52	×		210	700	150	2 to 3			×	?
Aiguille du Midi	F 14/07	*X* 0953.560 *Y* 2108.765	2,780	53	×		340	8,000	>100	<2		×		?
Grands Charmoz	R 17/07	*X* 0955.655 *Y* 2110.868	3,060	54	×		100	?	>100	?		×		?

Table 1 Continued

Site	Date	Location (extended Lambert II coordinate system)	Elevation of the scar centre (m a.s.l.)	Slope (°)	Rock type		Aspect (°)	Deposit area (m^2)	Collapsed volume (m^3)	Max. scar depth (m)	Permafrost occurrence			Ice seen in the scar
					Granite	Gneiss					Unlikely	Possible	Likely	
Aiguille du Midi	F 12/09	*X* 0953.383 *Y* 2108.495	3,020	48	×		330	?	>100	?			×	?
Aiguille de Talèfre	F 12/09	*X* 0961.795 *Y* 2110.515	3,430	48	×		235	8,000	>100	<2			×	?
Aiguille de Thoules	F 12/09	*X* 0955.985 *Y* 2104.245	3,310	38	×		120	3,500	>100	<2			×	?
Courtes	F 12/09	*X* 0961.545 *Y* 2113.318	3,320	44	×		220	?	>100	<2		×		?
Aiguille Pierre Joseph	F 29/06	*X* 0960.579 *Y* 2110.935	3,060	43	×		325	800	100	<2			×	?
Aiguille de Blaitière	F 16/07	*X* 0954.483 *Y* 2110.565	2,870	69	×		290	700	100	4	×			No
Aiguille des Pèlerins	F 21/07	*X* 0954.218 *Y* 2109.700	3,250	38	×		310	?	100	3 to 4		×		?
Arête inf. des Cosmiques	R 29/07	*X* 0952.972 *Y* 2107.156	3,580	48	×		140	300	100	< 2			×	?
Aiguille du Tacul	R 24/08	*X* 0958.264 *Y* 2108.845	2,880	67	×		280	500	100	?		×		?
Rognon du Dolent	F 06/09	*X* 0963.558 *Y* 2115.531	3,200	64	×		275	400	100	<2		×		?
Pointe de Pré Bar	F 06/09	*X* 0964.498 *Y* 2113.460	3,230	59	×		335	300	100	<2			×	?
Means			3,253	55	40	5	202	~7,000	>1,600	~3.3				
Total (45)								>260,000	>73,000		3	12	30	>10

Uncertainty on volumes can reach 25%

R the date of the rock fall, *F* the date of the first observation of the deposit

existence of permafrost for each sector is proposed. Permafrost is considered unlikely, possible, and likely when MAGST is >1°C, between 1°C and −1°C, and <−1°C, respectively.

Results: 45 observed rock falls in 2007, 21 in 2008

The database compiles the characteristics of the 45 and 21 rock falls observed in 2007 and 2008, respectively, in the Mont Blanc Massif (Tables 1 and 2; Fig. 2).

Most of these events took place between July 15 and September 15. Few were later (up to September 30 for the Tour des Grandes Jorasses event in 2007 on the Italian side of the massif) or earlier (especially the first two rock falls of the Arête des Grands Mulets, in April and May 2007)—sometimes much earlier (collapse of the Rognon Inférieur du Plan, in January 2007).

Fifty-five rock fall events (83%) occurred above 3,000 m a.s.l. while only 48% of the studied rock walls (elevation >2,000 a.s.l., slope angle >37°, not covered by glaciers) are located above this altitude. Thirty-two rock fall events (48%) occurred between 3,200 and 3,500 m a.s.l. (19% of the study area), none above 3,900 m (4% of the study area). The highest scar is the one on Tour des Grandes Jorasses (3,830 m a.s.l.; Fig. 4), on the Italian side.

A large number of rock falls (23%) detached on slopes with an angle in the range 53–57° (17% of the study area), but this value is probably underestimated, given the low resolution of the DEM. Rock falls particularly affect west and north faces, which do not correspond to the main class of the rock walls distribution in terms of aspect (SW).

