



HAL
open science

From Rockfall Observation to Operational Solutions: Nearly 20 years of Cryo-gravitational Hazard Studies in Mont-Blanc Massif

Florence Magnin, Ludovic Ravel, Matan Ben-Asher, Josué Bock, Maëva Cathala, Pierre-Allain Duvillard, Pierrick Jean, Jean-Yves Josnin, Suvrat Kaushik, André Revil, et al.

► To cite this version:

Florence Magnin, Ludovic Ravel, Matan Ben-Asher, Josué Bock, Maëva Cathala, et al.. From Rockfall Observation to Operational Solutions: Nearly 20 years of Cryo-gravitational Hazard Studies in Mont-Blanc Massif. *Revue de Géographie Alpine / Journal of Alpine Research*, 2023, 111-2, 10.4000/rga.11703 . hal-04773191

HAL Id: hal-04773191

<https://hal.science/hal-04773191v1>

Submitted on 8 Nov 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Journal of Alpine research/Revue de géographie alpine

111-2 | 2023

Les versants englacés de la haute montagne alpine :
évolution holocène et impacts de la crise climatique
actuelle

From Rockfall Observation to Operational Solutions: Nearly 20 years of Cryo-gravitational Hazard Studies in Mont-Blanc Massif

Florence Magnin, Ludovic Ravel, Matan Ben-Asher, Josué Bock, Maëva Cathala, Pierre-Allain Duvillard, Pierrick Jean, Jean-Yves Josnin, Suvrat Kaushik, André Revil and Philip Deline



Electronic version

URL: <https://journals.openedition.org/rga/11703>

DOI: 10.4000/rga.11703

ISSN: 1760-7426

This article is a translation of:

De l'observation des écroulements aux solutions opérationnelles : près de deux décennies d'études sur les risques cryo-gravitaires dans le massif du Mont-Blanc - URL : <https://journals.openedition.org/rga/11644> [fr]

Publisher:

UGA Éditions/Université Grenoble Alpes, Association pour la diffusion de la recherche alpine

Electronic reference

Florence Magnin, Ludovic Ravel, Matan Ben-Asher, Josué Bock, Maëva Cathala, Pierre-Allain Duvillard, Pierrick Jean, Jean-Yves Josnin, Suvrat Kaushik, André Revil and Philip Deline, "From Rockfall Observation to Operational Solutions: Nearly 20 years of Cryo-gravitational Hazard Studies in Mont-Blanc Massif", *Journal of Alpine Research / Revue de géographie alpine* [Online], 111-2 | 2023, Online since 02 November 2023, connection on 10 October 2024. URL: <http://journals.openedition.org/rga/11703> ; DOI: <https://doi.org/10.4000/rga.11703>

This text was automatically generated on October 10, 2024.



The text only may be used under licence CC BY-NC-ND 4.0. All other elements (illustrations, imported files) are "All rights reserved", unless otherwise stated.

From Rockfall Observation to Operational Solutions: Nearly 20 years of Cryo-gravitational Hazard Studies in Mont-Blanc Massif

Florence Magnin, Ludovic Ravel, Matan Ben-Asher, Josué Bock, Maëva Cathala, Pierre-Allain Duvillard, Pierrick Jean, Jean-Yves Josnin, Suvrat Kaushik, André Revil and Philip Deline

Researches carried out over the past 18 years in the MBM have been funded by several main research programs: EU Alcotra PERMAdataROC, PrévRisk Haute-Montagne, AdaPT Mont-Blanc, and PrévRisk CC projects; EU AlpineSpace PermaNET project; ANR-14-CE03-000 VIP Mont-Blanc and ANR-19-CE01-0018 WISPER projects. The authors would like to thank the Communauté de Communes de la Vallée de Chamonix Mont-Blanc, the Compagnie du Mont-Blanc, the Compagnie des Guides de Chamonix and the École Nationale de Ski et d'Alpinisme for their support since 2005, as well as the numerous colleagues who contributed to these projects, notably, but non-exhaustive: Paolo Pogliotti, Umberto Morra di Cella and Eduardo Cremonese from Agenzia Regionale per la Protezione dell'Ambiente Valle d'Aosta (Aosta, Italy), Jeannette Noetzli now in Institute for Snow and Avalanche Research (Davos, Switzerland), Stephan Gruber now in Carleton University (Ottawa, Canada), Michael Krautblatter now in Technical University of Munich (Germany), and Jan Beutel now in University of Innsbruck (Austria). The authors also acknowledge the editorial committee of the Journal of Alpine Research for handling the manuscript, the invited editor (Marta Chiarle), the anonymous reviewers and Lothar Schrott for their constructive comments and corrections on the manuscript.

Introduction

- 1 Since the end of the 1980s, climate change has initiated profound changes in landscapes, ecosystems, economic resources, and natural hazards in the high mountain. Landscapes dominated by bare rock and talus are replacing glaciers, with

accumulations of unconsolidated material, steep rock slopes and new lakes forming in glacier bed overdeepening or behind moraine dams (Haeberli *et al.*, 2016). At the same time, periglacial rock faces have become increasingly unstable, potentially causing infrastructure destabilisation (e.g., refuges, ski lifts, Duvillard *et al.*, 2019), disappearance or alteration of mountaineering routes (Mourey *et al.*, 2019), and major disasters through high-magnitude events and possible cascading hazards (Haeberli *et al.*, 2016). These emerging threats urge for the development of in-depth knowledge to set up targeted mitigation and adaptation strategies.

- 2 While glacial retreat is a well-known factor of slope destabilisation, notably through the process of paraglacial adjustment (Ballantyne *et al.*, 2014), the role of permafrost degradation—i.e., the thawing of terrain whose temperature remains permanently < 0 °C—in response to atmospheric warming, has gradually become the focus of scientific concerns (e.g., Gruber *et al.*, 2004). Lacking consideration of rock wall permafrost (i.e., permafrost affecting rock walls) until the early 2000s, primarily because of its invisibility, resulted in a crucial gap in the systemic understanding of high alpine morphodynamics. A return to early studies on frost weathering processes (e.g., Walder, 1985) and on cold environment engineering (e.g., Mellor, 1971), combined with the development of specific studies on rock wall permafrost (e.g., Gruber *et al.*, 2004) and permafrost-affected rock walls, i.e., rock walls that are likely affected by permafrost (e.g., Ravanel *et al.*, 2010), has contributed to theoretical assessments of the role of permafrost in the morphodynamics of steep rock slopes.
- 3 Several thermo-hydro-mechanical processes related to permafrost are considered as possible triggering mechanisms ($V > 100 \text{ m}^3$) (Krautblatter *et al.*, 2013). They operate in different depths and possess different response times to climate forcing ranging from seasonal time scales such as active layer thickening (i.e., shallow layer that thaws in summer and refreezes in winter), to millennial time scales with the degradation of permafrost formed during the Holocene at greater depth (Noetzli and Gruber, 2009). Frozen rock and ice-infill in cracks are mechanically weakened during warming and thawing, which makes frozen rock walls highly sensitive to atmospheric warming. But because normal stress control prevails in slope failures, the effectiveness of the various processes associated with thawing depends on the rock overburden. Detachment depths < 20 m are thought to involve failures along ice contact in cracks while detachment depths > 20 m are more likely to be caused by changes in rock mechanics (Krautblatter *et al.*, 2013). Explaining failures occurring along pre-existing cracks is challenging because they induce a variety of non-linear thermal, hydrogeological and mechanical processes. Heat propagates from the surface to depth through progressive conduction in the rock mass, but cracks favour air ventilation and heat advection from water infiltration, as well as latent heat exchange under freezing and melting of the ice/water-infill. In addition, water circulation in ice-sealed bedrock can lead to the development of a water column forming high hydrostatic pressure, so that changes in the thermal regime are not the only potential triggers. The frequent presence of ice and water in failure scars (e.g., Deline *et al.*, 2013) provides evidence of the plausibility of complex triggering mechanisms combining warming and melting of the ice-infill, as well as water-related thermal and mechanical processes. As a result, linking these theoretical explanations to a technical understanding of observed rock slope failures bears many challenges for the development of operational solutions for risk assessment.

