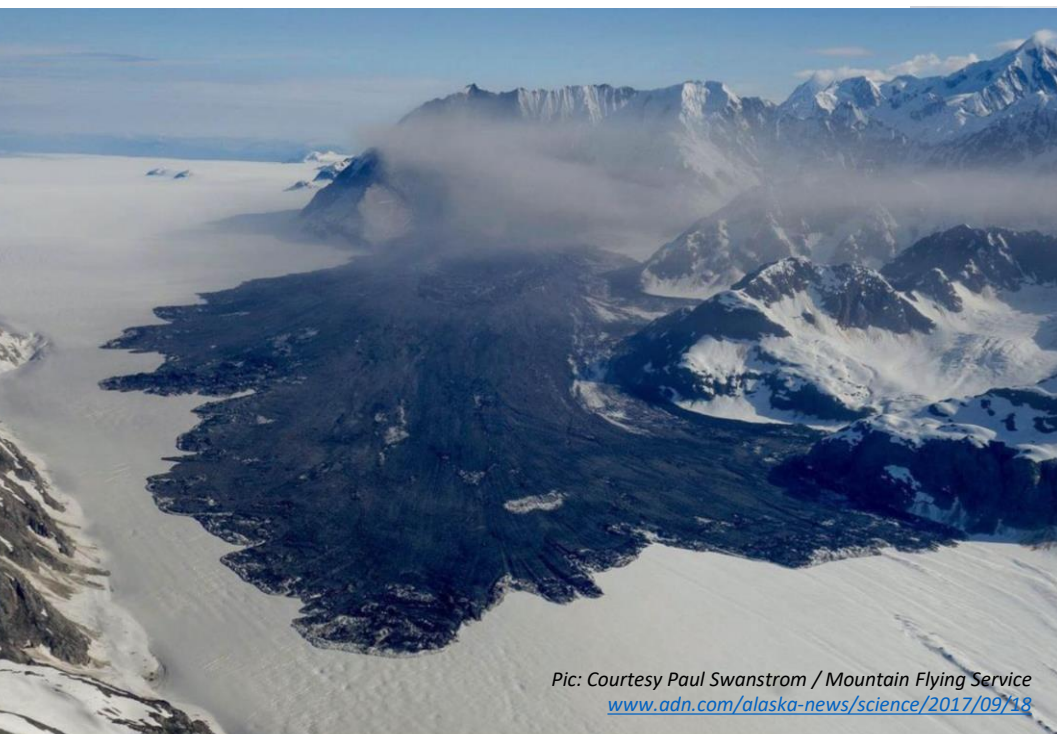


Recent advances in Rock wall Permafrost Modelling to Understand Bedrock Failures

Florence Magnin, J-Y. Josnin, A. Legay, L. Ravanel, P. Deline, P.A. Duvillard

Laboratoire EDYTEM (CNRS, Université Savoie Mont Blanc)

florence.magnin@univ-smb.fr



Pic: Courtesy Paul Swanstrom / Mountain Flying Service
www.adn.com/alaska-news/science/2017/09/18