The most important rock fall was at Tré-la-Tête (50,000 m^3, aspect 80°; Deline et al. 2008b; Fig. 5) in September 2008, on the Italian side. The second largest rock fall occurred at the Dent de Jethoula in August 2007 (15,000 m^3, aspect 180°), also on the Italian side, at one of the lowest elevations (2,810 m a.s.l.). The two other main events affected the Tour des Grandes Jorasses (10,000 m^3, aspect 160°, Italian side; Fig. 4) and the Droites (7,000 m^3, aspect 30°, French side), in 2007. Their scars are both located at high elevation (3,830 and 3,620 m a.s.l., respectively).

Discussion

Rock falls, as most of the instabilities in rock slopes, are usually related to existing fractures (mesoscale and fine-scale fracturation is poorly studied in the Mont Blanc Massif), along which a rock mass is destabilized by a triggering factor. The permafrost degradation could be an important one. Only four events (6%) are clearly out of the permafrost area. The 41 events (61%) that occurred where permafrost presence is likely could be related to permafrost degradation (active layer formation, active layer thickening, or warming at depth). Historical studies that are currently developed (e.g., Ravanel and Deline 2008) support this. They point out a clear evolution with a strong correlation between rock fall occurrences and the warmest periods over the last 150 years (see also Evans and Gardner 1989). It is to note that the years 2007 and 2008 have, respectively, the seventh and eighth highest mean annual temperatures in Chamonix for a century (MétéoFrance data) and probably for at least 500 years (see Casty et al. 2005). About 90% of the events took place during summer, i.e., the hottest period of the year (Fig. 6). Massive ice has besides been observed in about 12 scars (Fig. 4). This observation largely corroborates the ice-filled fractures thawing. Bonding of ice-filled fractures and its reduction or loss during degradation can be related to a combination of ice/rock interlocking and ice/rock

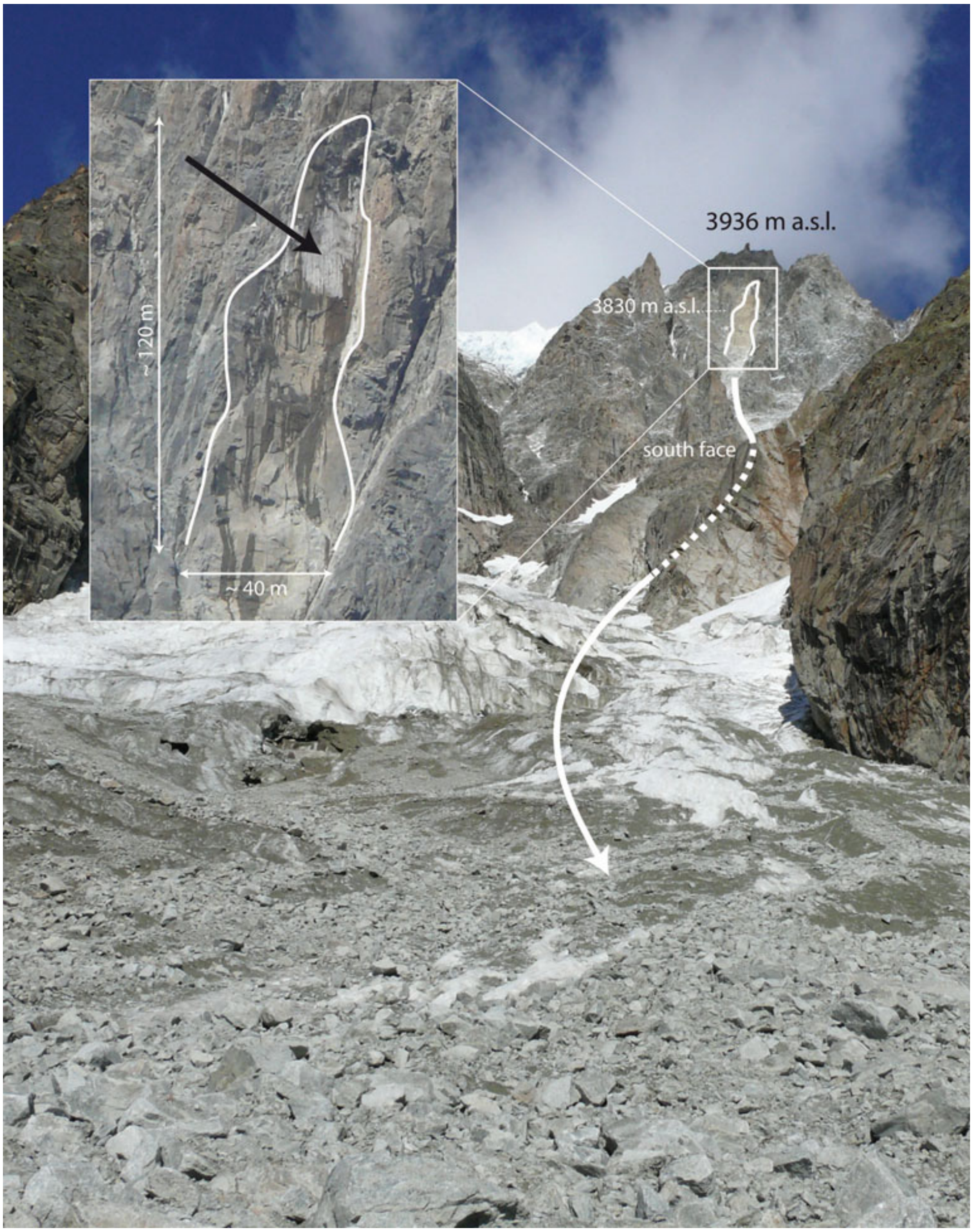
Table 2 Characteristics of the 21 rock falls of 2008 in the Mont Blanc Massif