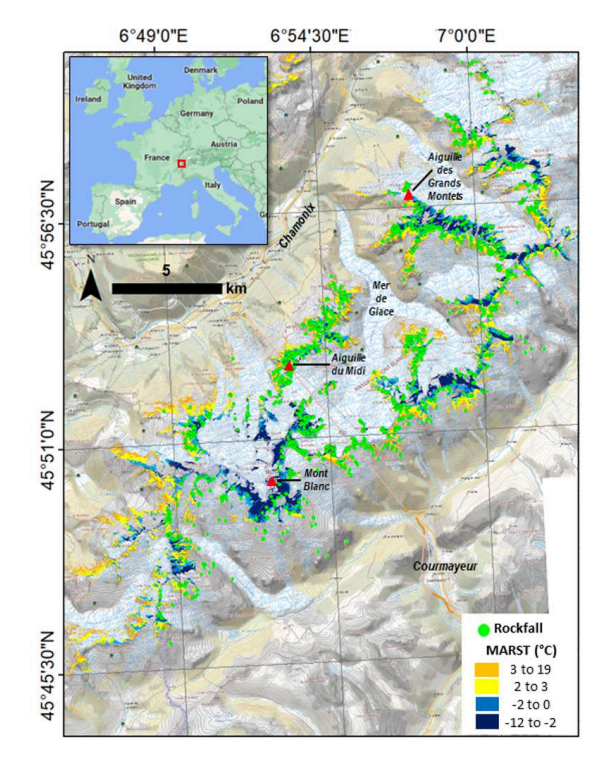
- 4 Following the pioneering studies on rock wall permafrost launched in Switzerland after the hot summer of 2003, marked by a numerous rockfalls (Gruber *et al.*, 2004), research began in France in the Mont Blanc massif (MBM) in 2005. MBM naturally emerged as a privileged study area, notably because of its unique combination of high-elevated peaks and pillars, and the rich tradition of researches on rock avalanches (Deline *et al.*, 2012). Several research projects have been carried out, largely initiated or directed by Philip Deline and are led now by several active researchers in the EDYTEM laboratory. This contribution summarises the first 18 years of research in the MBM on gravitational processes driven by the degradation of the cryosphere in steep slopes—here referenced as “cryo-gravitational processes”, and which address the following questions: where and when do cryo-gravitational hazards occur? What are the physical processes involved in their triggering?

The Mont Blanc Massif: A Privileged Open-Air Laboratory for Investigating Morphodynamics and Cryosphere of Alpine Rock Faces

General Settings

- 5 MBM is one of the external crystalline massifs of the western European Alps extending over 550 km² across France, Swiss and Italy. It is a window of the Variscan basement within the Penninic and Helvetic nappes, and is composed of two main lithological units: a 453 ± 3 Ma Variscan metamorphic series (mostly gneisses and mafic schists) intruded by a 304 ± 3 Ma calc-alkaline granite and aplitic veins (von Raumer and Bussy, 2004). Oriented SW-NE, the Variscan batholith is bounded to the NW by a wide shear zone and by thrusts in the E and SE. Faults and shear zones are mostly oriented NW-SE with subvertical dipping organised with a fan geometry across the range that outlines its main topographical features.
- 6 Strongly asymmetric, the average slope angle between Mont Blanc summit at 4808 m ASL and Courmayeur (1230 m) on its SE flank is about 40°, while it is 15° on its NW flank between the top and Chamonix at 1040 m. This asymmetry is also marked by the climate settings as the main crest line with 28 summits above 4000 m ASL acts as a climate border where Mediterranean and Atlantic fluxes meet. As a result, the Italian side is typically warmer and drier than the French side.
- 7 In the late 2000s, about 100 km² of the MBM were still glaciated (Gardent *et al.*, 2014; Fig. 1), but affected by pronounced glacier shrinkage since the 1980s (Gardent *et al.*, 2014), while the morphodynamics of its steep rock faces is accelerating, posing hazards and risks for the infrastructure and population (Deline *et al.*, 2012).

Figure 1



Mont Blanc Massif with inventoried rockfalls during the 2007-2021 period and predicted MARST for the 1981-2010 period. Background map from *Institut National de l'Information Géographique et Forestière*. Rockfall distribution according to MARST is illustrated in Figure 3.

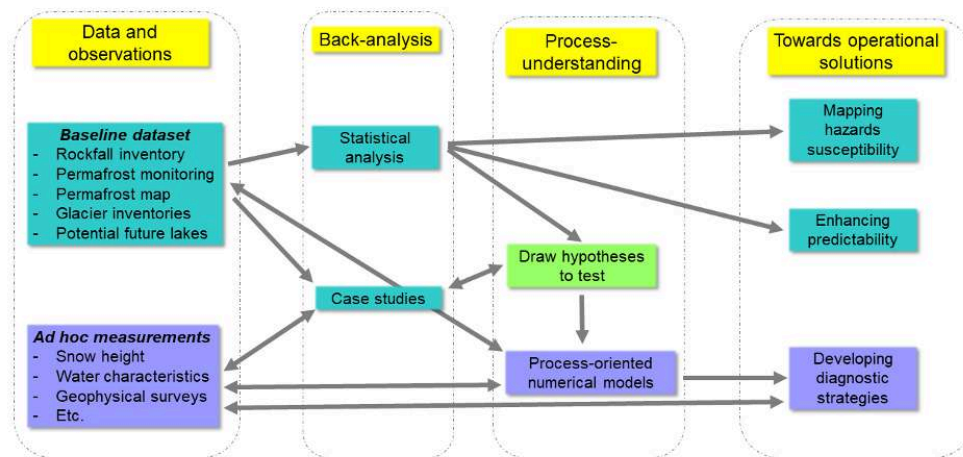
Main Data and Knowledge Gathered Over the Last 18 Years

- 8 Permafrost investigations started in autumn 2005, with the first temperature sensors installed at the near surface (3 to 55 cm depth) of Aiguille du Midi (AdM, 3842 asl) rock walls (Magnin *et al.*, 2015) while a few months before, the Bonatti pillar collapsed (292 000 m³; Guerin *et al.* (2020) and drew attention to the recent morphodynamics of MBM rock walls. Since then, a variety of data have been collected from field observations and created from models to better understand permafrost and rock wall dynamics and formulate hypotheses about the development of cryo-gravitational hazards (Fig. 2).
- 9 Analyses of the temporal distribution of rockfalls in MBM over millennial to seasonal time scales showed that phases of gravitational activity are concomitant to warm periods, such as the Holocene Climate Optimum (Gallach *et al.*, 2020), the 1940s and every decade since the 1990s (Raveland and Deline, 2011) or the hot summers of 2003 and 2015 (Raveland *et al.*, 2017). Since 2007, a network of observers reports rockfalls in the central part of the massif and contributes to the establishment of a detailed rockfall database (Fig. 1).
- 10 Concurrently, rock surface temperature data collected at AdM were included in an Alpine-wide data collection (Cremonese *et al.*, 2011) that has been used to calibrate a multiple linear regression model—the rock model (Boeckli *et al.*, 2012)—relating the Mean Annual Rock Surface Temperature (MARST) to the Mean Annual Air Temperature (MAAT) and the Potential Incoming Solar Radiation (PISR). The model was used to map

permafrost over the entire Alpine range and was later applied to MBM on a 4-m-resolution Digital Elevation Model (DEM). The same model implemented with the 1981–2010 MAAT measured in Chamonix and spatialised with a 0.55 °C/100 m lapse rate is displayed in Figure 1.

