WP 6 – Action 6.2 – State of the art report

Hazards related to permafrost and to permafrost degradation

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Editors

Philippe Schoeneich, Institut de Géographie Alpine, Université de Grenoble, France

Matteo Dall'Amico, Geological service, Autonomous Province of Trento, Italy

Philip Deline, EDYTEM, Université de Savoie, France

Andreas Zischg, Abenis Alpinexpert GmbH/srl, Bozen/Bolzano, Italy

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14 bis av. Marie-Reynoard

F-38100 Grenoble

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3.
Rockfalls

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Authors

Coordination : Philip Deline

Involved PPs and contributors :

- EDYTEM : Philip Deline, Ludovic Ravanel, EDYTEM, Université de Savoie, France
- RAVA : Michèle Curtaz, FMS, Courmayeur, Italy ; Gianni Mortara & Marta Chiarle, CNR-IRPI, Torino, Italy
- IGRS : Andreas Kellerer-Pirklbauer & Gerhard Karl Lieb, Institute of Geography and Regional Science, University of Graz, Austria
- GeoLAB : Volkmar Mayr

Content

Summary fo decision makers

Rockfalls (<0.1 M m^3) generate risks for mountaineering activity in the Alps, while rock avalanches (> 0.1-1 M m^3) can threaten valley inhabitants at very long distance from the source area. Permafrost is present in Alpine rockwalls at high elevation (e.g. above c. 3000 m and 3500 m a.s.l. on north- and south-facing slopes, respectively). Its climatically-driven degradation is probably one of the main triggers of recent, present and future rockfalls and rock avalanches.

Rockwall permafrost and its degradation are not directly observable. Monitoring with temperature sensors at different depths, aspects, and slope angles, and with geophysical methods (PermaNET WP4), and rock temperature modelling (PermaNET WP5) are crucial. But the relationship between permafrost changes and high mountain rockwall instability remained for a long time not well-established, because:

- Frequency and volume of instability events in high mountains are poorly known because of the lack of systematic observations.
- Physical processes linking permafrost, its degradation and rockfalls are not fully understood.

The hypothesis that the increase of high mountain rockwall instability relates to permafrost changes gains recently force because:

- Massive ice was observed in several starting zones;
- Mean annual air temperature has increased by more than 1°C in the Alps during the 20th Century, with an accelerated warming trend since the 1980s, whereas ice-bonded joints and water-saturated rock become weaker in 'warm' permafrost (i.e. close to 0°C).

Studies establish a clear relationship between climate and rockfall occurrence in the Mont Blanc massif:

- After the end of the Little Ice Age (1860), rockfalls started at the end of the 1940s, in correspondence with a very warm period. After this 1rst peak, rockfall frequency increased continuously since the 1970s.
- Hottest summers (1976, 1983, 2003, 2009) were characterized by a very high rockfall frequency.
- In some cases (Drus), rockfall magnitude tends to increase from 1950 to 2005.

Our different study cases (Mont Blanc massif, Matterhorn, Mt. Mittlerer Burgstall) suggest that:

- Elevation of scars is often close to the lower limit of the permafrost (depending on aspect and slope), where its degradation is more active.
- Ridges, spurs, and pillars are prone to collapse, probably because of heat fluxes from well-exposed rock faces.

Snow cover, controlled by the slope and the wind, is an important control factor of the permafrost degradation in rockwalls.

1. Introduction

Within the PermaNET WP 6 – Related natural hazards, this report is part of Action 6.2, the aim of which is to produce a state-of-the-art report about the effects of climate changes on permafrost and resulting hazards in risk management. It is the state-of-the-art report of Action 6.2 - Group 3, about the relationship between permafrost and rockfalls in the Alps

Involved PPs are: RAVA, IGRS, GeoLAB, ARPA Piemonte, ZAMG, BAFU, and CNRS-EDYTEM; group 3 leader is CNRS-EDYTEM (contact: Philip Deline; pdeli@univ-savoie.fr).

2. Process description

The processes

In the widest sense of the word, a rockfall is the natural downward motion of a detached rock mass with a variable volume, involving free falling, bouncing, rolling, and sliding. Three main types of rockfall can be distinguished:

Boulder fall: a small volume (< 100 m^3) of a rock mass that splits up in several boulders during its fall and travels on a short distance; boulders generally accumulate on the scree slope located at the foot of the rockwall. The frequency of boulder fall is roughly annual: it occurs in the spring when the thawing front is penetrating in the rockwall.

Rockfall s.s.: a larger volume (> 100 m^3) of a rock mass that travels on a longer distance (up to several hundreds of m) with a high velocity.

Rock avalanche: very large volume (> 1 M m^3) of rock that travels as an extremely rapid (> 25 m s^{-1}) flow movement of fragmenting rock particles (granular flow) on a very long distance (up to some km). Rock avalanche produces a deep headscarp, modifies its travel zone, and leaves large deposits in its runout zone. Its runout increases with the volume of the collapsed mass.

Rhythm of large rockfalls and, more still, of rock avalanches is neither seasonal nor annual, because it is under the control of a combination of three main factors: (i) sismicity, (ii) paraglacial dynamics (e.g. debuttressing of rockwall), and (iii) climatically-driven permafrost changes.

Limits in the observation/inventory of the events

In the two last decades, many large rock and rock/ice avalanches have occurred in high mountain areas worldwide (e.g. Mount Cook, NZ, 1991; Mount Fletscher, NZ, 1992; Mount Munday, Coast Mountains, 1997; Kolka-Karmadon, Caucasus, 2002; Alaska, 2002; Mount Steller, Alaska, 2005; Mount Steele, Yukon, 2007). In the Alps, Brenva Glacier (1997), Punta Thurwieser (2004), the West Face of Les Drus (2005), Dents Blanches (2006), the east face of Monte Rosa (2006, 2007), Bliggferner (2007), and Crammont (2008) are the most recent examples, while innumerable smaller rock falls have detached from steep rockwalls during the hot Summer of 2003 (Ravanel et al., submitted-a). The hypothesis that the increase of high mountain rockwall instability relates to permafrost changes gains force (Gruber & Haeberli, 2007) from the fact that (i) ice was observed in many starting zones; (ii) the mean annual air temperature has increased (in more than 1°C during in the Alps the 20th Century); (iii) and that the warming trend has accelerated since the 1980s.

However, on the one hand, ongoing permafrost changes in rockwalls remain poorly understood due to the difficulties in carrying on in situ measurements. So far, permafrost studies are mainly based on modelling, with a few existing instrumented sites – a problem that the PermaNET WP4 contributes to adress. On the other hand, frequency and volume of instability events in high mountains are still poorly known because of the lack of systematic observations. This knowledge would be improved by the compilation of representative databases from (i) present observations, by combining network of observers like mountain guides, field surveys and photos analysis (Ravanel et al., submitted-b), and (ii) analyses of the dynamics of remarkable mountains sides in recent decades, using testimonies and terrestrial and aerial photos.

Hazards resulting from these processes, impact on infrastructures and populations

Rockfalls generate risks for mountaineering activity in the Alps, where many alpinists and hikers are present all year. It is also a risk for infrastructures like cable cars, mountain railways and roads, and ski resorts, especially when large rockfalls occur. Rock avalanches in glacierized high mountains are often rock-ice avalanches: incorporation of ice and snow from the detachment or/and the travel zones fluidises the moving mass (Deline, 2009) and it threatens valley inhabitants at very long distance from the source area. Rock-ice avalanches can transform in a more complex mass movement, with effects at stunning distances as shown by the Kolka-Karmadon event that killed > 150 people in September 2002.

3. Permafrost and rockfalls

Authors: Philip Deline & Ludovic Ravanel, EDYTEM Lab, France (CNRS-EDYTEM/PP11)

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Permafrost degradation is considered today as a major mechanism by which the climate is driving the stability of rockwalls and, as a consequence, the landscape evolution and natural risk in mountain areas (Gruber & Haeberli, 2007). This approach is based on (i) a series of observations made in the world, mostly in the Alps, and (ii) physical processes. One of the main difficulties is to match physical processes (generally studied in laboratory) with observations, and vice-versa.

Recent observations on rockfalls affecting rockwalls with permafrost

In the Alps, the best documented area is the Italian side of the Mont Blanc massif (Porter & Orombelli,1980; Orombelli & Porter, 1981; Dutto & Mortara, 1991; Deline, 2001, 2009) while presence of rock glaciers in the area and ice in the deposit suggest a likely role of the permafrost degradation in the triggering of the 1987 Val Pola landslide, Italian Alps (Crosta *et al.*, 2004; Dramis *et al.,* 1995). Noetzli *et al.* (2003) studied the parameters of 20 large alpine collapses (Tab. 3.1) to investigate their thermal and topographic conditions and showed that permafrost is probably a determining element.

In a surprising way, the strong morphodynamics that affected high-elevated rockwalls in the Alps during the hot Summer of 2003 was little studied: only Keller (2003), Schiermeier (2003), and Vonder Mühll *et al.* (2007) noted the high number of collapses of this summer and linked it to a likely increased degradation of the permafrost. Gruber *et al.* (2004a) modelised the distribution and degradation of the permafrost in the rockwalls during the 2003 Summer, and considered that the rockfall intensity activity was certainly drived by a rapide warming of the subsurface due to the heat wave, with breaks in the ice-filled fractures. At the East face of Mont Rose (Italian Alps), Fischer *et al.* (2006) noted that the acceleration of the withdrawal of its snow and ice cover probably led to the rockfall increase.

Rockfall	Date	Elevation (m asl)	Aspect	Volume (× 10^6 m^3)	H (m)	L (m)	Gl.	T (°C)	Slope (°)	References
Triolet	1717	3600	E	18	1860	7200	*	-5.3	61	Porter & Orombelli, 1980
Fletschorn	1901	3615	NE	0.8	2115	5500	*	-9.7	48	Coaz, 1910
Brenva	1920	4200	E	2.5	2750	5000	*	-6.7	65	Deline, 2001
Felik	1936	3585	SW	0.2	1250	3000	*	-3.6	38	Dutto & Mortara, 1991
Jungfrau	1937	3800	SE	0.15	435	1200	*	-5.6	61	Alean, 1984
Matterhorn	1943	4150	SE	0.24	1000	850		-9.3	75	Vanni, 1943
Miage	1945	3050	NE	0.3	730	1700	*	-5.6	44	Deline, 2009
Luseney	1952	3150	SW	1.0	1650	3800	*	-1.2	38	Dutto & Mortara, 1991
Druesberg	1987	2100	NW	0.07	300	700		2.0	56	Wegmann, 1995
Val Pola	1987	2360	NE	34	1250	3470		1.8	30	Noetzli et al., 2003
Tschierva	1988	3280	SW	0.3	550	1000	*	-1.4	52	Noetzli et al., 2003
Piz Serscen	1988	3750	SE	?	500	1250	*	-4.1	63	Noetzli et al., 2003
Randa	1991	2300	SE	30	1020	1400		3.3	54	Noetzli et al., 2003
Miage	1988	3000	NW	0.3	550	1100	*	-5.0	53	Deline, 2009
Zuetribist	1996	2250	E	1.1	900	1250		0.3	74	Noetzli et al., 2003
Brenva	1997	3725	SE	2.0	2285	5760	*	-4.1	48	Noetzli et al., 2003
Mättenberg	2000	2720	NW	0.1	800	1200		-1.5	42	Noetzli et al., 2003
Zugspitze	2001	2630	N	0.03	600	?		?	60	Noetzli et al., 2003
Monte Rosa	2001	3100	E	0.005	700	1250	*	-5.6	45	Noetzli et al., 2003
Gruben	2002	3520	NW	1.0	530	1125	*	-5.8	50	Noetzli et al., 2003

Tab. 3.1 – Parameters of the rockfalls studied by Noetzli et al. (2003). The altitude relates to the upper point of the scarp. H: vertical distance, from the top of the scarp to the lowest point of the deposit; L: horizontal travel distance; stars in column Gl. indicate events in glacial environment; T: estimated surface temperature determined with PERMAMAP model; slope is the mean slope of the starting zone.

Since 2005, annually-repeated terrestrial laserscanning surveys on several rockwalls in the Mont Blanc massif allows to recognise elevation, aspect and slope of the areas prone to rockfalls (Fig. 3.1).

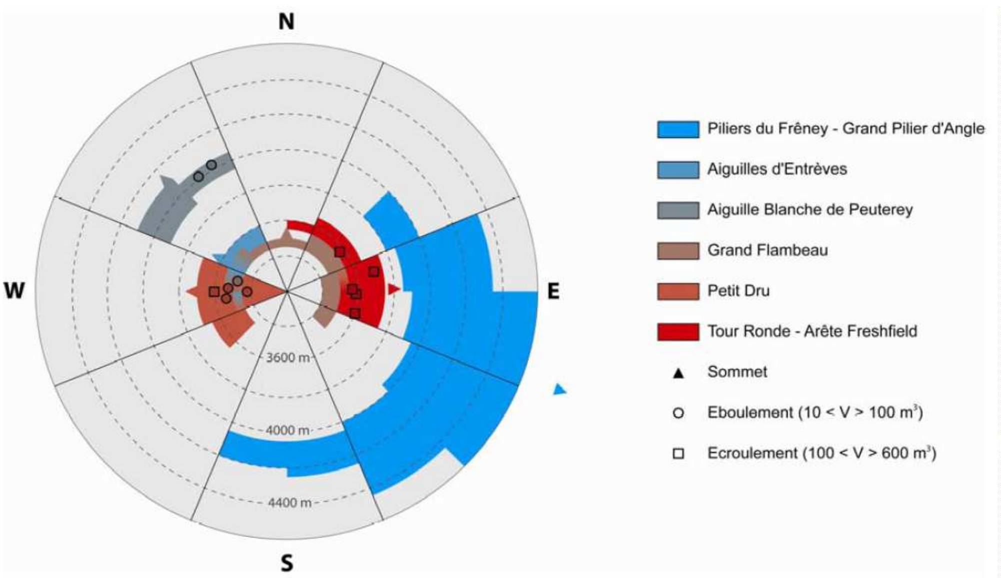

Fig. 3.1 – Distribution of rockfalls in the Mont Blanc massif in relation with elevation and aspect, surveyed with ground-based LiDAR (Ravanel et al., 2010). Circles: boulder falls; squares: rockfalls s.s.; triangles: summits.

Physical processes linking permafrost, its degradation and rockfalls

If rockfalls are documented, and Alpine permafrost and its evolution are investigated in the last two decades, relatively few studies (Davies *et al.*, 2000, 2001, 2003; Guenzel, 2008) exist about the physical link between both phenomena. Experiments by Mellor (1973) show a sudden increase of tensile and uniaxial compressive strength in water-saturated rocks when the interstitial water freezes (fig. 3.2): strength could increase by 300% from 0°C to -5°C (Krautblatter, 2009), because interstitial ice gives a strong cohesion to the rock in spite of its discontinuities (Cruden, 2003).