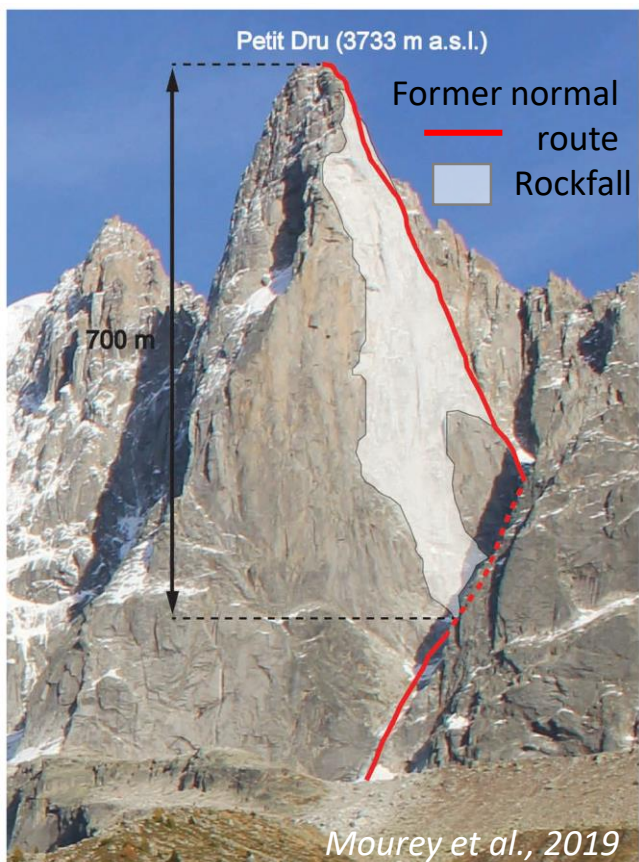
Pic : J-C Bèche



www.geopraevent.ch
Source : Scoria hut

Periglacial rock slope failures are increasing and impact Alpine and Arctic communities

Change in mountain practices and professional guiding activities



Piz Cengalo rock avalanche
 Switzerland- August 2017



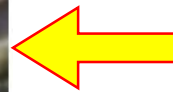
Chain reaction processes with far-reaching impacts

Rock avalanche in Karrat Fjord - Greenland – June 2017



Periglacial rock slope failures are increasing and impact Alpine and Arctic communities

Chamoli rock-ice avalanche—
February 2021

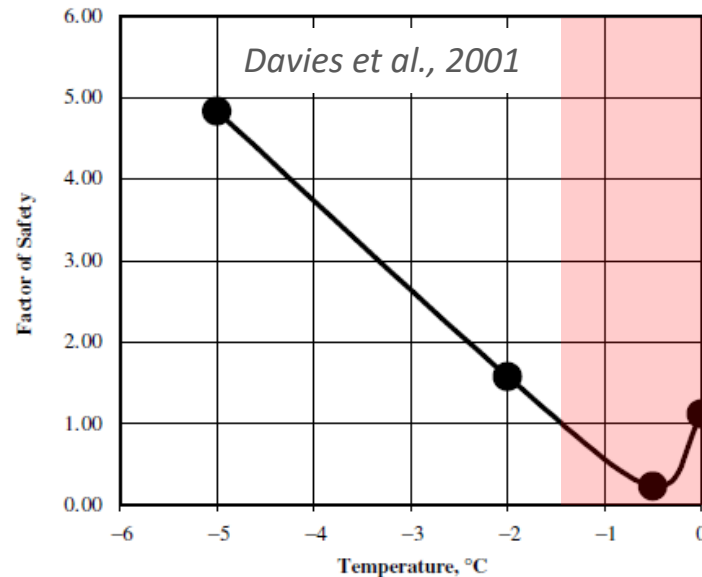


Permafrost degradation is most likely responsible for these increasing destabilisations