- 11 Since 2010, permafrost investigations are strengthened with temperature monitoring in 5 boreholes: 4 boreholes reaching a depth of 10-m at AdM (last one installed in 2021), and a 17-m-deep borehole installed in 2017 at Aiguille des Grands Montets.
- 12 Rock face monitoring based on repeated terrestrial laser scanning such as at Tour Ronde (3792 m asl, Rabatel *et al.*, 2008) has shed light on the possible relation between the melting of “ice aprons” (IAs, surface and immobile cold ice bodies) and rockfall occurrence. In their recent inventory, Kaushik *et al.* (2022) complete former glacier inventories (Gardent *et al.*, 2014) that have been used to model glacier-bed overdeepenings to appraise potential future lakes (Cathala *et al.*, 2021) that could be a source of high-magnitude chain-reaction hazards in the coming decades but at the same time could represent new economic resources (Haeberli *et al.*, 2016).
- 13 The most recent developments focus on bridging these different datasets to develop a comprehensive approach of cryo-gravitational hazards in order to support the development of operational solutions for land planners, geotechnicians and mountain practitioners (Fig. 2). Progress has been achieved in defining where and when cryo-gravitational hazards occur, but the main challenges are related to understanding how they develop and how they are triggered.

Figure 2



Organisation of the research on cryo-gravitational hazards in Mont Blanc Massif.

Spatio-temporal Distribution of Cryo-Gravitational Hazards

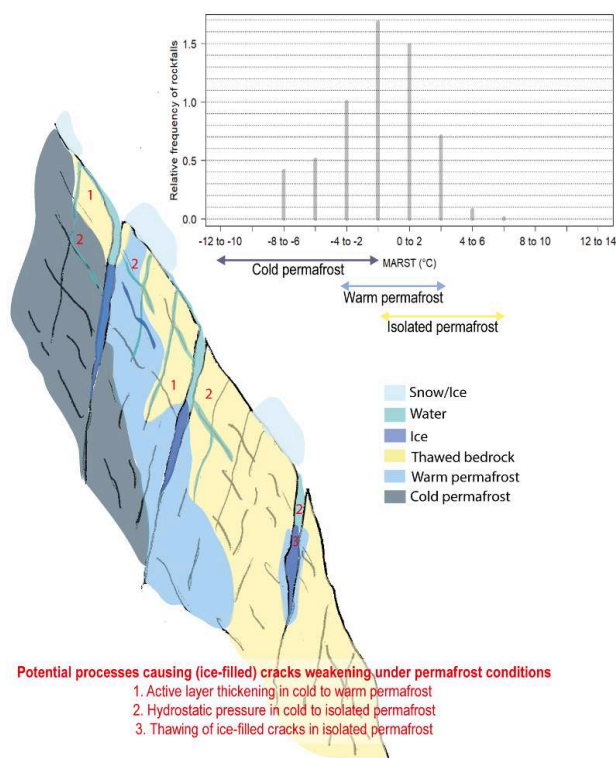
- 14 From 2007 to 2021, 1389 rockfalls > 100 m³ were inventoried with accurate coordinates, topographical settings, date of failure or detection, and if possible, a variety of additional characteristics such as scar depth or ice observation. Most events are shallow (median and average scar depth of approx. 4 m) and their occurrence, if related

to permafrost dynamics, is therefore most likely due to failure at the ice contact in cracks (Krautblatter *et al.*, 2013). Analysis of this dataset uncovers key features in the spatial and temporal distribution of rockfalls to link their occurrence with possible triggering mechanisms.

Are Rockfalls Linked to the Degradation of the Cryosphere?

- 15 Figure 3 shows the distribution of the 1152 events that occurred in the area covered by the MARST map (Fig. 1). Ignoring transient and 3D heat fluxes (Noetzli *et al.*, 2007; Noetzli and Gruber, 2009), this 30-year period steady state MARST calculated with the rock model is somewhat representative of expected permafrost conditions at depth. However, absolute values of MARST are partly biased by the limitations of the rock model: it does not take snow into account and its implementation on a DEM smooths out sharp reliefs. Therefore, we interpret these results in terms of isolated to cold permafrost, which is a qualitative interpretation of the calculated MARST. With all precautions taken, rockfalls appear to be strongly related to permafrost; no events have been observed in unfrozen rock walls. The peak of rockfall frequency is found in warm permafrost areas and fewer events occurred in cold as well as isolated permafrost conditions.
- 16 The wide range of permafrost conditions under which rockfalls occurred support the hypothesis that a variety of permafrost-related processes are likely to trigger rockfalls, from the warming of isolated ice-filled cracks that had remained due to the retarding effect of latent heat consumption when interstitial ice melts (Ravanel *et al.*, 2023a), to water infiltration into cold permafrost areas (Hasler *et al.*, 2011; Fig. 3). It also highlights that, areas close to the melting point (warm permafrost) are likely the most active ones.
- 17 In addition, 11.5% of rockfalls occurred in slopes that were covered by IAs in the 1950s (Ravanel *et al.*, 2023a). This quantification is limited because it does not take into account glacier shrinkage at the foot of rock walls and because of the possible mismatch between digitalised IAs and rockfall referencing. But this preliminary verification suggests that a portion of rockfall is directly related to thermal and mechanical disturbances associated with glacier retreat that include debuitressing (Ballantyne *et al.*, 2014), permafrost formation (Wegmann *et al.*, 1998), or active layer formation (Hartmeyer *et al.*, 2020).

Figure 3



Distribution of rockfalls (relative frequency: percentage of rockfall / percentage of rock wall surface area) in the Mont-Blanc massif according to interpreted permafrost conditions (top) and hypothesized permafrost-related trigger mechanisms.

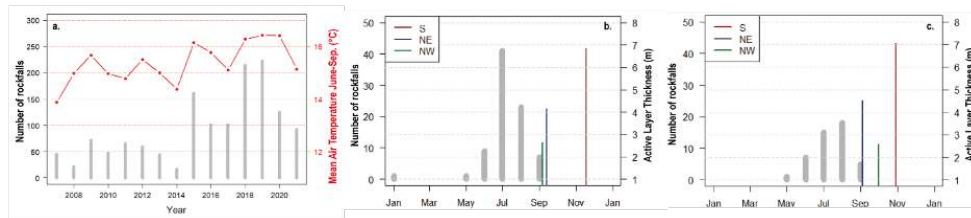
Are Rockfalls Caused by Seasonal Thawing?