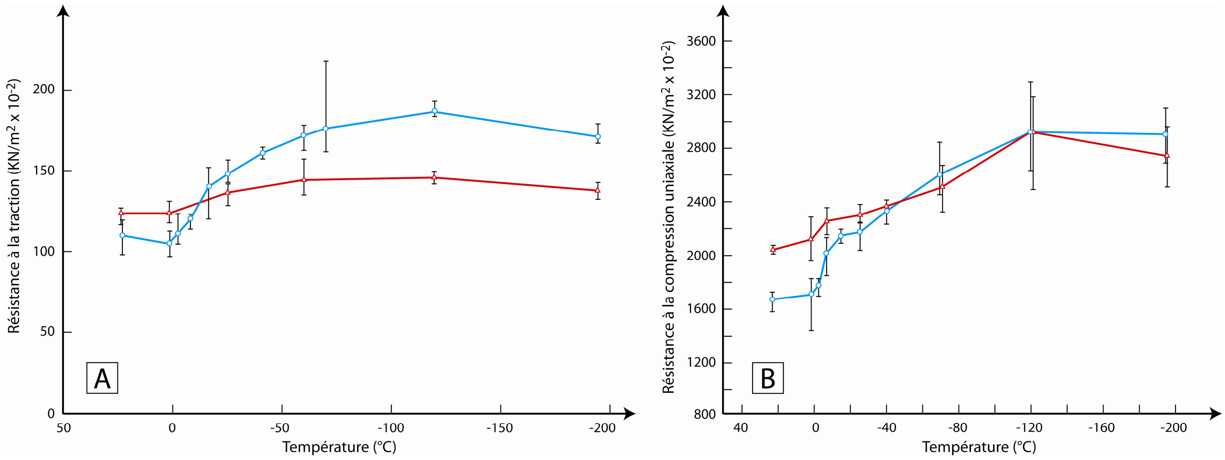

Fig. 3.2 – Tensile (A) and uniaxial compressive (B) strengths of dry (red) and water-satured (blue) granite (from Mellor, 1973).

Conditions of its formation, crystal size, and impurities, can strongly affect the resistance of the ice (Gruber & Haeberli, 2007), but submitted to stress, ice deforms, up to a limit beyond which it breaks (Sanderson, 1988). Ice strength is lowering as temperature is rising, especially when approaching the fusion point (Fish & Zaretsky, 1997), as shown by experiments in geotechnical centrifuge (Davies *et al.*, 2001): warming ice-bonded joints are weakest just before the thaw, at a temperature of c. 0.5ºC, and the warming of water-saturated rock from -5°C to 0°C enhances instability by reducing the friction along fractures and facilitating the progressive failure of rock bridges (Kraublatter, 2009).

But the deformation occurs not only inside the body of ice but at the ice-rock interface, with a loss of contact. The ice-rock contact is due to the nesting of the ice in the rock, because of its irregular surface (Davies *et al*., 2001), and to the adhesion of ice to the rock. This adhesion combines three main mechanisms (Ryzhkin & Petrenko, 1997; Petrenko, 2003): (i) electrostatic interaction between ice and rock ions, (ii) hydrogen bond between water and rock molecules, and (iii) dispersion force.

The traditional volume-expansion model predicts that numerous freeze-thaw cycles of the interstitial water will result in rock fatigue. To be effective, this process requires high water saturation (> 91%) and many cycles, and thus is expected only in the active layer (Wegmann & Gudmunsson, 1999). On the other hand, crack propagation due to segregation ice growth in water-saturated rocks with interconnected cracks could lead progressively to rock fractures in permafrost. It requires a moderate subfreezing temperature (−4 °C to −15 °C): sufficiently cold to attain high intra-crack pressures but warm enough that the permeability is not overly restricted by ice content (Walder & Hallet, 1985, 1986; Murton *et al.*, 2006); in this temperature range, granite may develop fractures enclosing an ice 3 m in length in a year.

The hydraulic pressure in the discontinuities, driven by the height of the water column in the linked satured zones (Gruber & Haeberli, 2007), affects the rock strength at different scales, from pores (Atkinson, 1984) to the whole rockwall (Fischer *et al.*, 2006). Several studies (Haeberli *et al.*, 1997; Haeberli *et al.*, 2004; Haeberli, 2005; Gruber & Haeberli, 2007; Huggel *et al.*, 2008) underlined how hydraulic pressure reduces strain in the fractures, whereas ice-filled areas, by preventing water drainage, enhances this pressure (Terzaghi, 1962), as suggests by the hydro-mechanical modelling (Fischer & Huggel, 2008) of the 1988 Tschierva rockfall (tab. 3.1).

Finally, water percolation in the largest clefts can accelerate ice melting by heat advection, much more efficient than heat conduction from the air (Gruber & Haeberli, 2007).

4. Cases studies

France

Authors: Philip Deline & Ludovic Ravanel, EDYTEM Lab, France (CNRS-EDYTEM/PP11)

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The two case studies in the Mont Blanc massif strongly suggest that the climate warming in the Alps since several decades is driving the rockfall frequency and magnitude, because of the permafrost degradation in the high-Alpine steep rockwalls.

Increasing rockfalls at les Drus since 1950

Post-Little Ice Age rockfalls that affect the well-known West face of les Drus were documented by Ravanel & Deline (2008), combining photocomparison (photos are ranging in date from 1854 to 2008) with historical descriptions of the rockfalls and ground-based LiDAR surveys.

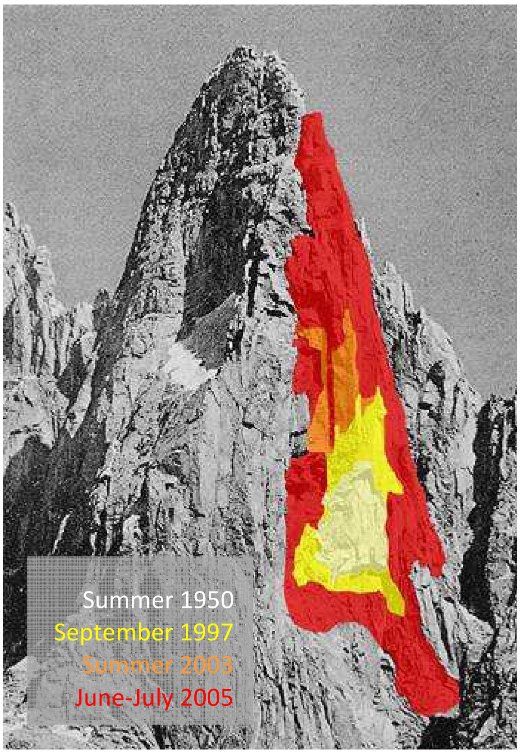

Fig. 3.3 – Development of the rockfall detachment zone in the West face of les Drus between 1950 and 2005.

The first post-LIA rockfall on the 1000 m-high West face (peaking at 3754 m a.s.l.) was triggered by the 13/08/1905 earthquake (9,000 ± 100 m^3). A small collapse occurred between the mid-1930s and the early 1940s (5,500 ± 500 m^3), but the first large post-LIA rockfall took place in 1950 (20,000 ± 2,000 m^3). Two small rockfalls detached during the 1970s and 1980s (1,750 ± 250 m^3, and 350 ± 50 m^3). In September 1997, two rockfalls removed the 1950 overhang (total volume: 27,500 ± 2,500 m^3). During the summer of 2003, the overhang formed during the previous rockfall collapsed (c. 6,500 ± 500 m^3). Finally, the whole Bonatti Pillar collapsed in 2005 in four events over several hours, involving a total volume of 265,000 ± 10,000 m^3. The total volume of rock detached during these 8 rockfalls is 335,000 ± 15,000 m^3 (fig. 3.3).

23 earthquakes of local intensity > 3 that affected the Mont-Blanc area over the last 150 years, but only the 1905 earthquake (the second most intense) directly triggered one Drus rockfall. Paraglacial control (i. e. self-weight stress within the rock mass, due to the downwastage and retreat of glaciers) has not affected the west face of Les Drus, because the LGM trimline was > 300 m below the scar. No ice was observed in the June 2005 scar, but water seepage persisted in it throughout the summer, and there is a strong correlation between Drus rockfall occurrences and the warmest periods over the last 100 years (fig. 3.4). Permafrost degradation was deep-seated because the Bonatti Pillar received strong heat flux on its south aspect, and the densely-fractured granite promotes active water drainage (heat transfer by advection into the rock mass), facilitated by the degradation of ice joints. Thus, the present climate warming is probably the main triggering factor of most rockfalls at the West face of Les Drus during the second half of the 20th century.

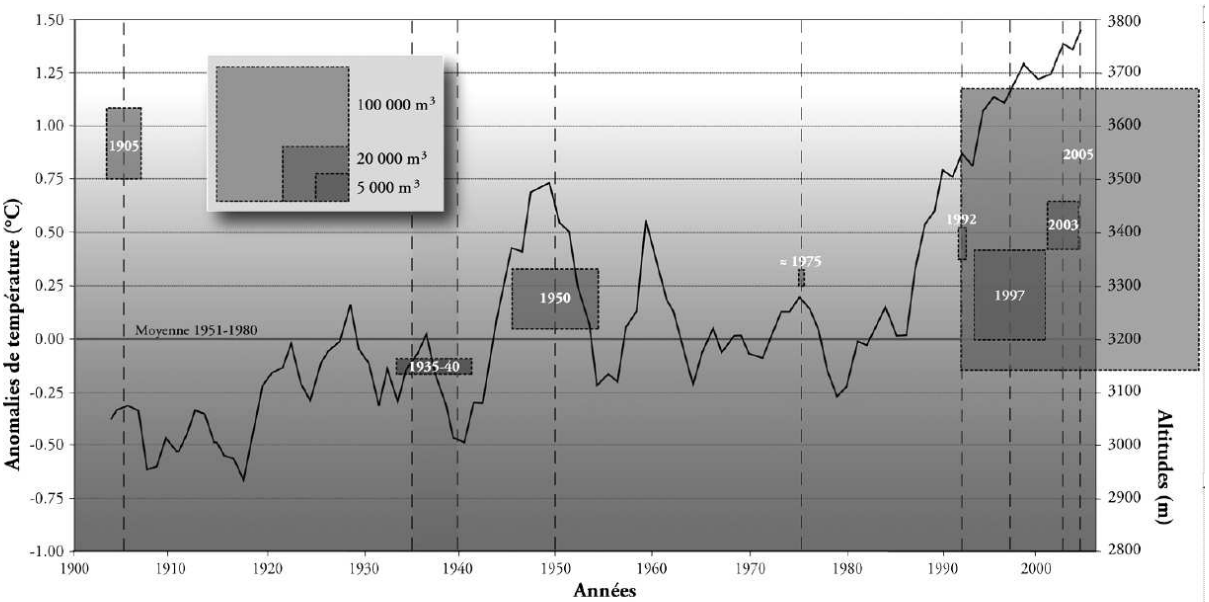

Fig. 3.4 - Mean annual air temperature in the Alps, and volume and frequency of rockfalls in the West face of les Drus between 1905 and 2005.

x-axis: year; left y-axis: temperature anomaly with regard to the 1951-1980 average; right y-axis: elevation (m a.s.l.); dotted quadrilaterals: rockfalls.

Increasing rockfalls in les Aiguilles de Chamonix since 1947

In a recent study, Ravanel & Deline (submitted) have documented 42 rockfalls on the North side of the Aiguilles de Chamonix (fig. 3.5), thanks to the comparison of old, recent and present photographs, and to geomorphological field data. Rockfalls of this inventory are ranging in volume from 500 to 65,000 m^3, with a total volume of 390,000 ± 60,000 m^3.

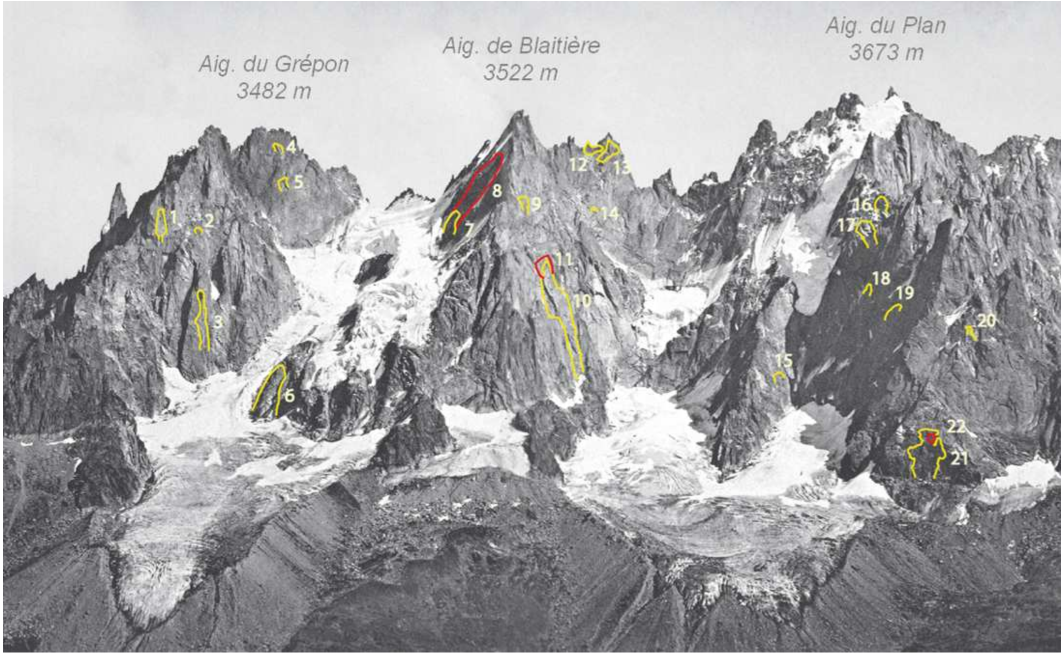

Fig. 3.5 - North faces of the Aiguilles des Grands Charmoz, du Grépon, de Blaitière and du Plan at the end of the LIA (Ph. Bisson brothers, 1862). Rockfall scars (volume > 500 m^3) recognized in this sector are delineated and numbered. When two scars are overlapping, the most recent appears in red.

Mostly N to NW-aspect and ranging in elevation from 2615 m to 3500 m a.s.l., the rockwalls affected by the rockfalls are in the modelled permafrost zone (fig. 3.6) – which does not mean that all result from its degradation.

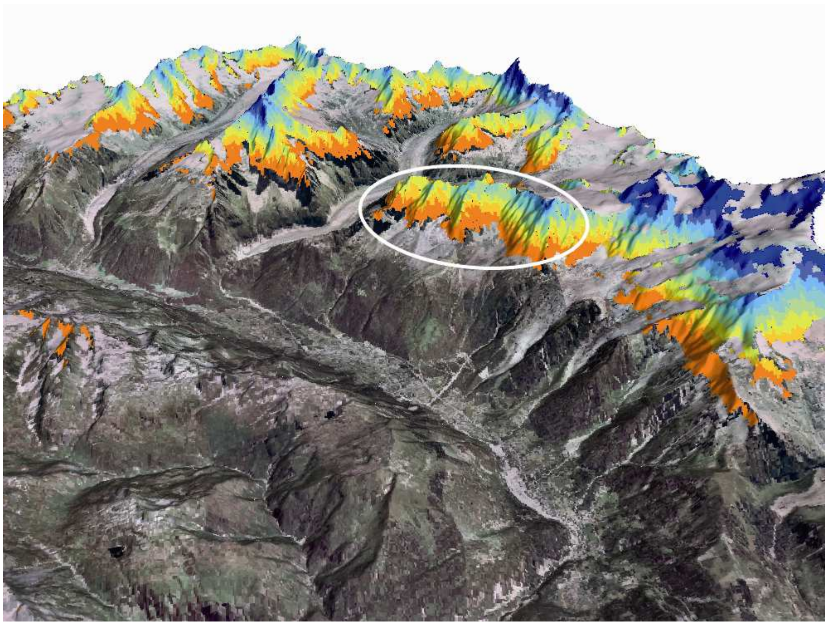

Fig. 3.6 – Modelled distribution of mean annual ground surface temperatures of the Mont-Blanc massif using the TEBAL model (S. Gruber). Temperature is ranging from 0°C (dark orange) to -13°C (dark blue). Ellipse indicates the Aiguilles de Chamonix.