Site	Date	Location (extended Lambert II coordinate system)	Elevation of the scar centre (m a.s.l.)	Slope (°)	Rock type		Aspect (°)	Deposit area (m^2)	Collapsed volume (m^3)	Max. scar depth (m)	Permafrost occurrence			Ice seen in the scar
					Granite	Gneiss					Unlikely	Possible	Likely	
Epaule orientale de Tré-la-Tête	R 10/09	*X* 0948.895 *Y* 2097.758	3,400	66		×	80	150,000	50,000	>20		×		?
Aiguille de Thoules	R 09/07	*X* 0956.068 *Y* 2104.465	3,410	49	×		162	10,000	5,000	~6		×		?
Arête des Grands Montets	F 07/08	*X* 0958.879 *Y* 2115.033	3,600	40	×		290	?	3,500	8			×	Yes
Aiguille du Midi	F 29/06	*X* 0952.905 *Y* 2108.520	2,920	56	×		315	7,000	3,000	?		×		?
Périades	F 26/06	*X* 0958.397 *Y* 2106.941	3,270	52	×		299	4,000	1,500	5			×	?
Aiguille du Chardonnet	F 03/08	*X* 0960.505 *Y* 2118.177	3,060	53	×		287	3,000	1,500	3		×		?
Aiguille à Bochard	F 23/06	*X* 0957.710 *Y* 2115.740	3,070	60		×	358	4,000	1,200	5		×		?
Aiguille du Passon	F 26/06	*X* 0960.295 *Y* 2119.220	3,110	52	×		344	2,500	1,200	2			×	?
Aiguille du Tacul	F 26/06	*X* 0958.440 *Y* 2109.044	3,090	41	×		276	8,000	1,000	> 2		×		?
Aiguille du Tacul	F 14/08	*X* 0958.750 *Y* 2109.273	3,000	58	×		339	?	900?	~5			×	Yes
Grands Charmoz	R 23/08	*X* 0954.720 *Y* 2110.950	2,720	69	×		339	2,000	500	2	×			?
Aiguilles Marbrées	F 14/08	*X* 0957.385 *Y* 2104.983	3,480	56	×		244	1,000	400	4			×	?
Tour Ronde	R 20/08	*X* 0955.093 *Y* 2104.250	3,450	43	×		48	1,200	400	?			×	?
Droites	R 24/06	*X* 0960.015 *Y* 2113.873	3,640	49	×		211	?	>300	<2			×	?
Droites	F 23/07	*X* 0960.885 *Y* 2114.395	3,520	44	×		61	?	300?	?			×	?
Aiguille de Blaitière	F 26/06	*X* 0954.493 *Y* 2110.518	2,880	72	×		174	?	250	<1		×		?
Aiguilles d'Entrèves	F 29/06	*X* 0955.938 *Y* 2103.822	3,250	55	×		59	800	250	2		×		?
Aiguille du Midi	R 05/08	*X* 0952.403 *Y* 2107.696	3,000	65	×		295	?	>200	?		×		?
Aiguille du Goûter	F 12/06	*X* 0949.154 *Y* 2105.317	3,380	40		×	8	300	200	3			×	?
Mont Dolent	F 18/08	*X* 0965.270 *Y* 2113.390	3,530	55	×		85	?	>100	?			×	?
Pointe Adolphe Rey	R 05/08	*X* 0954.460 *Y* 2105.146	3,420	49	×		22	?	>100	?			×	?
Means			3,248	54	18	3	205	~15,000	>3,200	~4,6				
Total (21)								>194,000	>67,000		1	9	11	2