- 18 Rockfalls mainly occurred during the thawing season: the June-September period gathers 96% of the events. Since 2015, the yearly number of rockfalls has dramatically increased, coinciding with a rise in mean air temperature (MAT) during the thawing season; as a general feature, the warmer the thawing season, the higher the rockfall frequency (Fig. 4a).
- 19 As a potential link between higher MAT and more frequent rockfalls, the deepening of the active layer thickness (ALT) and the subsequent warming and melting of ice-filled cracks (Fig. 3) may be considered as the main triggering mechanism. However, current field data on this matter is ambiguous and does not support a straightforward correlation. For example, in 2019 nearly twice as many rockfalls were observed as in 2020 (Fig. 4a), yet ALT has deepened between 2019 and 2020 in 2 of 3 boreholes at the AdM (Fig. 4bc) in coherence with higher MAT (Fig. 4a). Most rockfalls generally occur well before the maximum ALT is reached, (it is especially the case for 2020). Such finding has already been reported by comparing the rockfall frequency and modelled ALT for the 2003 summer season in Switzerland (Gruber *et al.*, 2004), which supports the hypothesis of water-related processes either accelerating the heat transfer or causing pressure that cannot be depicted through 1D measurements or a simple heat conduction model. Such hypothesis is also supported by recent estimation of the potential water infiltration calculated from snow melting and rainfall that showed that

more water was potentially available for infiltration in 2019 than in 2020, especially from rainfall (Ben-Asher *et al.*, 2022).

- 20 Appraising water-related processes has thus become a major challenge to better understand both permafrost degradation processes and rockfall triggering mechanisms (Krautblatter *et al.*, 2012).

Figure 4

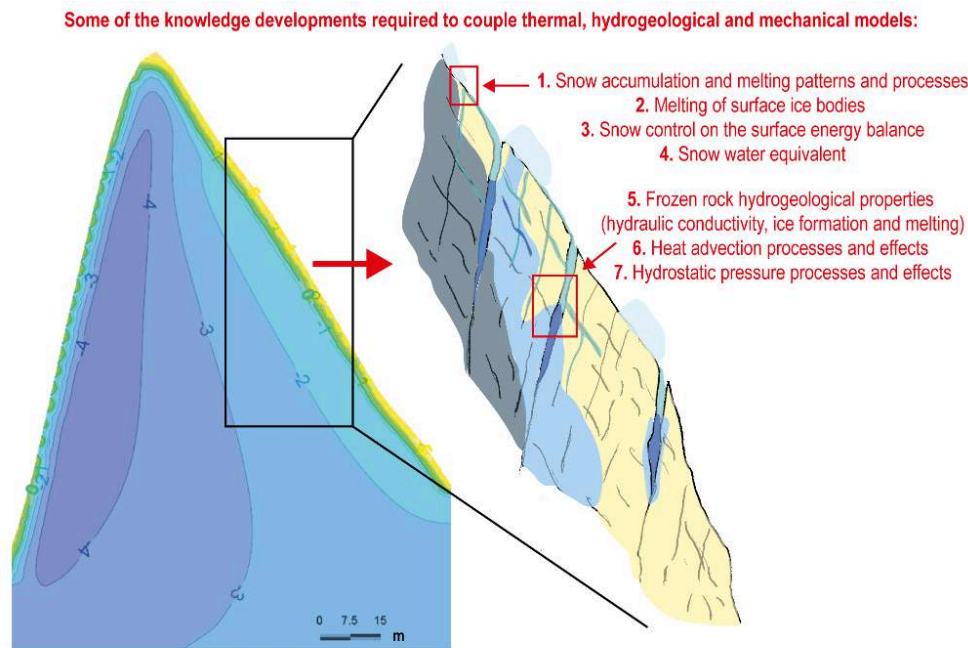


a. Rockfall distribution through year and summer air temperature. b. and c. Rockfall distribution (only those directly observed) in 2019 and in 2020 respectively, and Active Layer Thickness (ALT) in the S, NE and NW AdM boreholes placed at the date when the maximum ALT was reached.

Current Developments to Understand the Physical Processes behind Failures

- 21 To address the thermal and mechanical effects of water infiltration and circulation in permafrost rock walls, some attempts to couple thermal and hydrogeological models with advanced numerical modelling tools have been carried out (Magnin and Josnin, 2021). The ultimate aim would be to address processes acting at fine spatial and temporal scales and provide relevant data for mechanical models. Current limits are associated with (i) the ability to constrain the key physical parameters that drive and control hydrological and hydrogeological processes in mountain permafrost environment, (ii) the ability of conventional hydrogeological models to simulate the specific processes occurring in permafrost, and (iii) the lack of field measurements to constrain the models and validate simulations (Fig. 5).

Figure 5



Thermal model simulating permafrost conditions of steep rock slope (example for the AdM from Magnin *et al.* (2017a)) and some of the main challenges to solve (in red) to achieve the targeted spatial scales and processes of simulations.

Main Challenges in Quantifying Water Infiltration

- 22 The melting of snow that heterogeneously accumulates on rock walls throughout the years represents a major source of water in high mountains (Fig. 5). Yet, linking snowfall to water infiltration in such an environment is challenged by highly complex processes. Quantitative information on snow accumulation on rock walls is rare and measurement techniques bear large errors and uncertainties (e.g., Haberkorn *et al.*, 2017). Furthermore, infiltration of meltwater can occur days, weeks, and months after a snowfall event. During this period, snow may be redistributed by wind and gravity, sublimate or melt and refreeze, forming an impermeable ice crust (Phillips *et al.*, 2016).
- 23 In MBM, characterisation of snow accumulation was performed on the AdM S face using time-lapse photogrammetry, high-resolution photogrammetric models, and numerical modelling. About 25% of the fallen snow accumulates on the 55° steep and rugged rock face (Ben-Asher *et al.*, 2022), and that average snow depth steadily decreases between 40° slope angle, where it is approx. 1 m (up to > 2.5 m at point scale), and 70°, a threshold above which snow no longer accumulates. By coupling advanced climate, energy balance and heat transfer modelling tools, the same study quantified snow water equivalent and infiltration timing. It provided information on surface temperature and consequently on permafrost distribution, as well as input water data for further analysis with coupled thermal and hydrogeological models. These recent developments broaden the understanding gained in previous studies, showing the crucial control of snow on local rock wall permafrost conditions (Magnin *et al.*, 2017b) which is a key challenge for future studies. In addition to snow, the melting IAs, as seen during the hot summer of 2022, is another possible source of water with unclear

influence on the energy balance of the permafrost-affected rock faces (Ravel *et al.*, 2023b). Further challenges in determining water infiltration are associated with the limited knowledge on the hydraulic conductivity of fractured permafrost-affected rock slopes.