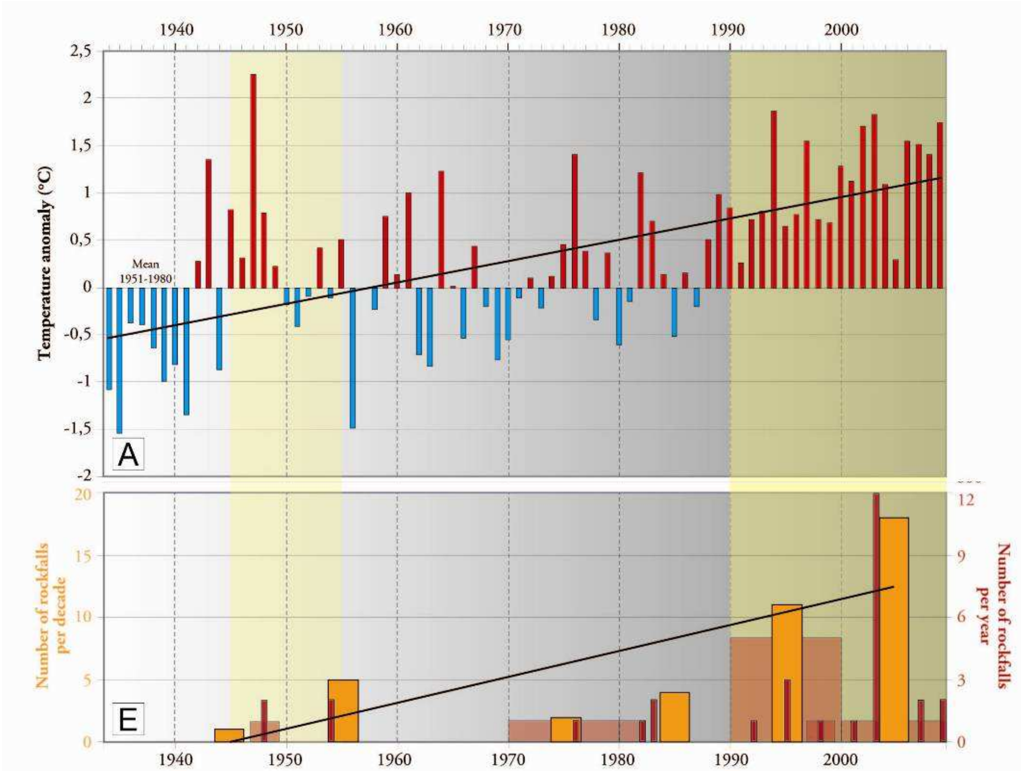

Fig. 3.7 – Comparative evolution of climate in Chamonix-Le Bouchet (1040 m a.s.l.) and rockfalls in the North side of the Aiguilles de Chamonix. A: mean annual air temperature anomaly in relation to the 1951-1980 mean; E: rockfalls number per decade and per year. Black line: trend (linear regression, decadal for E); wide bars in E rockfalls not precisely dated. (Meteorological dataset: Météo-France)

This study in the Aiguilles de Chamonix shows that:

- 70 % of the 42 rockfalls took place during the two last decades, characterized by the acceleration of global warming (fig. 3.7);
- Warm summers (1947, 1976, 1983, 2003) are periods of rockfall triggering;
- The average elevation of scars (3130 m a.s.l.) is close to the lower limit of the permafrost, where its degradation is more active;
- The total volume of the rockfalls corresponds to a rockwall retreat rate of 1.3-1.75 $mm.yr^{-1}$ over the period 1947-2009, against 0.55-0.75 $mm.yr^{-1}$ over the period 1862-2009;
- Ridges, spurs, and pillars, caracterized by heat fluxes from well-exposed rock faces (Noëtzli et al., 2007), are prone to collapses, due likely to a faster permafrost degradation.

Therefore, since the end of the LIA, triggering of the recognized rockfalls in the Aiguilles de Chamonix took place after 1947, being probably mostly controlled by the current permafrost degradation.

Italy

Authors: Michèle Curtaz, FMS, Courmayeur, Italy ; Gianni Mortara & Marta Chiarle, CNR-IRPI, Torino, Italy,

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Matterhorn Rockfalls

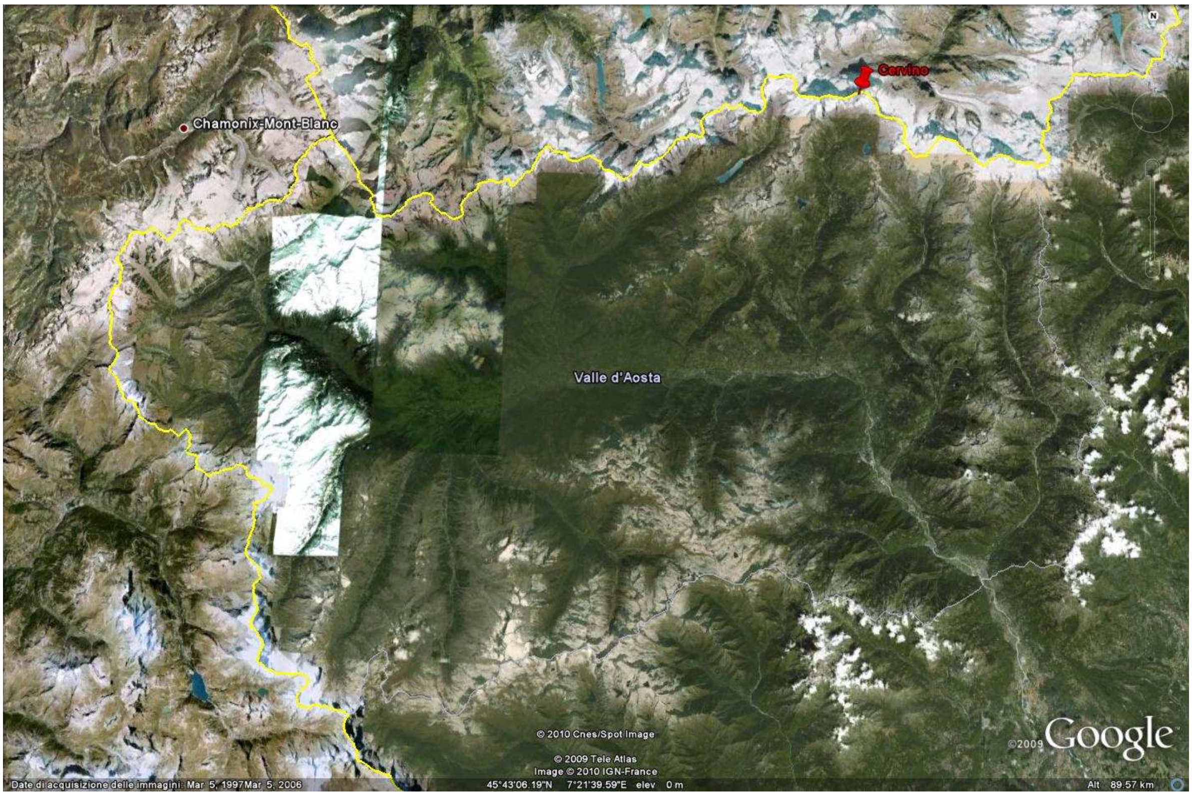

Fig. 3.8 – Site location, on South face of Matterhorn Mountain, Valtournenche - Aosta Valley, Italy.

The events interested the Italian side of the Matterhorn. In particular they are located on the South-West edge nearby the Carrel hut. Matterhorn is constituted by steep rock walls and fractured rock masses formed in the middle part by gneiss and mica schist of the so-called Sesia-Lanzo Zone.

Event description

Several episodes happened. In August 2003 (04/08/2003) a first instability (estimated in some tens of cubic meters of volume) interested the part above the Carrel hut (3830 m asl) at an elevation of 3850 m asl. The rock mass in this point is very fractured and disaggregated and it's made by rock blocks, coarse and fine material bound by ice. The passage so-called "Corda della Sveglia" ("*get up rope*", as it is the first passage to be climbed after getting off from the hut) had to be changed and the rope for the ascent was moved. Some small rockfall events in the South face were recorded between 11th and 13th of August.

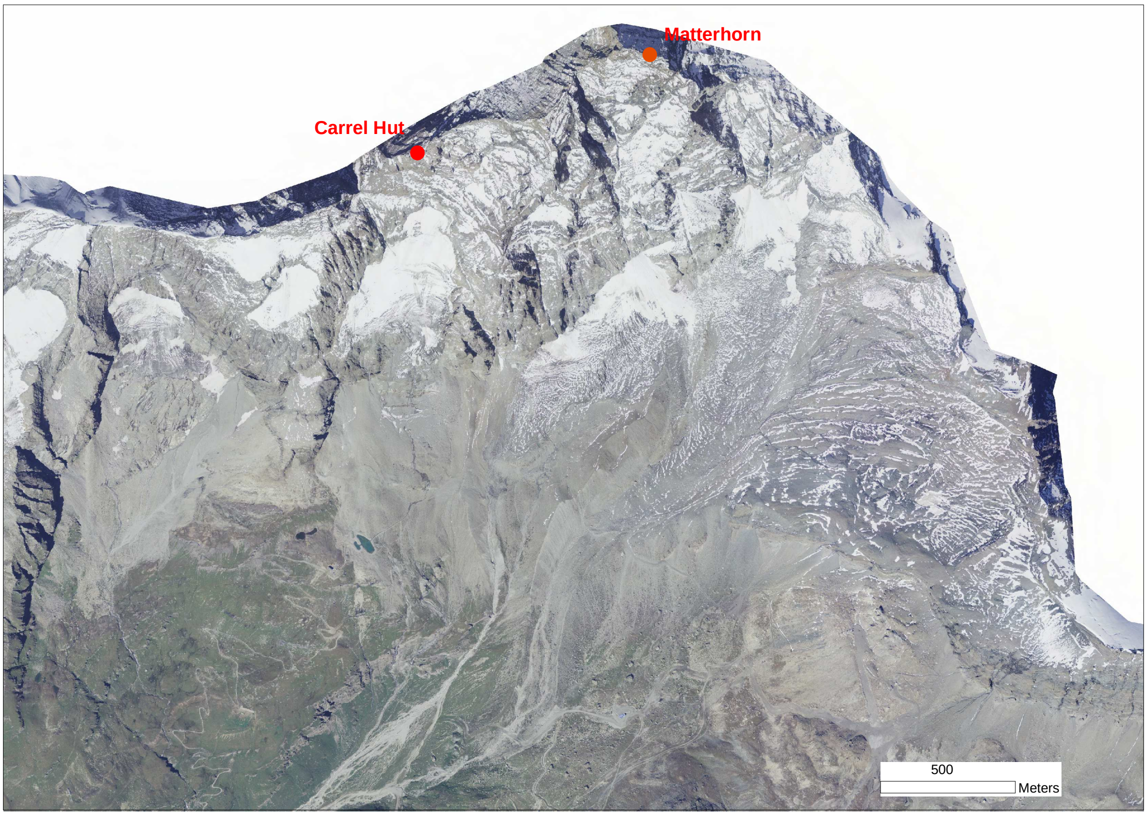

Fig. 3.9 – The south face of Matterhorn, with the location of the Carrel Hut.

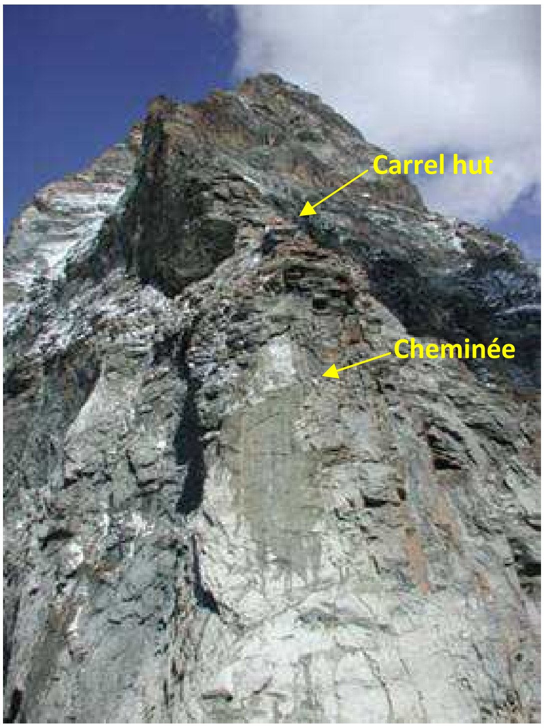

Fig. 3.10 (left) – The Cheminée after the rockfall of 2003. The water below the Cheminée comes from the melting of the ice lense uncovered by the rockfall.

Fig. 3.11 (right) – Rockfall scar of 2006 event in the lower right corner, c. 100 m below the Carrel hut. The yellow dot is the position of the rock temperature sensor (photo Servizio geologico regionale RAVA).

Two weeks after the first episodes, the Cheminée passage below the Carrel hut fell (19/08/2003 assessed volume of some hundreds of cubic meters). The photos of this event, documenting the ice uncovered by the rock fall, are well known all over the world. The high temperatures of the 2003 summer (isotherm zero above 4000 m asl for several days continously) have been immediately considered the triggering factor of the rockfalls because of the degradation of the permafrost state of the rock mass.

In Summer 2006 (25/07/2006) another rockfall occurred along the north west side of Matterhorn about 80-100 m below the Carrel hut. The volume of the fall was assessed in about 200-300 m^3 but the deposit wasn't clearly visible and the estimation is thereby not sure. The visible scar was estimated to be 50 m wide. The fall was heard by the people in the hut and made the hut shaking but no damages arrived at the structure; no problem occurred along the ascent way because at this elevation it goes on another side. Rock temperature measurements recorded by ARPA VdA few tens meters above the rockfall scar, shows that the event occurred during the hottest period of the summer 2006 (fig. 3.12) during which the minimum daily temperature (blue line) was above 0°C for several consecutive days.

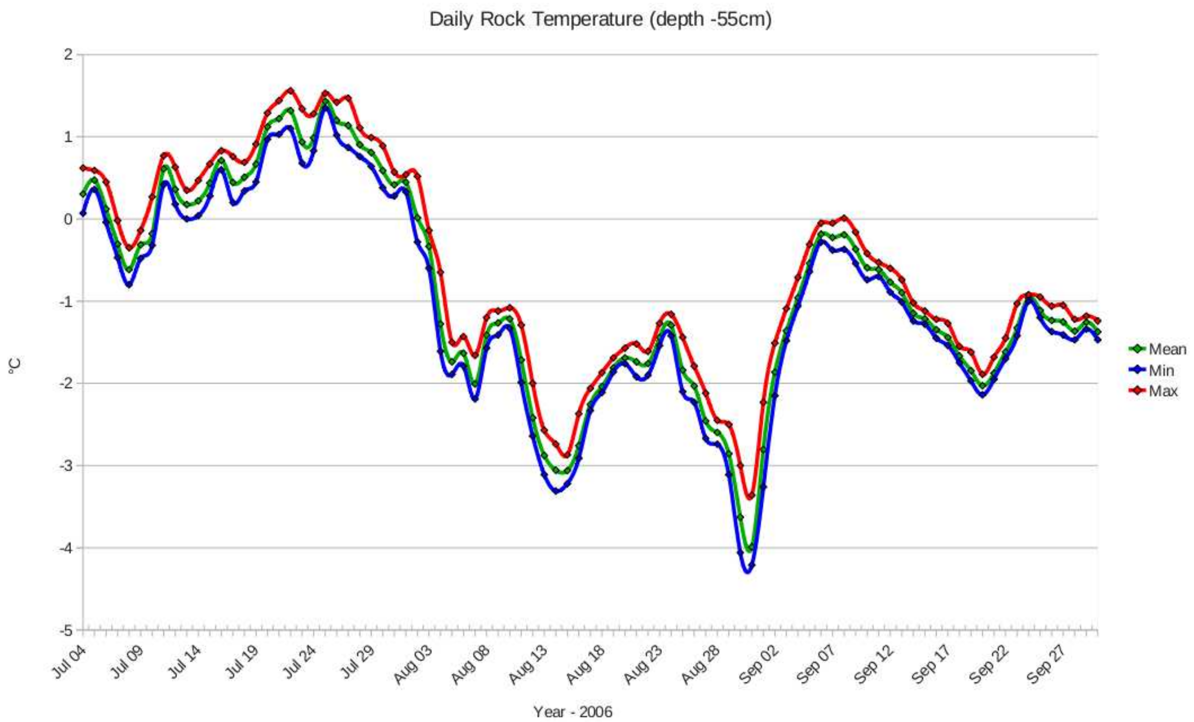

Fig. 3.12 – Daily rock temperature measured on the NW side of Matterhorn during summer 2006. The measure is performed at 55 cm depth. Red line: maximum daily rock temperature; green line: mean daily rock temperature; blue line: minimum daily rock temperature.