Uncertainty on volumes can reach 25%

R the date of the rock fall, *F* the date of the first observation of the deposit

Fig. 4 The September 2007 rock fall at the Tour des Grandes Jorasses, seen from the bottom of the rock wall, and its scar. *Black arrow* shows massive ice still present in the scar 2 weeks after the rock fall. The seeping water in the lower part of the scar corresponds to just melt ice

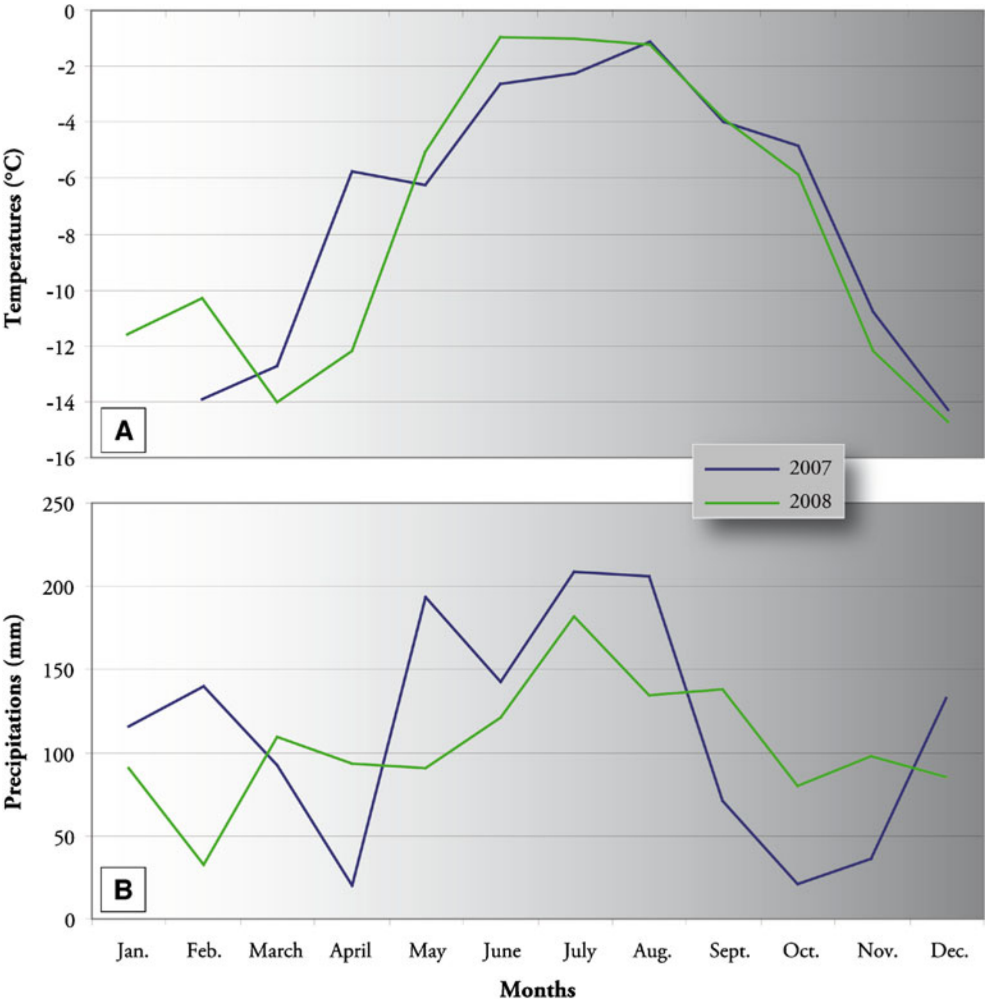


adhesion (Gruber and Haeberli 2007). Moreover, many events have originated from ridges and spurs, possibly due to more rapid thaw in such geometries (Noetzli et al. 2007). Two of the three main events, the Tour des Grandes Jorasses and the Tré-la-Tête events, occurred in September, i.e., when the active layer (i.e., the top layer of the permafrost that thaws during the summer) is almost the deepest (see Gruber et al. 2004a). The parameter "permafrost" could also explain the development of collapses in cold and deemed stable north faces. The average altitude of scars on north-facing slopes is indeed well smaller (3,090 m a.s.l.) than the one of the west-facing (3,270 m a.s.l.) and especially the ones of the east-facing (3,390 m a.s.l.) and south-facing slopes (3,370 m a.s.l.). This asymmetry is consistent with the temperature distribution at and below the surface of steep rock walls (see Noetzli et al. 2007). However, there is no clear trend regarding the orientation of the rock walls affected by the most important rock falls: among the six events with a volume ≥5,000 m^3, three have affected south faces, one a west face, one a NE face, and one a north face. Several years of observations are probably necessary to establish a relationship between aspect and volume of the scars.

Mean annual air temperature of 2007 and 2008 at the Aiguille du Midi are quite the same (−7.5°C and −7.8°C, respectively) as the summer temperatures (Fig. 6) and cannot explain the significant difference in number of events between 2007 and 2008. Only the April mean temperature was really higher in 2007 (−5.8°C) than in 2008 (−12.2°C). So, the thawing period should have begun earlier in 