Main Challenges in Appraising Hydrogeological Processes

- 24 In low permeability rock, water flow pathways are mostly concentrated in cracks whose hydraulic conductivity can vary depending on the saturation and degree of freezing of the interstitial water, which can change seasonally. This can effectively influence the macro-scale capability of water to flow, and hence alter hydraulic conductivity.
- 25 The use of numerical tools to support the overall understanding of hydrogeological features and processes faces several difficulties when applied to frozen rock. The relevant spatial and temporal scales of the aforementioned processes span over several orders of magnitude and require strong numerical capabilities (CPU time spanning several weeks). Physical equations describing hydrological processes in unsaturated conditions such as those prevailing in permafrost-affected fractured media are also strongly non-linear, which leads to numerical instabilities. Last but not least, phase changes at subfreezing temperature are not always fully implemented in all conditions in hydrogeological models: for instance, the PiFreeze module that deals with freezing water in the Feflow® program is not implemented to work on discrete feature elements, that would be the best suited to describe fractures. Yet, software improvement and enhanced computing capability could overcome current limitations.
- 26 While these numerical challenges are tackled, efforts are carried out in parallel to gain direct observations of water flow characteristics. Indeed, observations of hydrogeological processes in mountain permafrost rock walls are scarce and mostly attained indirectly as temperature anomalies (e.g., Phillips *et al.*, 2016). At AdM, galleries have been equipped since summer 2022 with a system measuring and sampling water flow to gain insights on water quantity, discharge, age as well as fracture connectivity. Geophysical surveys also bear hope to appraise hydrogeological processes with promising perspectives for geotechnical purposes.

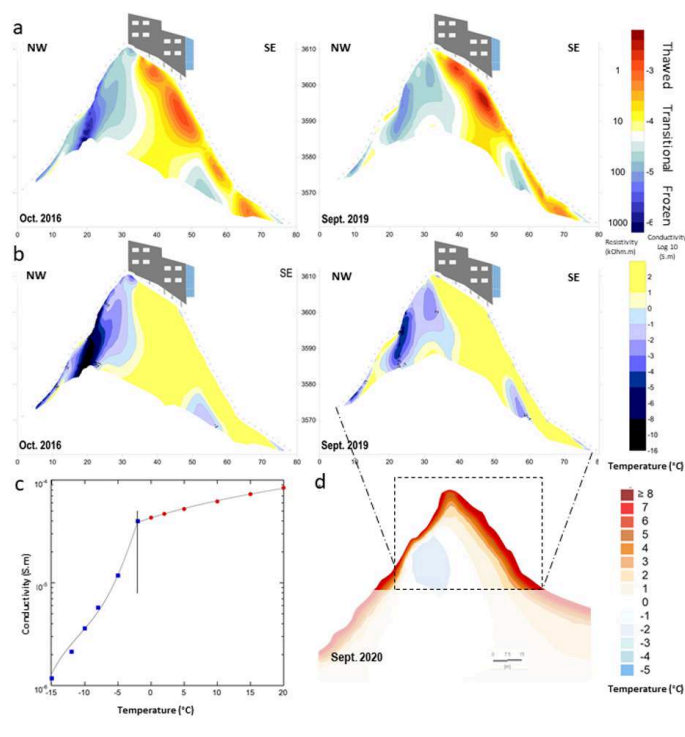
Towards Operational Solutions for Mitigating Cryo-Gravitational Hazards

- 27 Cryo-gravitational hazards pose different types of risks in MBM, whose mitigation urgently needs appropriate anticipatory approaches. For geotechnics, *in-situ* diagnostics are challenged by the difficulty to assess the ground ice-content, distribution and characteristics. For mountain practitioners, determining the most dangerous periods is needed while for land planners, anticipating the spatial extent and magnitude of hazards is necessary. Three main research directions are thus outlined that could feed into future operational solutions.

Developing Diagnosis Strategies

- 28 In MBM, 60 infrastructure elements, including ski lift components, avalanche gas exploders, and mountain huts, are settled on permafrost ground (e.g., Duvillard *et al.*, 2019) encompassing rock walls, highly fractured and intermediately steep bedrock, and sometimes non-consolidated materials. While permafrost conditions can be roughly assessed, geotechnical maintenance would benefit from a detailed understanding of the thermal state and ground ice content, distribution and potential evolution. Core or destructive boreholes allow such quantitative assessment but their spatial representativeness is poor. Furthermore, current modelling approaches to map or to simulate permafrost evolution at depth are not designed for bedrock with a high degree of fracturing and potentially a relatively high ice content. To overcome these limitations, geophysical methods appear to be promising.
- 29 Despite their indirect character (i.e., measurement of permafrost proxies), combined electric resistivity tomography and induced polarisation measurements offer new opportunities to access relevant ground parameters such as temperature and liquid water content (Duvillard *et al.*, 2021). These techniques have the main advantage to be non-invasive and non-destructive and more spatially representative thanks to 2D to 3D inversions (Fig. 6ab). Coupled with recent advances in petrophysics models (Fig. 6c) and compared to thermal models (Fig. 6d), water and ice content could be interpreted quantitatively (e.g., Wagner *et al.*, 2019).
- 30 The joint inversion of galvanometric/electromagnetic data with seismic and ground-penetrating radar data as well as the fusion with petrophysical models and thermal modelling will be key to obtain 3D distribution of the relevant cryo/hydromechanical properties of alpine settings and their potential evolution towards critical states (Wagner *et al.*, 2019). Future challenges also include the development of joint inversion methods that use terrain or geophysical data, or direct observations from deep boreholes as well as time-guided inversions by combining time-lapse geophysical data, thermal modelling, and mechanical modelling results. As many mountain sites are hardly accessible, the use of drone swarm doing geophysical time-domain electromagnetic measurements remotely provides another perspective.

Figure 6



Example of recent geoelectrical developments combining repeated ERT and IP surveys, petrophysical models and thermal model applied to Cosmiques ridge as extended from Duvillard *et al.* (2021) and Magnin *et al.* (2017a). **a.** Inverted geoelectrical profiles **b.** Modelled ground temperature distribution (only negative values are reliable) from **c.** laboratory testings on rock samples and fitted petrophysical model. **d.** Modelled ground temperature with the Feflow® program such as carried out by Magnin *et al.*, (2017a).

Enhancing Predictability of Cryo-Gravitational Hazards

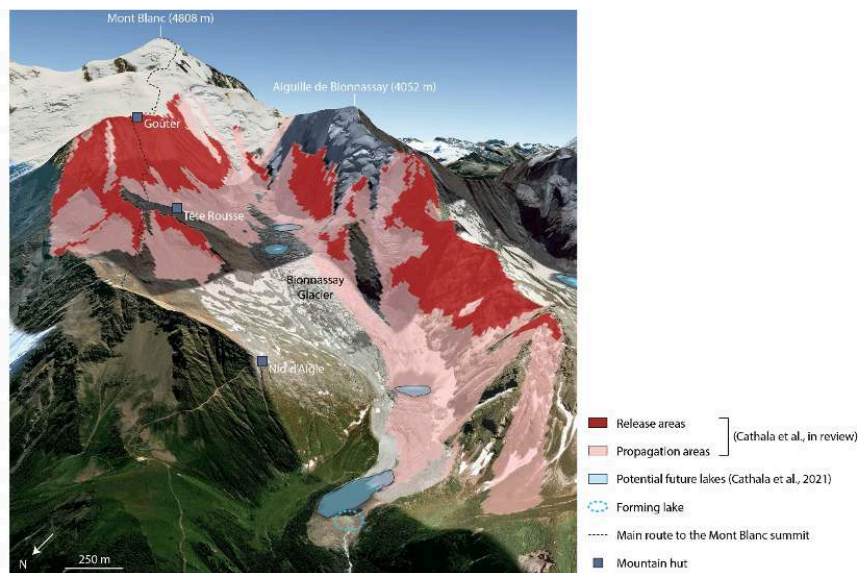
- 31 The increasing rockfall frequency and volume threaten the sustainability of high mountain activities (Mourey *et al.*, 2019). Recent statistical analysis of simulated surface and scar-depth temperature of inventoried rockfalls showed high statistical significance between higher than usual surface and scar-depth temperatures and rockfall occurrences, showing the promise of rockfall probability forecast (Legay *et al.*, 2021) that could support mountaineers in their risk analysis. Several improvements could be considered to strengthen the predictability of rockfall occurrence. First, the study could be updated with recent events (2016–2022) as this would improve the statistical robustness. In addition, the statistical significance could be improved by comparing the results of temperature simulations at the real events to some random events defined according to the main topographical features of the real events (see Legay *et al.* [2021] for more details).
- 32 Another source of improvement lies in the accuracy of the predicted surface temperature that could be better achieved by using energy balance modelling taking into account snow processes (Ben-Asher *et al.*, 2022). It would also be interesting to consider other variables than the daily air temperature to determine the parameters associated with failure occurrences, such as the date of snow melt which partly controls the surface temperature but can also be used as a proxy for water infiltration,