During the surveys in this sector another dangerous situation was recognized above the hut because of a huge rock block (1500-2000 m^3) already isolated by joints where ice and melt water were observed. In case of collapse, the rock material could reach the hut nearby.

In August 2009 another alarm was launched: 50 m above the Carrel hut, the rock blocks on which the rope called "Corda della Sveglia" had been installed were considered unstableand the way to the Matterhorn peak was closed: the total unstable volume was assessed in 100-150 m^3. The unstable blocks were removed and after some days the way to the Matterhorn was opened.

Permafrost relation

Presence of ice in the rockfall scar (e.g. Cheminée rockfall) and in the rock joints was seen during the different surveys. The high temperatures of summers (in particular of summer 2003) have been immediately considered the cause of the melting of ice in the rock mass fractures and of the permafrost degradation.

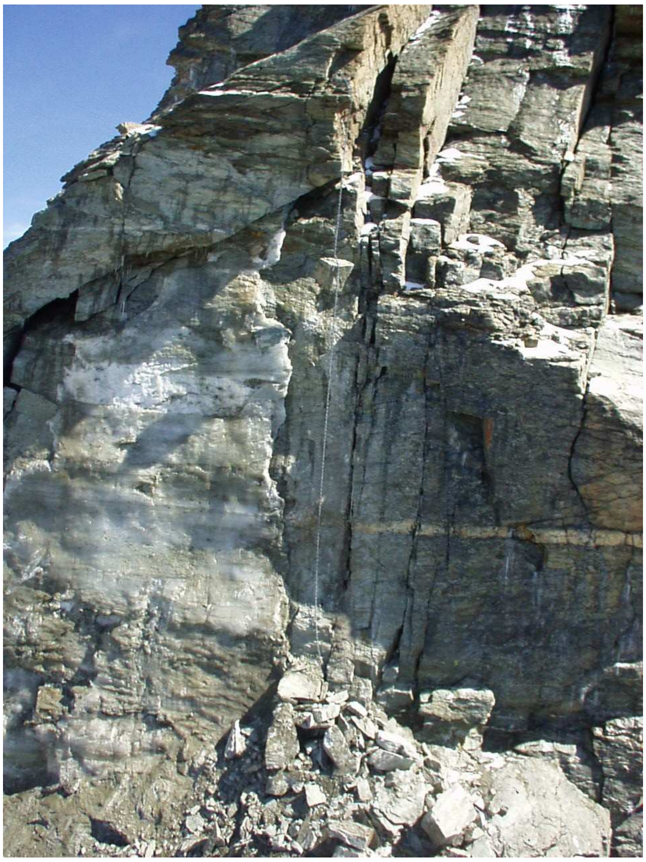

Fig. 3.13 – Ice visible after the Cheminée rockfall – August 2003 (photo L. Trucco).

Consequences/Damages

No damages and injuries occurred during all the events, but in some case climbers had to be rescued by helicopter, as the climbing route was not anymore practicable. In 2003 the Carrel hut was closed; in 2006 and 2009 the Italian way to the Matterhorn was closed during the works and until a good level of safeness was reached. This decision had consequences on the alpinism tourism of the valley. The climbing route has changed after the Cheminée rockfall and the bad conditions of the rock mass above the Carrel hut as well as the rockfall of 04/08/2003 imposed some interventions on the Corda della Sveglia passage.

Intervention measures

In order to secure the sector above the Carrel hut where the route to the Matterhorn goes, the unstable blocks left from the rockfall of 04/08/2003 were removed and the rope for the ascent was moved in a more secure place. During the works the hut and the Italian way to the Matterhorn were closed. The unstable blocks at Corda della Sveglia were removed to restore the route.

The Carrel hut is located on a very fractured rock spur which also underwent some deformation during the hot summer 2003, even if did not collapse. As a consequence, the rock spur had to be consolidated, in order to guarantee the stability of the hutAfter the phenomena of 2003 this site started to be a case study where different monitoring techniques were applied. From 2005 a continuous monitoring of surface rock temperature, air temperature and air humidity is performed by ARPA VdA. Actually 3 monitoring sites are active in the areas sourrounding the Carrel Hut and the Cheminèe. Experimental measures of incoming and outgoing solar radiation on near vertical rockwall have been performed during 2006 and 2007. In the frame of the same project, a geophone network has been installed by CNR-IRPI, with the support of Regione Valle d'Aosta and Solgeo (Occhiena et al., 2008). Data analysis, realised in cooperation with the Politecnico of Turin, was aimed to detect deforming areas and relations with temperature records.

Punta Patri Rockfalls

Site location: Punta Patrì Nord, Valeille Valley (Cogne) - Aosta Valley, Italy

The Valeille Valley is in the Gran Paradiso Parc in the municipality of Cogne. It's a secondary valley of Cogne Valley in the South part of Aosta Valley Region. The peak Punta Patrì is located almost at the bottom of Valeille at the border with the Piedmont Region.

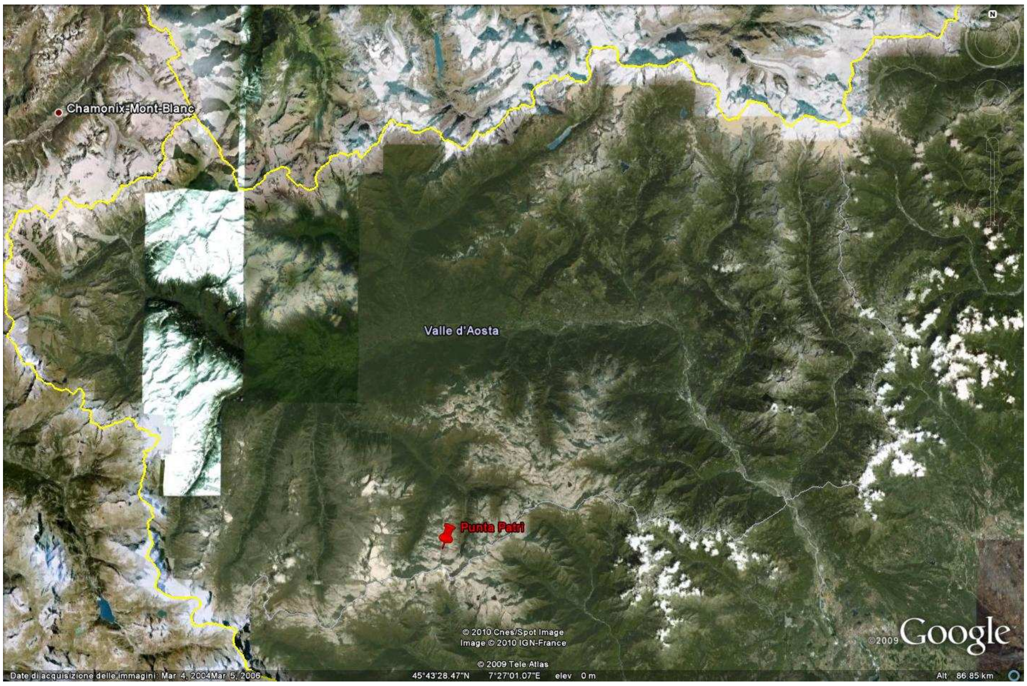

Fig. 3.14 – Location of the site in the Valleille valley, Italy.

Geomorphology: Punta Patrì (or Pène Blanche) Nord is a peak in the mountains between the Valeille and the Valnontey. There are two summits: the northern, Punta Nord (3358 m asl) and the southern, Punta Sud (3579 m asl). The rockfalls started from the ridge below the Punta Nord (East side) and run on the both sides of it (towards North and towards South). On the northern side of the ridge bedrock outcrops extend from the summit down to 2800 m asl, below the slope is covered by debris; on the southern side some debris couloirs end in cones located at an elevation of about 2900 m asl. In the valley bottom, at an elevation of about 2350 m asl, the Torrent Valeille runs.

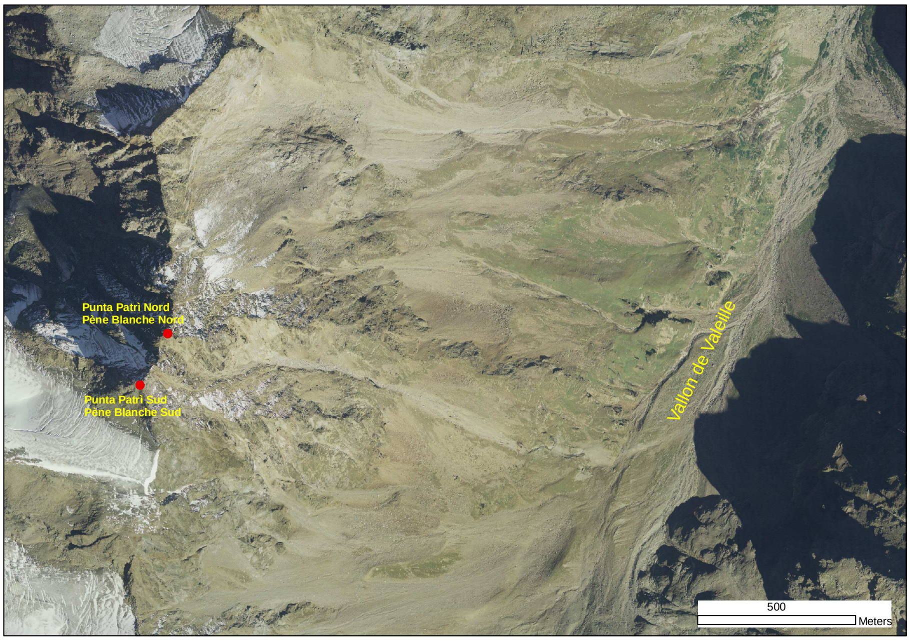

Fig. 3.15 – Aerial orthophoto of the site.

Event description: Several events happened during the summer 2007 and 2008. A first rockfall developing on the north side of the ridge was seen the 12th August 2007. In 2008 bigger events happened the 17th and the 18th of September: two rock scars formed at an elevation of 3200-3400 m asl in the north and the south side of the ridge and the rock material fell along both sides of the rock nose. The largest event was the southern one and involved the same starting zone of 2007: the detached material went through a steep couloir with a drop of about 400 m then it parted in different lobes, one of which could reach the valley floor and climb up the opposite side of the Valeille Valley. The deposit is heterogeneous and chaotic (decameter blocs) and in some parts it's more than 10 m thick, for a total surface of 150000 m². The rockfall from the northern scar caused a smaller continuous deposit near the rock wall. Part of the fallen material went through three small couloirs and stop on the cones at the end, only some blocks arrived at an altitude of 2500 m asl.

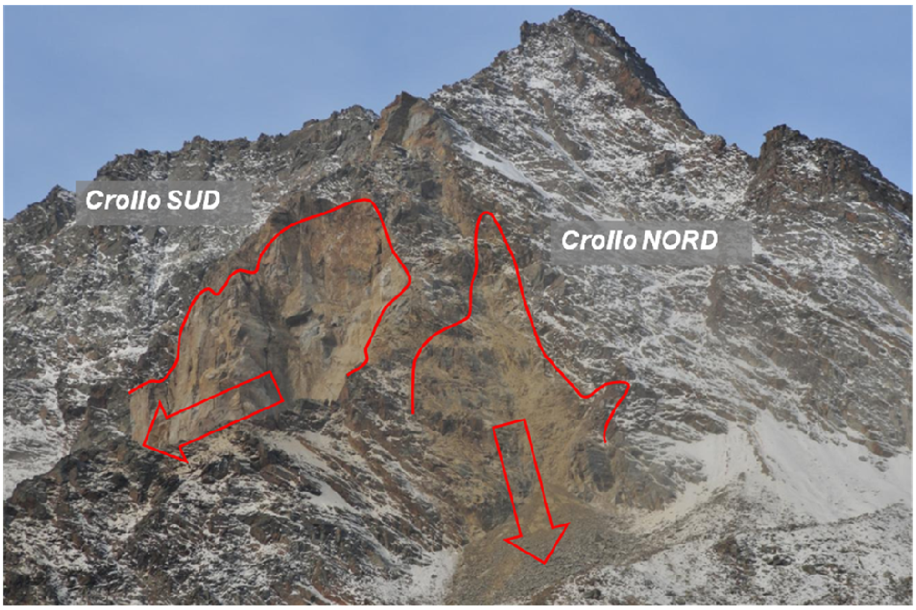

Fig. 3.16 – Rock scars on the North and South side of the ridge below Punta Patrì Nord (photo D. De Siena in Mortara et al., 2009a)

The total surface covered by the deposits of the two rockfalls is more than 220 000 m² for an estimated volume of 100 000 m^3.

The days before the events, just weak and discontinuous precipitations were recorded (35,8 mm from 01/09 to 17/09 at nearest meteorological station of Cogne-Gimillan, 1788 m asl), so the precipitation was not inferred to be the trigerring factor. The strongly fractured structure of the rock mass and the water coming from melt ice were recognized as probable causes.

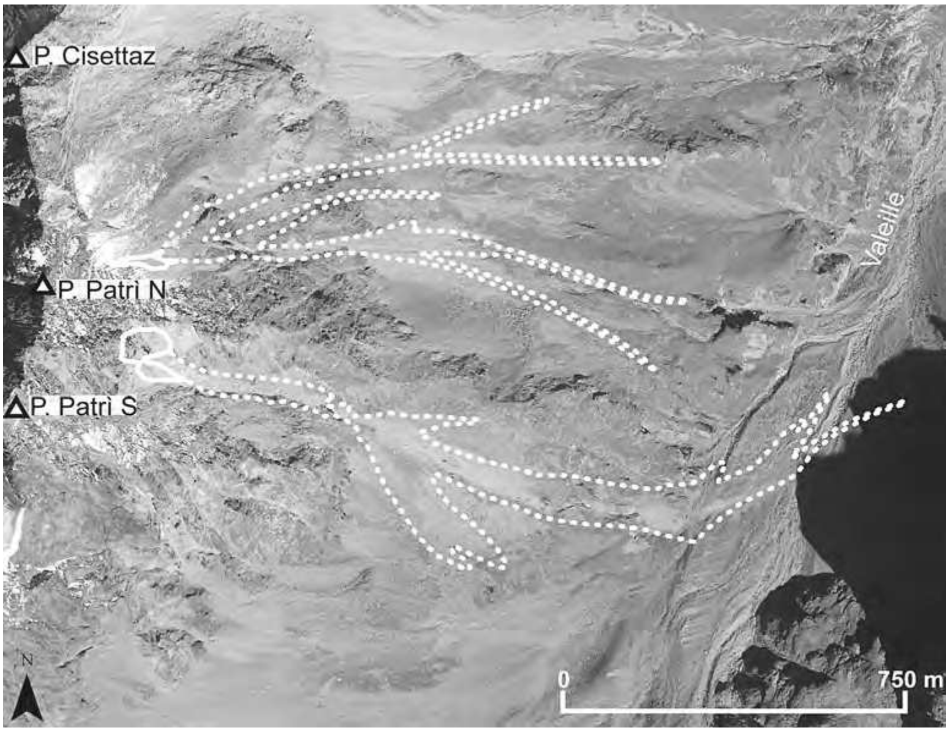

Fig. 3.17 – Map of the deposits: the continuous line marks the rockfall scars, the dashed lines delimits the deposit (from Mortara et al., 2009b).