2007 than in 2008. Concerning precipitations, summer 2007 has been largely wetter than summer 2008 (Fig. 6). With higher air temperatures, percolating water in fractures could have more degraded permafrost by advection of heat, in complement of slower heat conduction from the surface (see Gruber and Haeberli 2007). This may explain, at least in part, the difference in number of events (45 rock falls in 2007, 21 in 2008).

Fig. 5 The rock fall of Tré-la-Tête occurred in September 2008. *Left* September 2005, *right* October 2008 (ph. M. Tamponi)

Fig. 6 **a** 2007 and 2008 monthly means of the daily temperature at the Aiguille du Midi (3,842 m a.s.l.); **b** 2007 and 2008 monthly precipitation amounts in Chamonix (1,042 m a.s.l.). Data from MétéoFrance



Concluding remarks and prospects

Developed since 2005, a network of rock fall observers in the Mont Blanc Massif surveys for the first time and as exhaustively as possible the rock instability in high alpine steep rock walls. In 2007 and 2008, 66 events were observed and documented. Most of the starting zones are located in warm permafrost areas (0 to −5°C; see Noetzli et al. 2003), which is most sensitive to warming. For several rock falls, massive ice has been observed in the detachment zone; this supports the relevance of the thaw of the ice, which fills fractures in high alpine rock walls ("ice-cemented").

Permafrost conditions seem today more and more important because warming is thought to be a mechanism through which climate controls rock wall stability and, consequently, natural hazard in mountain areas. Thus, to study the role of permafrost degradation in rock fall triggering, subsurface rock temperature has to be modeled for each rock fall scar. A standard statistical analysis of the distribution of rock walls, according to elevation and aspect, is in progress. It is complemented by historical research to characterize the recent evolution of the frequency and volume of rock falls, which is essential to argue that global warming is affecting rock fall triggering through permafrost degradation.

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