or the maxima and minima of air temperature, for example. This would be specifically relevant for rockfalls occurring in the early summer as snow often persists at high elevation until then. The peak of rockfall occurrence in MBM in July 2019 (Fig. 4b), that was reached far before the maximum ALT developed, could for example be related to the rather high amount of available water from snowmelt and rainfall in the early summer (Ben-Asher *et al.*, 2022).

Mapping Current and Future Cryo-gravitational Hazards Susceptibility

- 33 Integrative approaches coupling permafrost assessment, melting of ice faces, glaciers retreat and induced landscape changes are important for land planners who need to anticipate the spatial mutation of hazards in the changing climate and cryosphere conditions, as well as potential economic resources (Haeberli *et al.*, 2016).
- 34 The spatial distribution of inventoried rockfalls can be used to map potential release areas in a hazard assessment approach such as in Figure 7 (not published yet) that shows all rock walls with predicted MARST < 0 °C and the potential runout areas of rockfalls in the MBM and predicted future lakes in the Bionnassay watershed (Cathala *et al.*, 2021). This watershed clearly appears as a hot spot with numerous lakes that could form or are currently forming, and which are possibly exposed to rock or ice falls. Land planners may survey this area with great attention in order to anticipate potential high magnitude events. This area would also be particularly interesting to investigate the relationship between permafrost and hanging glaciers. A key question here is whether hanging glaciers are melting or destabilising due to permafrost degradation taking place in surrounding rock walls?

Figure 7



Example of integrating approach considering potentially unstable slopes, estimated runout distances from rockfall observations, and sources of cascading hazards to be deepened for land-planning purposes.

Conclusions

- 35 Over the past three decades, steep rock slopes in cold environments have become increasingly unstable, with more frequent rockfalls and large-scale events sometimes causing devastating cascading hazards downslope, promoted by the storage of unconsolidated and unstable materials left behind retreating glaciers. In the European Alps, MBM has naturally emerged as an open-air laboratory for studying permafrost-affected rock faces because of the acceleration of its morphodynamics since the 1990s, the uniqueness of its high-elevated rock peaks, the variety of its glacial systems, and the pronounced societal implications of its environmental dynamics.
- 36 Within the past 18 years, a baseline dataset has been established to better understand when and where rock wall destabilisation occurs. The acquired data suggests a dominant influence of permafrost-related processes on rock slope destabilisation. Main research directions are targeting:
- i. the deepening of statistical analyses that could serve the development of forecasting tools in order to assess periods and areas of high risk,
 - ii. the advancement of physics-based models to couple thermal processes with hydrogeological processes and ultimately with mechanical processes, that, together with geophysical surveys, could offer new diagnosis approaches for geotechnical purposes,
 - iii. the investigation of the interaction between surface ice bodies (IAs and hanging glaciers) and permafrost and their relative control on each other,
 - iv. and finally, the development of integrative approaches combining state-of-the-art knowledge in order to anticipate landscape changes and support land planners in their evaluation of risks and economic resources.
- 37 These research directions will deepen the work initiated nearly 20 years ago that has made the MBM a world-renowned field for the observation of permafrost-affected rock walls, of rock wall permafrost, and more generally of the cryosphere of steep alpine rock walls and its geomorphological and societal implications.

BIBLIOGRAPHY

- Ballantyne, C. K., Sandeman, G. F., Stone, J. O., Wilson, P., 2014.- “Rock-slope failure following Late Pleistocene deglaciation on tectonically stable mountainous terrain”, *Quaternary Science Reviews*, vol. 86, pp. 144–157. DOI: <https://doi.org/10.1016/j.quascirev.2013.12.021>.
- Ben-Asher, M., Magnin, F., Westermann, S., Malet, E., Berthet, J., Bock, J., Ravanel, L., Deline, P., 2022.- “Estimating surface water availability in high mountain rock slopes using a numerical energy balance model”, *Earth Surface Dynamics Discussion* [preprint], pp. 1–25. DOI: <https://doi.org/10.5194/esurf-2022-58>.
- Boeckli, L., Brenning, A., Gruber, S., Noetzli, J., 2012.- “A statistical approach to modelling permafrost distribution in the European Alps or similar mountain ranges”, *The Cryosphere*, vol. 6, pp. 125–140. DOI: <https://doi.org/10.5194/tc-6-125-2012>.