Fig. 3.18 – Ice in the rock mass and water coming from the melting of the ice lens uncovered by the rockfall (19/09/2008, photo Servizio geologico regionale RAVA)

Permafrost relation: During the survey in 2008 ice was seen in the rockfall scar of the northern side.

Consequences/Damages: The Valleille is not populated: infrastructures and civil habitations are far away downstream from this site (about 6 km). Some rock material reached the track going to the Antoldi hut.

Intervention measures: No measures.

Pellaud rockfalls and debris flows

Site location: Pellaud basin, Rhêmes Valley - Aosta Valley, Italy

The Pellaud catchment basin is on the orographical right side of the upper Rhêmes Valley, a secondary valley of Aosta Valley Region.

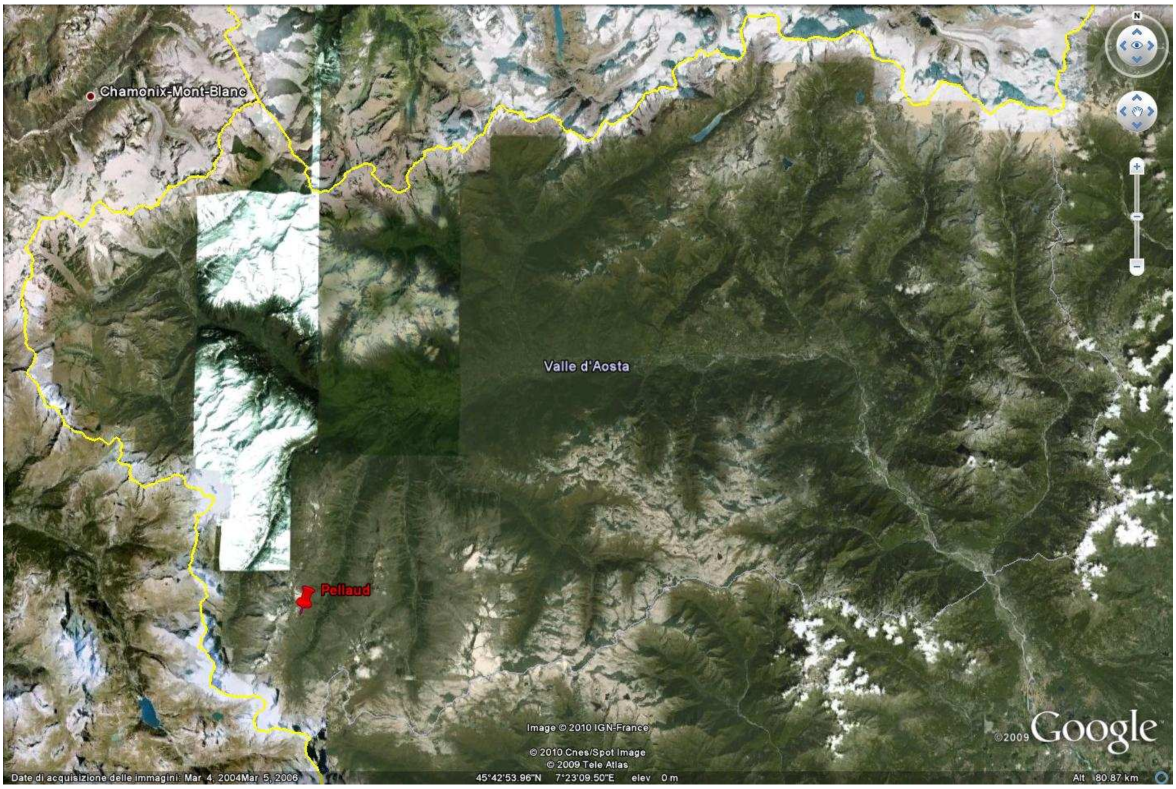

Fig. 3.19 – Location of the site.

Geomorphology: The catchment is a circle surronded by metamorphic rock walls (gneiss and mica schist) about 500 m high, from 3550 m asl to 3000 m asl; below there are steep slopes (always more than 30°) with some cliffs that end at 2200 m asl in the alluvial fan where the Pellaud torrent runs up to the confluence (1810 m asl) with the main torrent of Rhêmes Valley, the Dora di Rhêmes. In the upper part of the basin there is a glacier (Pellaud Glacier) which has almost totally disappeared leaving some loose material on the slopes.

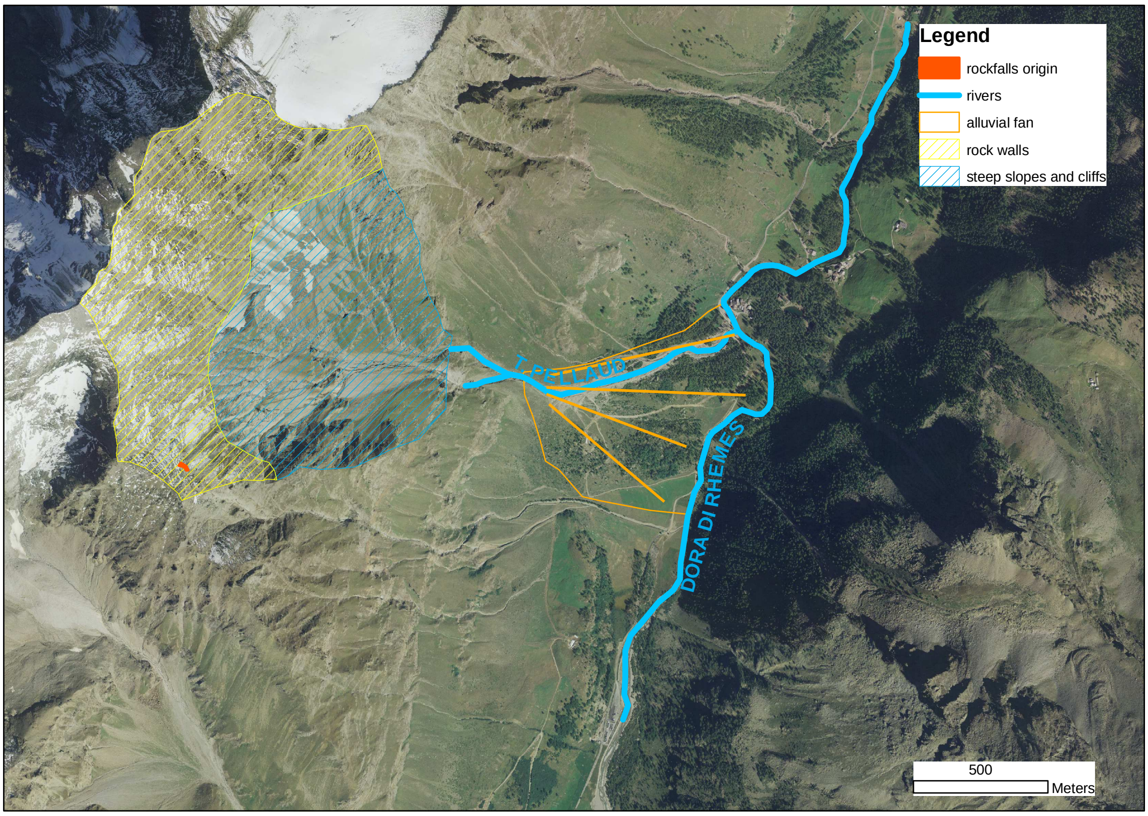

Fig. 3.20 – The Pellaud catchment basin.

Event description: In autumn 2005 some rockfalls happened on the eastern side of the Becca di Fos (3459 m asl), in Rhêmes Valley (Aosta Valley – Italy). After being deposited on the steep slopes below the rockwalls, the rock material was carried by strong rainfall runoff to the lower part of the basin causing debris flows.

This is a complex case, where the degradation of permafrost in fractured rock walls can trigger rockfalls that feed scree slopes and lead to bigger events of solid transport by the water. The site is still active: strong precipitations carry the fallen rock material deposited on the steep faces and transport it in the Pellaud Torrent producing debris flows events. The magnitude of these debris flows has been assessed variable in each event in the range 5000-15000 m^3.

Permafrost relation: In Autumn 2005 during the surveys by helicopter ice was seen in the fractured rock mass and in the scar of the rockfall.

Fig. 3.21 – Ice in the rock mass (autumn 2005 – photo Servizio geologico regionale RAVA).

Consequences/Damages: When the rockfall happened along the torrent Pellaud there were the yard for the construction of prevention measures necessary after the flood event of July 1996; the yard were evacuated and scaling works were done to reduce the still instable rock mass (30000 m^3). In spite of these intervention measures the rockfall and the debris flows didn't stop. Other events produced during the next years (2006-2007) and the site is still active. The increase in the frequency and in the magnitude of the debris flows lead to stop the construction of the torrent protection measures (the yard was in danger and every time they have to clean the river bed from the material trasported and deposited in). The original design should be modified to take in account the new situation.

Intervention measures: To reduce the volume instable, estimed in about 30000 m^3, the regional administration intervened in Autumn 2005 by scaling. The new situation requires changes in the original prevention measures design to consider the increasing debris flows correlated to the rockfalls.

Case studies – South Tyrol

Rockfall Plattkofel (Sasso Piatto)

Latitude	46.516389°
Longitude	11.712222°
Elevation [m a.s.l.]	2.650
Slope	North-east exposed; sub vertically
Aspect	
Type of soil	fractured rock
Evidence of permafrost	Ice
Presence of infrastructure	Yes
Type of infrastructure	Fixed rope route
Evidence of movement	/
Typology of movement	Rockfall
Area of phenomenon	20 x 35m
Volume of phenomenon	700 m^3
Date	19^{th} August 2010

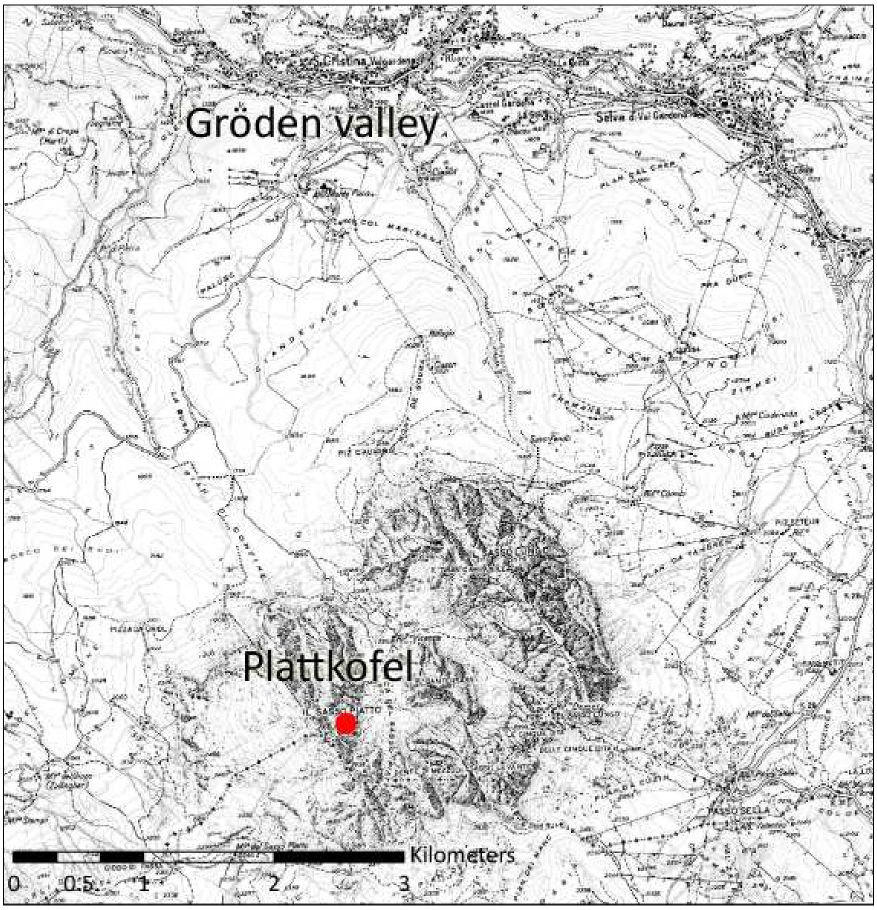

Fig. 3.21 – Location of the Plattkofel massif. The red mark shows the point of rockfall.

Site location: The Plattkofel massif is located in the western Dolomites, in the Autonomous Province of Bozen – Südtirol (South Tyrol). The rockfall happened at the north-east side of the massif, at an elevation of 2.650 m.

Geology and Geomorphology: The Plattkofel massif is a dolomitised carbonate platform slope (upper Ladinian – lower Carnian). It is highly fractured, has m-thick breccia beds and is locally also unstratified and massive.

Event description: On the 19th August 2010, at 15:00 o'clock, a rock fall happened in the upper part of the Plattkofel massif. The rock fall interrupted the Oskar-Schuster fixed rope route in two points. At the top of the break-off point the route was destroyed. In the gorge at the base of the rockwall the itinerary was overwhelmed by blocks and debris.

The break-off zone has a width of circa 20 m and a vertically extension of circa 35 m. The volume of the rock fall material is in the order of circa 700m^3.

Fig. 3.22 – Break-off point in the upper part of the Plattkofel massif.

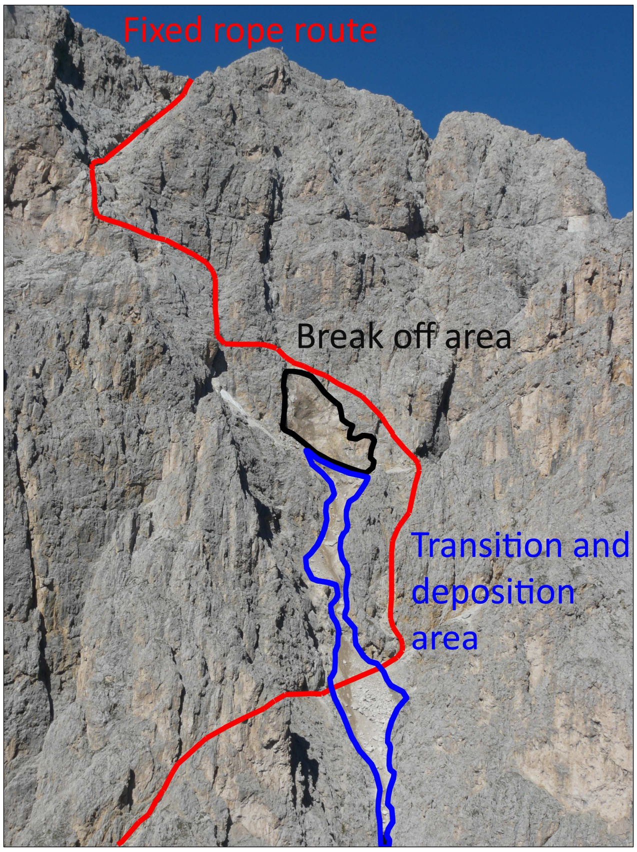

Fig. 3.23 – The Oskar-Schuster fixed rope route was interrupted at two points at the upper part of the itinerary.