- Cathala, M., Magnin, F., Linsbauer, A., Haeberli, W., 2021.- “Modelling and characterizing glacier-bed overdeepenings as sites for potential future lakes in the deglaciating French Alps”, *Géomorphologie : relief, processus, environnement*, vol. 27, n° 1, pp. 19–36. DOI: <https://doi.org/10.4000/geomorphologie.15255>.
- Cathala, M., Magnin, F., Ravanel, L., Dorren, L., Zuanon, N., Berger, F., Bourrier, F., Deline, P., 2023.- “Mapping Release and Propagation Areas of Permafrost-Related Rock Slope Failures in the French Alps”, *Geomorphology*, article soumis. DOI: <https://doi.org/10.2139/ssrn.4522860>.
- Cremonese, E., Gruber, S., Phillips, M., Pogliotti, P., Boeckli, L., Noetzli, J., Suter, C., Bodin, X., Crepez, A., Kellerer-Pirklbauer, A., Lang, K., Letey, S., Mair, V., Morra di Cella, U., Ravanel, L., Scapozza, C., Seppi, R., Zischg, A., 2011.- “Brief Communication: ‘An inventory of permafrost evidence for the European’”, *The Cryosphere*, vol. 5, pp. 651–657. DOI: <https://doi.org/10.5194/tc-5-651-2011>.
- Deline, P., Gardent, M., Magnin, F., Ravanel, L., 2012.- “The Morphodynamics of the Mont Blanc Massif in a Changing Cryosphere: A Comprehensive Review”, *Geografiska Annaler: Series A, Physical Geography*, vol. 94, pp. 265–283. DOI: <https://doi.org/10.1111/j.1468-0459.2012.00467.x>.
- Deline, P., Broccolato, M., Noetzli, J., Ravanel, L., Tamburini, A., 2013.- “The December 2008 Crammont Rock Avalanche, Mont Blanc Massif Area, Italy”, in C. Margottini, P. Canuti, and K. Sassa (eds.), *Landslide Science and Practice, Volume 4, Global Environmental Change*, Springer, Berlin, Heidelberg, pp. 403–408. DOI: https://doi.org/10.1007/978-3-642-31337-0_52.
- Duvillard, P.-A., Ravanel, L., Marcer, M., Schoeneich, P., 2019.- “Recent evolution of damage to infrastructure on permafrost in the French Alps”, *Reg. Environ. Change*, vol. 19, pp. 1281–1293. DOI: <https://doi.org/10.1007/s10113-019-01465-z>.
- Duvillard, P.-A., Magnin, F., Revil, A., Legay, A., Ravanel, L., Abdulsamad, F., Coperey, A., 2021.- “Temperature distribution in a permafrost-affected rock ridge from conductivity and induced polarization tomography”, *Geophysical Journal International*, vol. 225, n° 2. DOI: <https://doi.org/10.1093/gji/ggaa597>.
- Gallach, X., Carcaillet, J., Ravanel, L., Deline, P., Ogier, C., Rossi, M., Malet, E., Garcia-Sellés, D., 2020.- “Climatic and structural controls on Late-glacial and Holocene rockfall occurrence in high-elevated rock walls of the Mont Blanc massif (Western Alps)”, *Earth Surface Processes and Landforms*, vol. 45, pp. 3071–3091. DOI: <https://doi.org/10.1002/esp.4952>.
- Gardent, M., Rabatel, A., Dedieu, J.-P., Deline, P., 2014.- “Multitemporal glacier inventory of the French Alps from the late 1960s to the late 2000s”, *Global and Planetary Change*, vol. 120, pp. 24–37. DOI: <https://doi.org/10.1016/j.gloplacha.2014.05.004>.
- Gruber, S., Hoelzle, M., Haeberli, W., 2004.- “Permafrost thaw and destabilization of Alpine rock walls in the hot summer of 2003”, *Geophysical Research Letters*, vol. 31. DOI: <https://doi.org/10.1029/2004GL020051>.
- Guerin, A., Ravanel, L., Matasci, B., Jaboyedoff, M., Deline, P., 2020.- “The three-stage rock failure dynamics of the Drus (Mont Blanc massif, France) since the June 2005 large event”, *Nature Scientific Reports*, vol. 10, 17330. DOI: <https://doi.org/10.1038/s41598-020-74162-1>.
- Haberkorn, A., Wever, N., Hoelzle, M., Phillips, M., Kenner, R., Bavay, M., Lehning, M., 2017.- “Distributed snow and rock temperature modelling in steep rock walls using Alpine3D”, *The Cryosphere*, vol. 11, pp. 585–607. DOI: <https://doi.org/10.5194/tc-11-585-2017>.

- Haerberli, W., Buetler, M., Huggel, C., Friedli, T. L., Schaub, Y., Schleiss, A. J., 2016.- “New lakes in deglaciating high-mountain regions—opportunities and risks”, *Climatic Change*, vol. 139, pp. 201–214. DOI: <https://doi.org/10.1007/s10584-016-1771-5>.
- Hartmeyer, I., Delleske, R., Keuschnig, M., Krautblatter, M., Lang, A., Schrott, L., Otto, J.-C., 2020.- “Current glacier recession causes significant rockfall increase: the immediate paraglacial response of deglaciating cirque walls”, *Earth Surface Dynamics*, vol. 8, pp. 729–751. DOI: <https://doi.org/10.5194/esurf-8-729-2020>.
- Hasler, A., Gruber, S., Font, M., Dubois, A. 2011.- “Advective Heat Transport in Frozen Rock Clefts: Conceptual Model, Laboratory Experiments and Numerical Simulation”, *Permafrost and Periglacial Processes*, vol. 22, n°4, pp. 378–389. DOI: <https://doi.org/10.1002/ppp.737>.
- Kaushik, S., Ravel, L., Magnin, F., Trouvé, E., Yan, Y., 2022.- “Ice Aprons in the Mont Blanc Massif (Western European Alps): Topographic Characteristics and Relations with Glaciers and Other Types of Perennial Surface Ice Features”, *Remote Sensing*, vol. 14, n° 21, 5557. DOI: <https://doi.org/10.3390/rs14215557>.
- Krautblatter, M., Huggel, C., Deline, P., Hasler, A., 2012.- “Research Perspectives on Unstable High-alpine Bedrock Permafrost: Measurement, Modelling and Process Understanding”, *Permafrost and Periglacial Processes*, vol. 23, n° 1, pp. 80–88. DOI: <https://doi.org/10.1002/ppp.740>.
- Krautblatter, M., Funk, D., Günzel, F. K., 2013.- “Why permafrost rocks become unstable: a rock–ice-mechanical model in time and space”, *Earth Surface Processes and Landforms*, vol. 38, n° 8, pp. 876–887. DOI: <https://doi.org/10.1002/esp.3374>.
- Legay, A., Magnin, F., Ravel, L., 2021.- “Rock temperature prior to failure: Analysis of 209 rockfall events in the Mont Blanc massif (Western European Alps)”, *Permafrost and Periglacial Processes*, vol. 32, n° 3, pp. 520–536. DOI: <https://doi.org/10.1002/ppp.2110>.
- Magnin, F., Josnin, J.-Y. 2021.- “Water Flows in Rock Wall Permafrost: A Numerical Approach Coupling Hydrological and Thermal Processes”, *Journal of Geophysical Research: Earth Surface*, vol. 126, n° 11, e2021JF006394. DOI: <https://doi.org/10.1029/2021JF006394>.
- Magnin, F., Deline, P., Ravel, L., Noetzli, J., Pogliotti, P., 2015.- “Thermal characteristics of permafrost in the steep alpine rock walls of the Aiguille du Midi (Mont Blanc Massif, 3842 m a.s.l.)”, *The Cryosphere*, vol. 9, pp. 109–121. DOI: <https://doi.org/10.5194/tc-9-109-2015>.
- Magnin, F., Josnin, J.-Y., Ravel, L., Pergaud, J., Pohl, B., Deline, P., 2017.- “Modelling rock wall permafrost degradation in the Mont Blanc massif from the LIA to the end of the 21st century”, *The Cryosphere*, vol. 11, pp. 1813–1834. DOI: <https://doi.org/10.5194/tc-11-1813-2017>.
- Magnin, F., Westermann, S., Pogliotti, P., Ravel, L., Deline, P., Malet, E., 2017.- “Snow control on active layer thickness in steep alpine rock walls (Aiguille du Midi, 3842 m a.s.l., Mont Blanc massif)”, *CATENA*, vol. 149, n° 2, pp. 648–662. DOI: <https://doi.org/10.1016/j.catena.2016.06.006>.
- Mellor, M., 1971.- “Strength and Deformability of Rocks at Low Temperatures, Corps of Engineers, U.S. Army”, *Cold Regions Research and Engineering Laboratory*, 88 p.
- Mourey, J., Marcuzzi, M., Ravel, L., Pallandre, F., 2019.- “Effects of climate change on high Alpine mountain environments: Evolution of mountaineering routes in the Mont Blanc massif (Western Alps) over half a century”, *Arctic, Antarctic, and Alpine Research*, vol. 51, n° 1, pp. 176–189. DOI: <https://doi.org/10.1080/15230430.2019.1612216>.
- Noetzli, J., Gruber, S. 2009.- “Transient thermal effects in Alpine permafrost”, *The Cryosphere*, vol. 3, pp. 85–99. DOI: <https://doi.org/10.5194/tc-3-85-2009>.