Permafrost relation: On the 21st August 2010 the break off area was studied in detail by means of helicopter flight and roping. In doing so, ice was detected on the rupture surface of the break off area. The rupture surface was partially covered by dirty ice that contained particles of the host rock (sand – gravel). This is a clear evidence for permafrost melting as a trigger for the rockfall. Furthermore, other permafrost evidences, such as small rock glaciers and perennial snow fields, were observed in the Plattkofel-cirque.

Fig. 3.24 – Clear permafrost evidence at the Plattkofel massif. The break-off zone is partially covered by an ice-debris mixture. On the left picture the two principally ice covers on the rupture surface are marked. The picture on the right shows the permafrost ice layer in detail.

Rockfall Hohe Wilde (L'Altissima)

Latitude	46.766389°
Longitude	11.023611°
Elevation [m a.s.l.]	3.400
Slope	East exposed; sub vertically
Aspect	
Type of soil	fractured rock
Evidence of permafrost	The break-off area was wet
Presence of infrastructure	Yes
Type of infrastructure	Hiking trail
Evidence of movement	/
Typology of movement	Rockfall
Area of phenomenon	Ca. 4 x 20m
Volume of phenomenon	150 m^3
Date	30^{th} July 2008

Site location: The Hohe Wilde is a mountain in the Ötztal Alps at the border between Austria and Italy. The 3.480 m high peak is a quite popular destination for alpinists and is accessible from the Schnals Valley (Pfossental) or the Passeier Valley. The trail leading from the refuge (Stettiner Hütte, rifugio Petrarca, 2.875 m) to the Hohe Wilde summit crosses the very steep eastern face, characterized by a concave morphology, that concentrates all rock fall on a 50 m wide area. This area is crosscut three times by the trail. After the event of 30^{th} July 2008 the trail has been abandoned and deviated to the southern crest.

Geology and Geomorphology: Highly fractured and fissured gneisses and micaschists of the Ötztal Crystalline Basement.

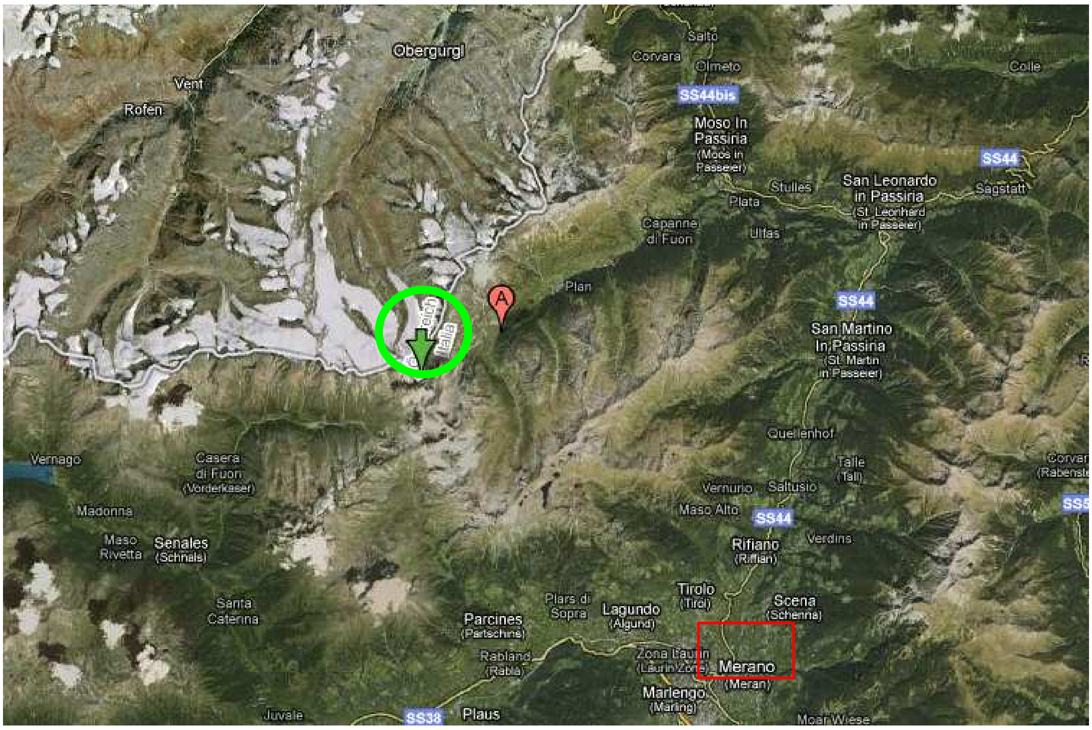

Fig. 3.25 Location of the hohe Wilde

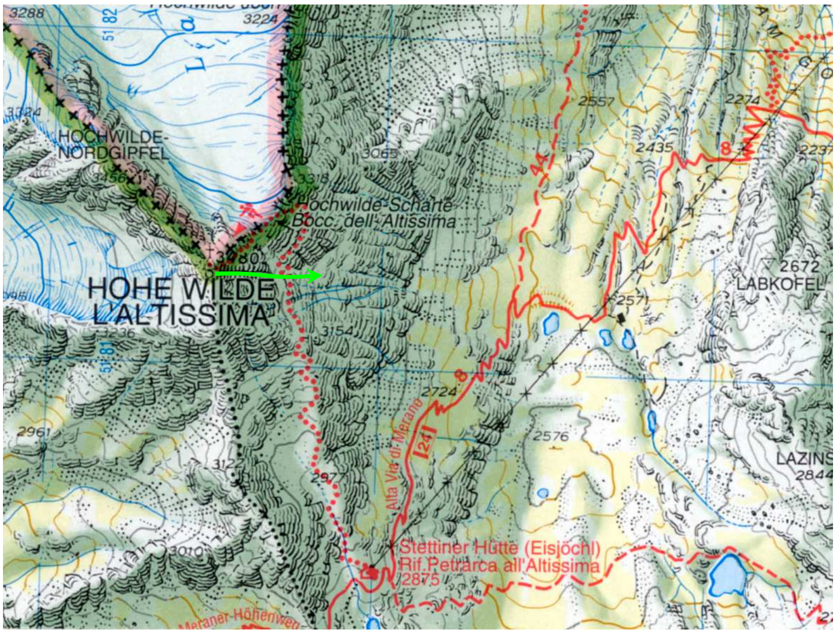

Fig. 3.26 – Location map of the Hohe Wilde. The green arrow shows where the rockfall happened.

Event description: On the 30th July 2008 a rockfall happened below the Hohe Wilde summit. The rockfall interrupted the hiking trail on a length of 50 m. One person was slightly hurt. The rockslide happened in the very steep eastern face.

Permafrost relation: Elevation (> 3.000 m a.s.l.) and exposition. Water from melting ice was visible at the break-off zone

Fig. 3.27 – Location of the rockfall.

Austria

Authors: Andreas Kellerer-Pirklbauer & Gerhard Karl Lieb, Institute of Geography and Regional Science, University of Graz (IGRS/PP8)

Version: February 12th 2010

4.4.1. Example Mt. Mittlerer Burgstall, Hohe Tauern, Austria: Rock fall events in 2007

1. Introduction

Ongoing global climate change has a number of consequences on processes which are controlled by atmospheric conditions. Landslides occurring at high mountain areas which are generally underlain and stabilized by permafrost or at slopes that are affected by retreating glaciers are getting more frequent in recent years (e.g. Noetzli *et al.*, 2003).

The geomorphic effects of the rock fall example presented here occurred during spring to early summer 2007 thereby changing completely the shape of the 2933 m high Mt. Mittlerer Burgstall, Austria (Fig. 3.28). As it is shown in the following paragraphs, the reasons for the high susceptibility to rock slope failure at Mt. Mittlerer Burgstall are presumably a combination of (a) glacial erosion, (b) glacier retreat, (c) permafrost changes and (d) unfavourable geological conditions. The triggering event for the rock falls in 2007 at this site was most likely the effect of the (e) warm winter 2006/2007 which influenced and changed the thermal situation as well as liquid water distribution within the mountain substantially compared to normal years.

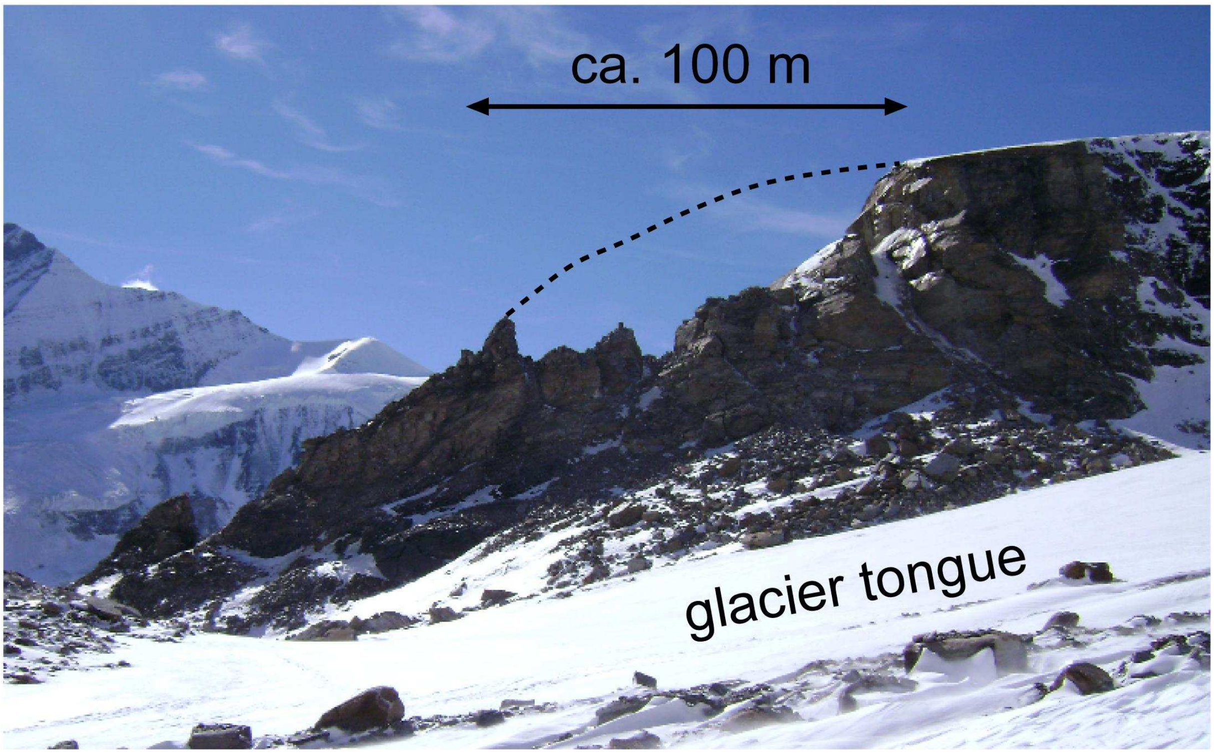

Fig. 3.28 – Morphological changes caused by rock fall events in spring and summer 2007 at Mt. Mittlerer Burstall. View towards W (Photograph by A. Kellerer-Pirklbauer).

2. Mt. Mittlerer Burgstall and its surrounding

Mt. Mittlerer Burgstall (N47°06'07'', E12°42'36'', 2933 m asl.) is a former *nunatak* that was surrounded by Pasterze Glacier, the largest glacier of the Eastern Alps, during the Little Ice Age (LIA) around 1850 AD (Fig. 3.29). Pasterze Glacier is a compound valley glacier fed by a number of tributaries, ranges from 2,065 to c. 3,500 m a.s.l. and covers an area of 17.5 km² (in 2002). Furthermore, Mt. Mittlerer Burgstall is in close vicinity to Mt. Großglockner (3798 m a.s.l.), the highest summit of Austria.

Mt. Mittlerer Burgstall is characterised by a flat mountain plateau with steep rock walls delineating the plateau on all slope orientations apart from NW, where the mountain is gently sloping towards the glacier. Pasterze Glacier is characterised by two unequal sized glacier tongues. The main glacier tongue is located in the SW of the mountain, whereas the substantially smaller one is located at the footslope in the NE of Mt. Mittlerer Burgstall. A distinct NW-SE ridge was formed during the Pleistocene and Holocene on both sides/flanks of the mountain caused by former glacier erosional action. This ridge as well as the two rock wall flanks of the mountain resemble a turned over hull (*cf.* Fig. 3.30 & 3.31). On the SW to S facing slope the vertical distance down to the main tongue of Pasterze Glacier is about 500 m. In contrast, it is only some 100 m down to the smaller glacier tongue in the NE.

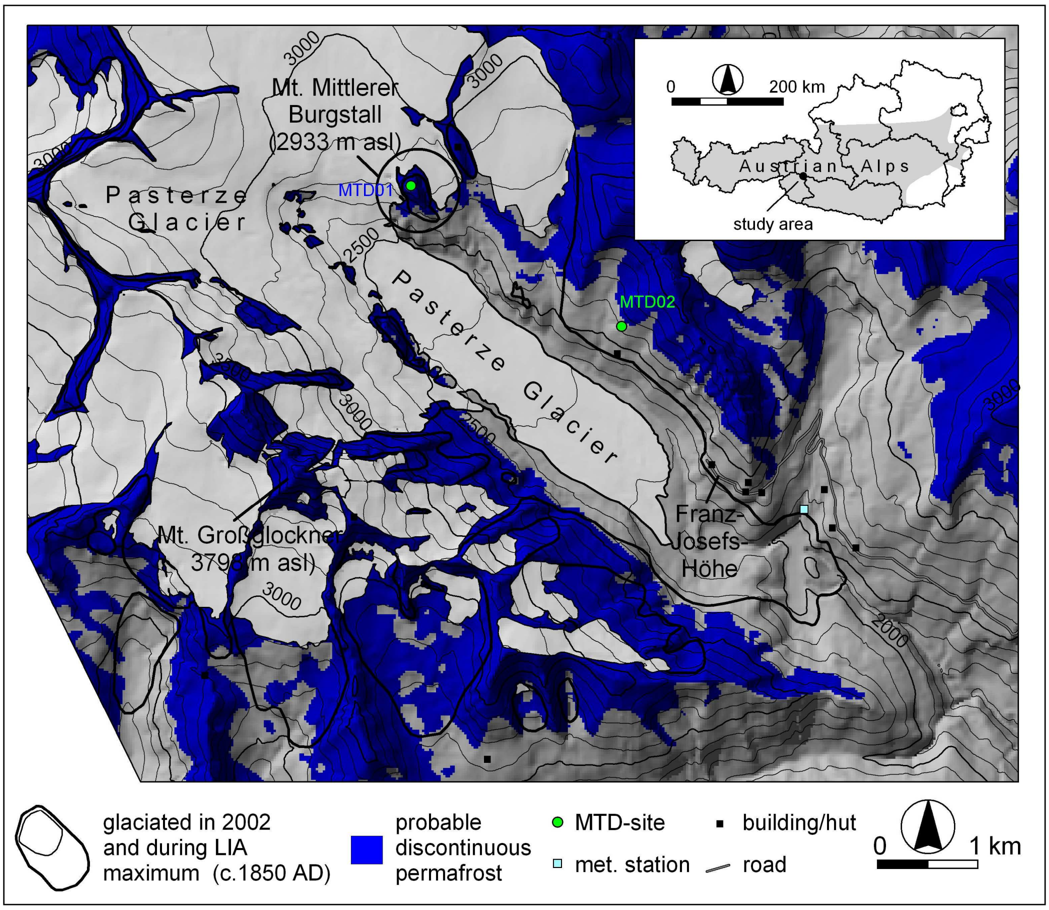

Fig. 3.29 – Location of Mt. Mittlerer Burgstall within the Austrian Alps and its spatial relation to Pasterze Glacier, the largest glacier in Austria. The map indicates the present glaciation as well as glaciation during the maximum extent during the Little Ice Age (LIA) around 1850 AD. Note that the Mt. Mittlerer Burgstall was surrounded by ice during the LIA. Location of a relevant meteorological station and the two sites were miniature temperature dataloggers (MTD) are installed are indicated. The modelled spatial extent of probable discontinuous permafrost is indicated (see text for details).

Since the end of the LIA the surface of the glacier tongue S and SW of the Mittlerer Burgstall lowered by about 300 m in elevation exposing steep slopes with bedrock outcrops and sediments to geomorphic processes. This glacier shrinkage caused a substantial increase of the supraglacial debris cover during the last decades (Kellerer-Pirklbauer, 2008) which had a strong influence on ablation rates at the glacier tongue (Kellerer-Pirklbauer *et al.,* 2008a).

3. Rock falls in 2007 and resulting morphological changes

In late spring to early summer 2007, a large part of the SW-trending crest of Mt. Mittlerer Burgstall totally collapsed. The debris which was detached fell on both sides of the remaining ridge partly covering glacier ice (Figs. 4.4.3 & 4.4.4). According to all the information available there were several rock fall events. After the authors had discovered the new morphological situation on June 25th 2007, which means that the main rock fall events occurred earlier, they tried to find witnesses. Between September 17th and 20th 2007 altogether four persons (Ernst Rieger, head of the regional mountain guide association, and 3 staff members of the GROHAG company which runs the Grossglockner high alpine road) informed us about their observations. Regarding these personal communications, the rock fall was multi-phased probably with a major event that was preceded or followed by smaller ones. All the interviewed persons evidenced the events by loud noises and/or dust clouds from the distance (most of them from the famous panorama point *Franz-Josefs-Höhe* (see Fig. 4.4.4A for viewing direction). Regarding the photographs which are taken by G. K. Lieb every year in September within the framework of annual glacier measurement campaign, the rock fall activity continued with smaller events – yet resulting in visible changes of the mountain's shape – at least until summer 2008.

Geomorphological mapping and the analysis of digital terrain models (DTM) reveal the following results. The entire area of detachment covers some 2700 m², with a length of about 90-100 m and a width 25-30 m. The areas of transportation and deposition cover about 85,000 m² including small parts of the main tongue of Pasterze Glacier located at the SW foot of the rock fall scar about 500 m lower in elevation (Figs. 3.30 & 3.31). The volume of all rock falls which happened during spring to early summer 2007 is about 35.000 m³.

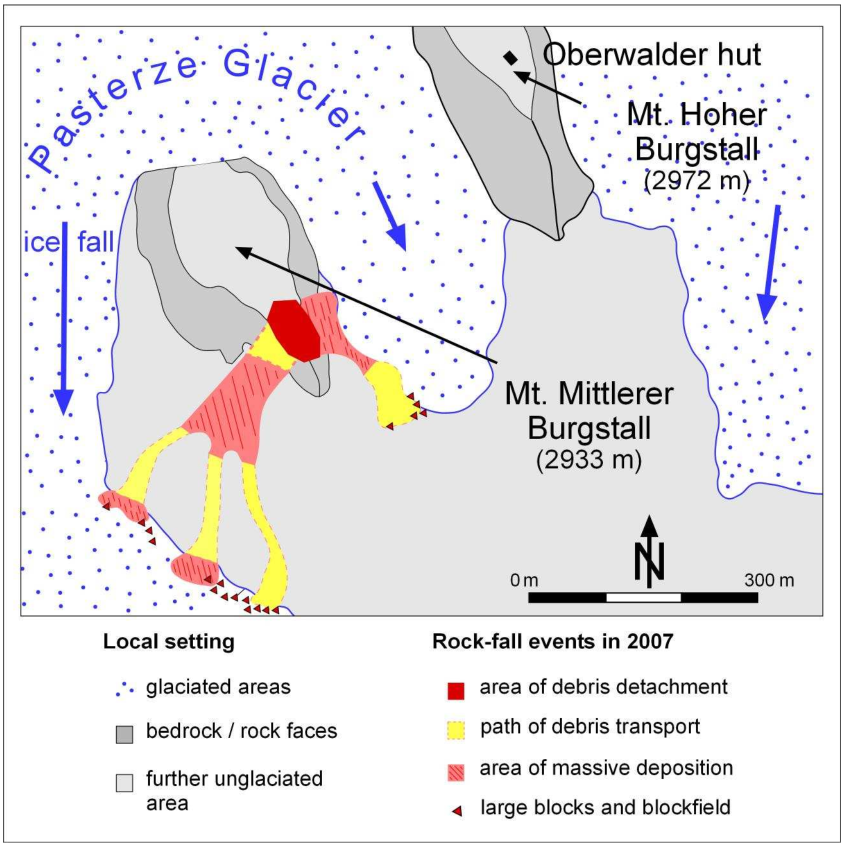

Fig. 3.30 – Geomorphological map indicating the area of debris detachment, transport and deposition of the rock fall events in 2007.

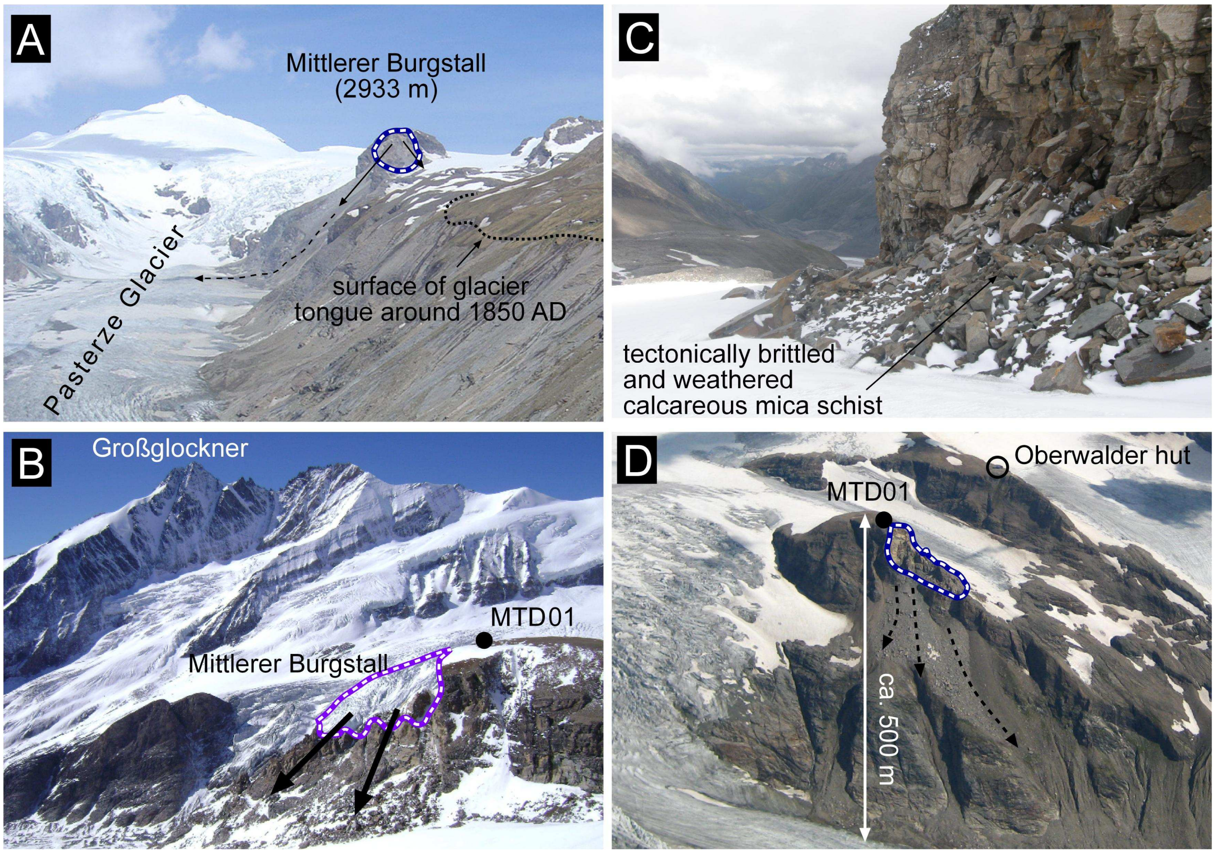

Fig. 3.31 – Field situation and geomorphic effects of the rock fall events at Mt. Mittlerer Burgstall in 2007: (A) Situation as seen from the look out point "Franz-Josefs-Höhe". View towards NE. Arrows indicate the main direction of debris movement. Polygon indicates area of debris detachment. (B) Situation as seen from Mt. Hoher Burgstall with Mt. Großglockner (3798 m asl) in the background. View towards SW. Location of a miniature temperature datalogger in the summit plateau (MTD01) monitoring surface and near surface ground temperatures is indicated. (C) The NE-facing rock wall of Mt. Mittlerer Burgstall with its tectonically brittled and weathered calcareous mica schist. View towards SE. (D) Situation as seen from Mt. Großglockner. Location of the Oberwalder hut located at the summit plateau of Mt. Hoher Burgstall (2972 m a.s.l.) is indicated. Note the mighty ice fall of Pasterze Glacier as well as the two glacier tongues on both sides of Mt. Mittlerer Burgstall. View towards N (Photographs A-C by A. Kellerer-Pirklbauer, D by K. Sindlhofer).

4. Possible causes for the rock falls in 2007 at Mt. Mittlerer Burstall

The reasons for the susceptibility to rock slope failure at Mt. Mittlerer Burgstall are presumably a combination of different factors explained in this chapter. These are *glacial erosion and glacial retreat since LIA, permafrost distribution and thermal state of permafrost* and *unfavourable geological conditions*. The triggering event for the rock falls was most likely the *warm winter 2006/2007*. Therefore, one might distinguish between factors influencing the general stability of Mt. Mittlerer Burgstall and the triggering event following the "disposition concept" by Zimmermann *et al.* (1997).

Glacial erosion and glacial retreat since LIA

The withdrawal of glacier ice from glaciated valleys that have experienced oversteepening by glacial erosion as it is the case at Pasterze Glacier causes destabilisation of the valley sidewalls due to stress-release and unloading or thermal disturbance. Such a paraglacial landscape is susceptible to rapid morphological changes due to an unstable or metastable state (Ballantyne, 2002). Thermal disturbance involves the aggregation or degradation of permafrost and ground ice in combination with freeze-thaw action, which can also result in slope failures (e.g. Wegmann et al., 1998). Morphological changes of valley sidewalls caused by glacial unloading can be expressed as: (a) slope adjustment in the form of slow rock mass creep, (b) the occurrence of catastrophic rock slope failures in the form of rock falls, large rockslides and avalanches, or (c) the modification of debris-mantled slopes and stream channels by debris flows and related processes. As it is the case at Mt. Mittlerer Burgstall, slow rock mass creep possibly preceded the rock slope failure in 2007.

The glacier extent of Pasterze Glacier was at its ultimate maximum during the LIA in 1851/56 (Nicolussi and Patzelt, 2000) with 26.5 km² (Paschinger, 1969). Since then, glaciation in the area decreased substantially. Pasterze Glacier retreated more than 1.8 km during this period. In the same time, the surface of the main glacier tongue SW of Mt. Mittlerer Burgstall lowered by about 300 m in elevation (cf. Fig. 3.31D) as mentioned already above. The LIA extent of the LIA-glaciers in Fig. 3.29 was mapped manually from aerial photographs and during field work. At most locations, margins of the former glaciers are clearly visible by moraine ridges or distinct boundaries of vegetation cover (e.g. Fig. 3.31A). The glacier extent in 2002 as indicated in Fig. 3.29 is based on the topographical map Alpenvereinskarte Glocknergruppe published by the German Alpine Association, scale 1:25,000.

Permafrost distribution and thermal state of permafrost

The potential extent of permafrost in the wider study area was modelled using an adaptation of the empirical-based program PERMAKART (Keller, 1992) resulting in the classification of areas with probable and no occurrence of discontinuous mountain permafrost with respect to altitude, aspect and topographical position as published in Lieb et al. (2007) and indicated in Fig. 3.29. The lower limits of permafrost occurrence were used as defined in Lieb (1998). This simple permafrost modelling approach indicates that the entire area of detachment is located at the lower margin of discontinuous permafrost. Furthermore, the modelling results indicate that permafrost aggregation might have occurred at the slopes around Mt. Mittlerer Burgstall due to the lateral shrinkage of the warm-based Pasterze Glacier since the end of LIA (Fig. 3.29).

Ground temperature measurements by using miniature temperature datalogger (MTD) are carried out in the Pasterze Glacier area since 2006 within the project ALPCHANGE and since 2008 within the project PermaNET. The data of one 1-channel MTD (Geoprecision) from a SW-facing wind-exposed site, at 2600 m a.s.l. and ca. 2 km SE of Mt. Mittlerer Burgstall are used for the study presented here (see Fig. 3.29 for location). The Geoprecision MTD are characterised by an accuracy of +/- 0.05°C, a measurement range between -40 and +100°C and a very high long-term stability (calibration drift <0.01°C/year). The used data from this MTD site, abbreviated hereafter as site MTD02, cover the period Sept. 2006 to Sept. 2009. After the 2007 rock fall events it was decided to install a shallow surface borehole (site MTD01; 2932 m a.s.l.) on the summit plateau some 10 m behind the rock fall scar (see Figs. 3.29 & 3.32). Temperature sensors connected to a 3-channel MTD (Geoprecision) were placed at the ground surface (sheltered by platy rocks) and at 10 and 55 cm depths logging continuously every 60 minutes. So far, data from site MTD01 for the two years period Sept. 2007 to Sept. 2009 are available. Both sites MTD01 and MTD02 are located at wind-exposed sites with – if at all – only thin winter snow covers during short periods also as seen in the temperature data in Fig. 3.33.

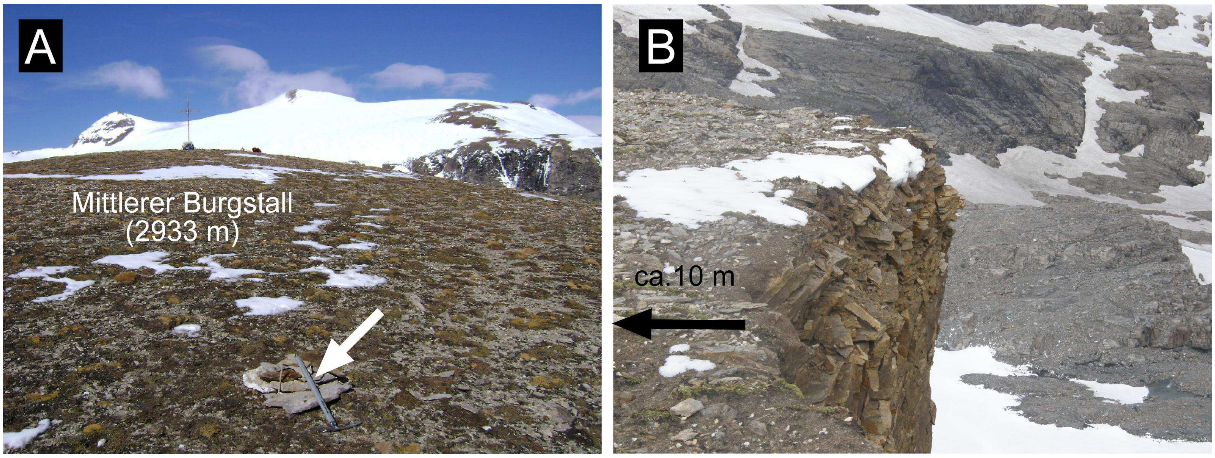

Fig. 3.32 – Location of the miniature temperature datalogger (MTD) at the summit plateau of Mt. Mittlerer Burgstall, about 10 m from the rock fall scar at 2932 m a.s.l. Note the brittled rock at the rock fall scar in the right photograph. (A) view towards NW, (B) view towards N (Photographs by A. Kellerer-Pirklbauer).