Noetzli, J., Gruber, S., Kohl, T., Salzmann, N., Haerberli, W., 2007.- “Three-dimensional distribution and evolution of permafrost temperatures in idealized high-mountain topography”, *Journal of Geophysical Research: Earth Surface*, vol. 112. DOI: <https://doi.org/10.1029/2006JF000545>.

Phillips, M., Haberkorn, A., Draebing, D., Krautblatter, M., Rhyner, H., Kenner, R., 2016.- “Seasonally intermittent water flow through deep fractures in an Alpine Rock Ridge: Gemsstock, Central Swiss Alps”, *Cold Regions Science and Technology*, vol. 125, pp. 117–127. DOI: <https://doi.org/10.1016/j.coldregions.2016.02.010>.

von Raumer, J. F., Bussy, F., 2004.- “Mont Blanc and Aiguilles Rouges Geology of their polymetamorphic Basement (External Massifs, Western Alps, France-Switzerland)”, Section des Sciences de la Terre, Université de Lausanne, Lausanne.

Rabatel A., Deline P., Jaillet S., Ravanel L., 2008.- “Rock falls in high-alpine rock walls quantified by terrestrial LiDAR measurements: a case study in the Mont Blanc area”, *Geophysical Research Letters*, vol. 35, n° 10, L10502. DOI: <https://doi.org/10.1029/2008GL033424>.

Ravanel, L., Duvillard, P.-A., Astrade, L., Faug, T., Deline, P., Berthet, J., Cathala, M., Magnin, F., Baratier, A., Bodin, X., 2023.- “The Taconnaz rockfall (Mont-Blanc massif, European Alps) of November 2018: A complex and at-risk rockwall-glacier-torrent morphodynamic continuum”, *Applied Sciences*, vol. 13, n° 17, 9716.

Ravanel, L., Guillet, G., Kaushik, S., Preunkert, S., Malet, E., Magnin, F., Trouvé, E., Montagnat, M., Yan, Y., Deline, P., 2023.- “Ice aprons on steep high-alpine slopes: insights from the Mont-Blanc massif, Western Alps”, *Journal of Glaciology*, pp. 1–17. DOI: <https://doi.org/10.1017/jog.2023.15>.

Ravanel, L., Deline, P. 2011.- “Climate influence on rockfalls in high-Alpine steep rockwalls: The north side of the Aiguilles de Chamonix (Mont Blanc massif) since the end of the “Little Ice Age””, *The Holocene*, vol. 21, n° 2, pp. 357–365. DOI: <https://doi.org/10.1177/0959683610374887>.

Ravanel, L., Magnin, F., Deline, P. 2017.- “Impacts of the 2003 and 2015 summer heatwaves on permafrost-affected rock-walls in the Mont Blanc massif”, *Science of The Total Environment*, vol. 609, p. 132–143. DOI: <https://doi.org/10.1016/j.scitotenv.2017.07.055>.

Wagner, F. M., Mollaret, C., Günther, T., Kemna, A., Hauck, C., 2019.- “Quantitative imaging of water, ice and air in permafrost systems through petrophysical joint inversion of seismic refraction and electrical resistivity data”, *Geophysical Journal International*, vol. 219, n° 3, pp. 1866–1875. DOI: <https://doi.org/10.1093/gji/ggz402>.

Walder, J., 1985.- “A theoretical model of the fracture of rock during freezing”, *Geological Society of America Bulletin*.

Wegmann, M., Gudmundsson, G. H., Haerberli, W. 1998.- “Permafrost changes in rock walls and the retreat of alpine glaciers: a thermal modelling approach”, *Permafrost and Periglacial Processes*, vol. 9, n° 1, pp. 23–33. DOI: [https://doi.org/10.1002/\(SICI\)1099-1530\(199801/03\)9:1<23::AID-PPP274>3.0.CO;2-Y](https://doi.org/10.1002/(SICI)1099-1530(199801/03)9:1<23::AID-PPP274>3.0.CO;2-Y).

ABSTRACTS

The enhanced rockfall frequency ($V > 100 \text{ m}^3$) first noticed in the European Alps, has motivated investigations on high mountain rock walls and rock wall permafrost since the 2000s. Mont-Blanc massif (MBM) has become a pilot study area thanks to the wealth of data and knowledge on rockfall and permafrost dynamics acquired through successive research projects. Statistical analysis of rockfall distribution (> 1300 events inventoried between 2007 and 2021) shows that

they are related to permafrost distribution and increasing atmospheric temperature, opening promising perspective for developing forecasting tools to support mountain practitioners in their risk mitigation strategy. However, understanding how rock wall destabilizations develop is challenged by the variety of potentially involved thermo-hydro-mechanical processes. To face these challenges, research currently carried out in the MBM focuses on water infiltration and circulation processes in frozen rock walls by combining advanced numerical modelling approaches and *ad hoc* field surveys. The coupling of models simulating heat and water transport with geoelectrical imaging methods could allow assessment of ground water/ice distributions and contents that is highly relevant for geotechnical purposes. Concurrently, the combination of acquired data and knowledge in integrative approaches of landscape changes and hazards involving permafrost degradation, glacier retreat, possible lake formation and rock wall destabilization appears as an essential basis for land-planning concerns. Finally, thermal and hydrological interactions between rock wall permafrost and ice bodies nestled on rock faces (ice aprons and hanging glaciers) is another direction of research to be pursued with cross-disciplinary implications.

INDEX

Keywords: permafrost-affected rock walls, rock wall permafrost, rockfall, Mont-Blanc massif

AUTHORS

FLORENCE MAGNIN

Univ. Grenoble Alpes, Univ. Savoie Mont-Blanc, CNRS, UMR CNRS 5204, EDYTEM

LUDOVIC RAVANEL

Univ. Grenoble Alpes, Univ. Savoie Mont-Blanc, CNRS, UMR CNRS 5204, EDYTEM

MATAN BEN-ASHER

Univ. Grenoble Alpes, Univ. Savoie Mont-Blanc, CNRS, UMR CNRS 5204, EDYTEM

JOSUÉ BOCK

Univ. Grenoble Alpes, Univ. Savoie Mont-Blanc, CNRS, UMR CNRS 5204, EDYTEM

MAËVA CATHALA

Univ. Grenoble Alpes, Univ. Savoie Mont-Blanc, CNRS, UMR CNRS 5204, EDYTEM

PIERRE-ALLAIN DUVILLARD

NAGA Geophysics

PIERRICK JEAN

Univ. Grenoble Alpes, Univ. Savoie Mont-Blanc, CNRS, UMR CNRS 5204, EDYTEM

JEAN-YVES JOSNIN

Univ. Grenoble Alpes, Univ. Savoie Mont-Blanc, CNRS, UMR CNRS 5204, EDYTEM

SUVRAT KAUSHIK

Univ. Grenoble Alpes, Univ. Savoie Mont-Blanc, CNRS, UMR CNRS 5204, EDYTEM

ANDRÉ REVIL

Univ. Grenoble Alpes, Univ. Savoie Mont-Blanc, CNRS, UMR CNRS 5204, EDYTEM

PHILIP DELINE

Univ. Grenoble Alpes, Univ. Savoie Mont-Blanc, CNRS, UMR CNRS 5204, EDYTEM