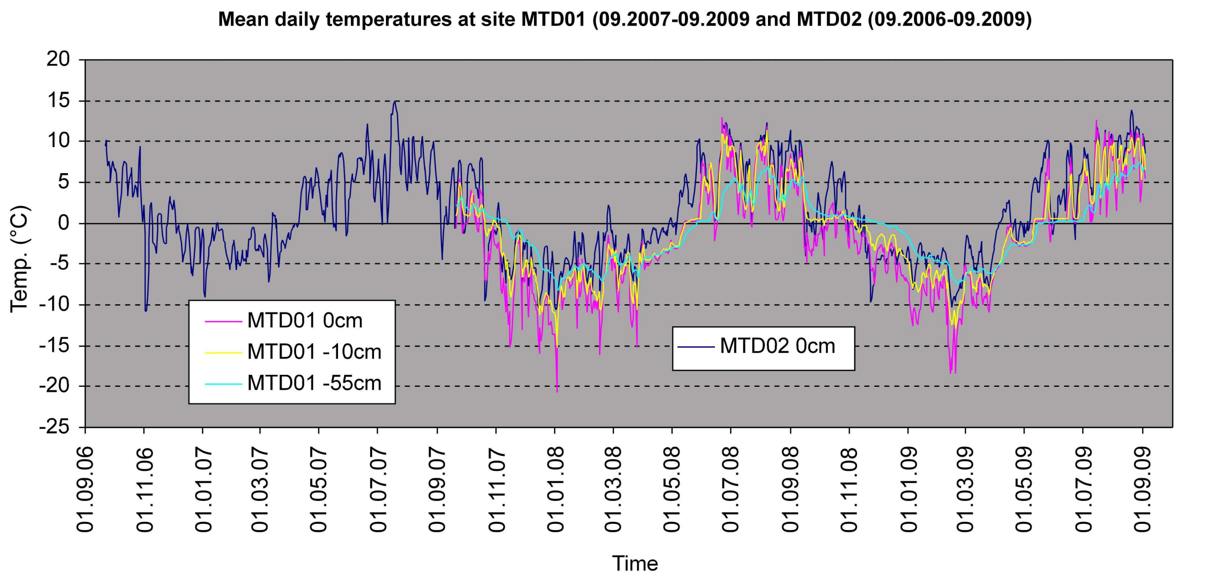

Fig. 3.33 – Thermal regime at the summit plateau of Mt. Mittlerer Burgstall (site MTD01; 2932 m a.s.l.) at the surface and at depths -10 and -55 cm and at a nearby site (site MTD02; 2600 m a.s.l.) at the surface for the periods, respectively, 09.2007 to 09.2009 and 09.2006 to 09.2009. The general high fluctuation in the daily data of MTD01-0cm and MTD02 (both at the surface) also in winter indicate that both sites are snow poor with only rather short periods of winter snow covers and accompanying zero-curtain periods.

Temperature monitoring in the shallow borehole MTD01 support the permafrost modelling results (Fig. 3.33). The mean temperature for the 23.5 months monitoring period 20.09.2007 to 03.09.2009 of the snow blown site is -2.2°C at the surface, - 1.1°C at 10 cm depth and -0.8°C at 55 cm depth. By using a normal temperature lapse rate of 0.65°C per 100 m, the 0°C isotherm of the mean ground surface temperature (MAGST) at Mt. Mittlerer Burgstall can be expected at about 2600 m a.s.l., which is in accordance to the modelling results depicted in Fig. 3.29. The mean temperatures at the surface and down to a depth of 55 cm also indicate that permafrost is relatively warm and thin at Mt. Mittlerer Burgstall. Fig. 3.34A depicts the minimum, maximum and mean temperature profiles for the two year period based on mean daily values. According to this graph, the seasonally active layer is at least about 1.5 m in thickness. Furthermore, the mean ground temperature at a depth of about 2 m can be calculated to 0°C if linear trends based on the data from -10 and -55 cm depths are used. By contrast, Fig. 3.34B depicts mean ground temperatures at site MTD01 for the calendar year 2008 based on monthly values where the mean annual temperature, the mean of the coldest month and the mean of the hottest month are plotted against depth. The (in general non-linear) trends of the temperatures of the hottest and warmest months tend to meet at a point where the daily and annual amplitude is 0°C (van Everdingen, 1985). Hence, by applying this method the depth of the zero annual amplitude (ZAA) can be estimated. This indicates at site MTD01 for the year 2008, that the active layer exceeded 2 m in thickness. The depth of the ZAA was at about 235 m depth with a temperature of slightly below 0°C indicating, again, the existence of warm and only thin permafrost at the summit plateau of Mt. Mittlerer Burgstall.

Only shallow surface borehole data are available at this site and the thermal offset – i.e. the temperature difference between the MAGST and the temperature at the top of permafrost (TTOP) – can only estimated as shown in Fig. 3.34B. However, the thermal offset is larger at sites with little winter snow cover. Therefore, it can be expected that this offset is >1K at the summit plateau of Mt. Mittlerer Burgstall (Burn & Smith, 1988) allowing a thicker permafrost body to exist as discussed above and indicated in Fig. 3.34.

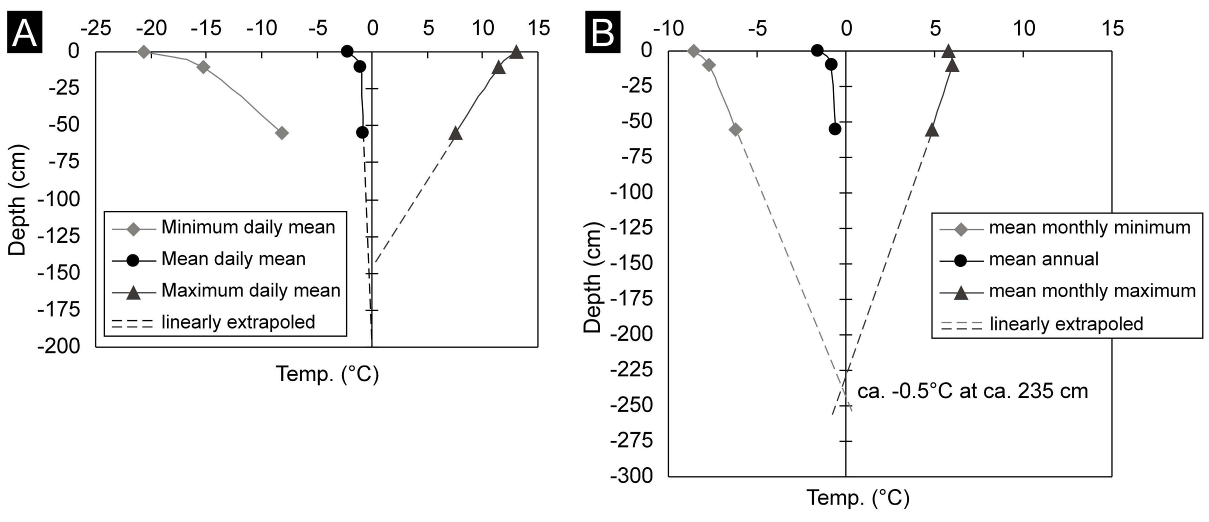

Fig. 3.34 – Mean temperature profiles at site MTD01 (2932 m a.s.l.) at summit plateau of Mt. Mittlerer Burgstall: (A) Minimum, maximum and mean temperature profiles for the two year period 09.2007 to 09.2009 based on mean daily values. Linear trends based on the data from depths 10 and 55cm are indicated for mean and maximum. (B) Mean annual (based on monthly values), mean monthly minimum and mean monthly maximum temperatures for the calendar year 2008. Linear trends for the minimum and maximum temperatures are shown indicating the depth of the zero annual amplitude.

By comparing the MTD data of site MTD01 with the ones of MTD02, where data are available since September 2006, it is getting clear that the first year of observation (P1) including the warm winter 2006/2007 (*cf.* further below) was substantially warmer compared to the second and third year of observation (Table 1). The observation period 2006/2007 was about 1.3K warmer at site MTD02 compared to the ones of 2007/2008 and 2008/2009. The mean daily temperature data for the period Sept. 2007 to Sept. 2009 at site MTD02 and the ones at MTD01 0cm (surface) are highly correlated (r=0.94**). This indicates that the ground temperatures at Mt. Mittlerer Burgstall were also substantially warmer in the period 2006/2007 influencing the thermal system and the presence and the spatial distribution of liquid water at Mt. Mittlerer Burgstall certainly substantially.

Table 3.2 – Mean annual ground temperatures (MAGT) for sites MTD01 and MTD02 for the period September 2006 to September 2009. Values in °C. Note for site MTD02 that the MAGT was more than 1.3K warmer during the first year of observation compared to the following two observation years.

Observation period	MTD02	MTD01 0cm	MTD01 -10cm	MTD01 -55cm
P1: 21.09.2006-20.09.2007	2.12	n.d.	n.d.	n.d.
P2: 21.09.2007-20.09.2008	0.78	-2.33	-1.23	-0.92
P3: 21.09.2008-03.09.2009	0.76	-1.99	-0.90	-0.70

Unfavourable geological conditions

Metamorphic crystalline rocks form the bedrock in the area, particularly calcareous mica schist and prasinite (a type of greenschist consisting of metamorphic basalts) with some amphibolite (Höck & Pestal, 1994). As depicted in Figs. 3.31C and 3.32B, the rock walls around Mt. Mittlerer Burgstall and in particular at the rock fall scar are heavily tectonically brittled and weathered. In particular the calcareous mica schist that predominantly builds up Mt. Mittlerer Burgstall is unstable. In addition to this type of mica schist, prasinite and geneiss are found on the SW-facing rock face of the mountain. The dominant dipping direction of the foliation systems around Mt. Mittlerer Burgstall is E to SE with only a gentle dip (Höck & Pestal, 1994).

Warm winter 2006/2007

Time series on recent temperature evolution in the area are available from the nearby station Margaritze located 5.5 km to the SE of Mt. Mittlerer Burgstall at about 2070 m a.s.l. (see Fig. 3.29 for location). The station is operated by the Austrian Hydro Powers (AHP). Temperature data covering the period January 2000 to December 2007 are presented in Fig. 3.35 clearly indicating the exceptional warm winter (DJF) of 2006/2007. As it is shown in Fig. 3.35B, the deviations from the mean winter temperature since the winter 1999/2000 is in the range of +2.2°C (2000/2001) and +4.8°C (2005/2006) with a mean value of +3.5°C.

The warm winter 2006/2007 possibly caused an incomplete backfreezing of the seasonally unfrozen active layer at Mt. Mittlerer Burgstall and allowed the existence of unfrozen zones or taliks substantially larger as during normal years. As a consequence, this allowed the existence of liquid water in near-surface zones of the mountain even during winter. The presence of liquid water influenced the hydrostatic pressures, in particular if it was sandwiched in between frozen layers as it can be expected. The liquid winter water possibly percolated into deeper parts of the mountain can be expected. The liquid winter water possibly percolated into deeper parts of the mountain causing

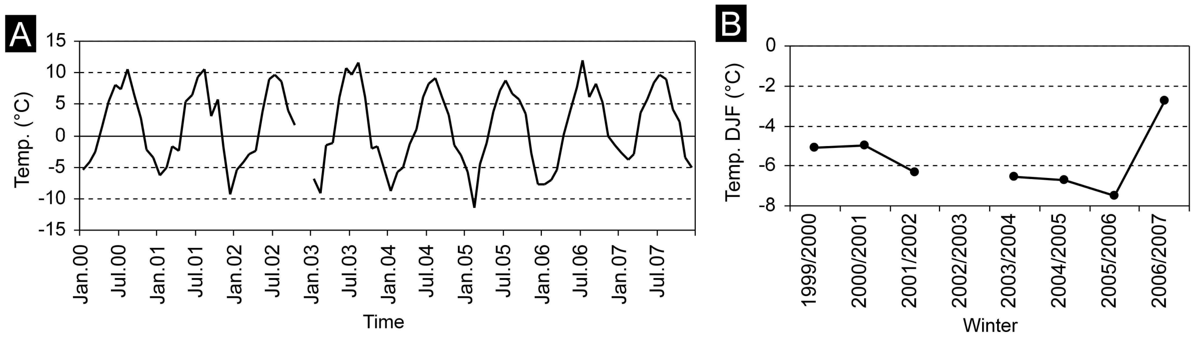

Fig. 3.35 – Temperature data from the meteorological station Margaritze (2070 m a.s.l.), : (A) Mean monthly temperature values at Margaritze (2070 m asl.) during the period 01.2000 to 12.2007. (B) Mean winter temperatures (DJF) at Margaritze for the winters 1999/00 to 2006/07. Data for DJF 2002/2003 are incomplete. Data kindly provided by Austrian Hydro Powers (AHP).

further destabilisation. Furthermore, the generally warmer temperatures in winter 2006/2007 influenced the amount of daily freeze-thaw cycles which as a further consequence influenced the superficial rock weathering on the rock walls of Mt. Mittlerer Burgstall (cf. Kellerer-Pirklbauer *et al.,* 2008b). The warm winter also possibly caused the formation of a thicker active layer during summer 2007, general permafrost warming (warmer permafrost has a higher susceptibility to slope failure compared to cooler temperatures) and more liquid water in the mountain as during normal years.

5. Natural hazard for mountaineers: at present and in the future

This rock fall events fortunately did not affect persons or infrastructure in any way. The reason for this is – despite the high frequency of hikers and climbers in the region around Austria's highest summit – the very remote position of Mt. Mittlerer Burgstall. No marked path leads closer than some 600 m to the area affected by the events. In addition there are no frequently used unmarked climbing routes in the vicinity which is due to the fact that climbers avoid this area which is mostly built of brittled rock. Also the tongue of Pasterze Glacier to the S and W of Mt. Mittlerer Burgstall is visited only by a few persons annually or even not visited at all.

Yet it has to be mentioned that the neighboring Mt. Hoher Burgstall (2972 m a.s.l.) is characterized by nearly the same susceptibility to rock slope failure (see Figs. 3 & 4D). The mountain is located some 600 m to the NE of Mt. Mittlerer Burgstall and houses the shelter hut *Oberwalder Hütte* on its plateau. The hut is run by the Austrian Alpine Club in a hotel-like manner during summer. This hut is a very popular goal of mountain trekking and often houses training courses in ice climbing which means that the number of visitors there is probably in the order of magnitude of several thousand persons per year. There are first visible signs of the destabilization of the SW orientated rock face of Mt. Hoher Burgstall. Larger rock fall events have not yet been observed there but due to the comparable shape, position and permafrost situation it cannot be excluded that they will occur in the future with further increase in (permafrost) temperatures and ongoing shrinkage of the glacier surfaces at both sides. This of course would mean a remarkable hazard to a great number of people and hence would result in the closing of this popular area for visitors.

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5. Conclusions

The different scenarii for the Global warming during the 21th Century (IPCC, 2007) suggest that permafrost degradation in the rockwalls will accelerate in the next decades. As a consequence, collapses should affect rockwalls at a higher elevation than in the recent past, with an increase of the frequency and, possibly, the magnitude of rockfalls. Thus, inhabited areas in the Alps would be exposed at a much higher risk due to permafrost-related rock avalanche hazards, while mountaineering will be more threaten by increasing rockfalls.

But our knowledge has to be strongly improved out (i) characteristics and evolution of rockwall permafrost; (ii) physical processes that link climate and permafrost, at different time and space scales; (iii) past, recent and present dynamics of rockwalls. The PermaNET Project is one of the means for this challenge.

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