The Trident du Tacul rock fall
sep. 26th, 2018

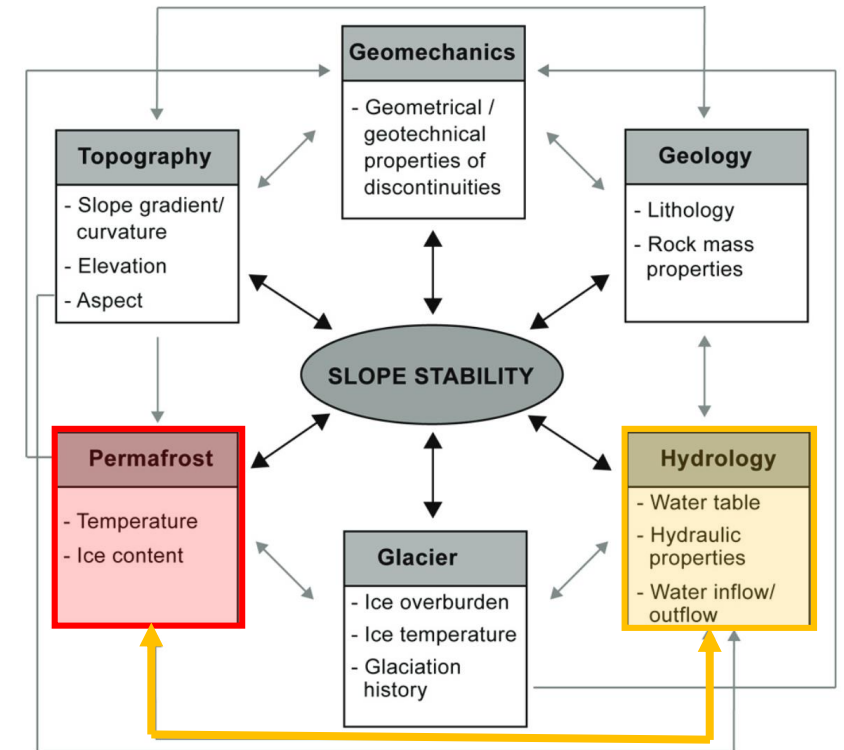


Shear resistance of an ice-filled joint
between bedrock compartments



F. Magnin - Mar. 2nd, 2021 - IAG

Fischer and Huggel, 2008



Rockfalls may be triggered by:

- A decrease of shear resistance of ice-filled fractures, either caused by the steady heat propagation by conduction, or by accelerated warming through advection (from water)
- High hydrostatic pressures at perched water tables

Background and research directions to better understand periglacial rock slope failures

1. Systematic inventory of rockfalls in the Mont Blanc massif since 2007

→ has shown an evident relationship between hot periods (decade or season) and rockfalls frequency

→ Is there a statistical relationship between rockwall temperature and rockfall occurrence ?



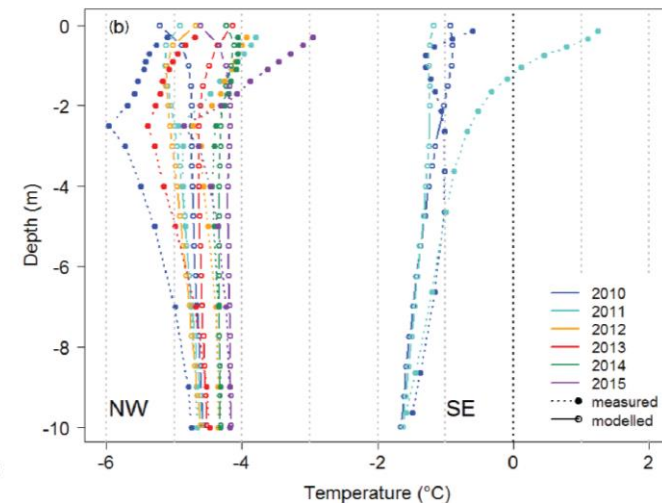
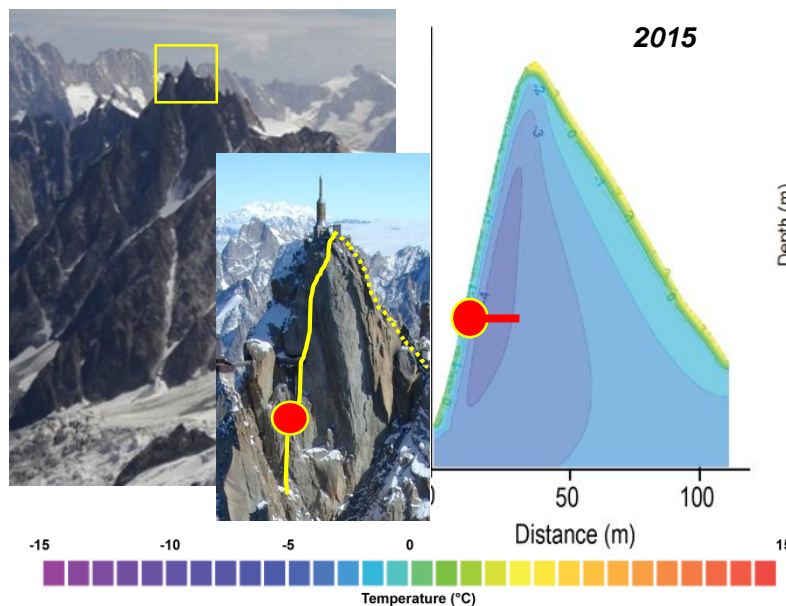
2. Transient thermal models compared to borehole temperature data

→ Rockwall permafrost has degraded over the past 3 decades

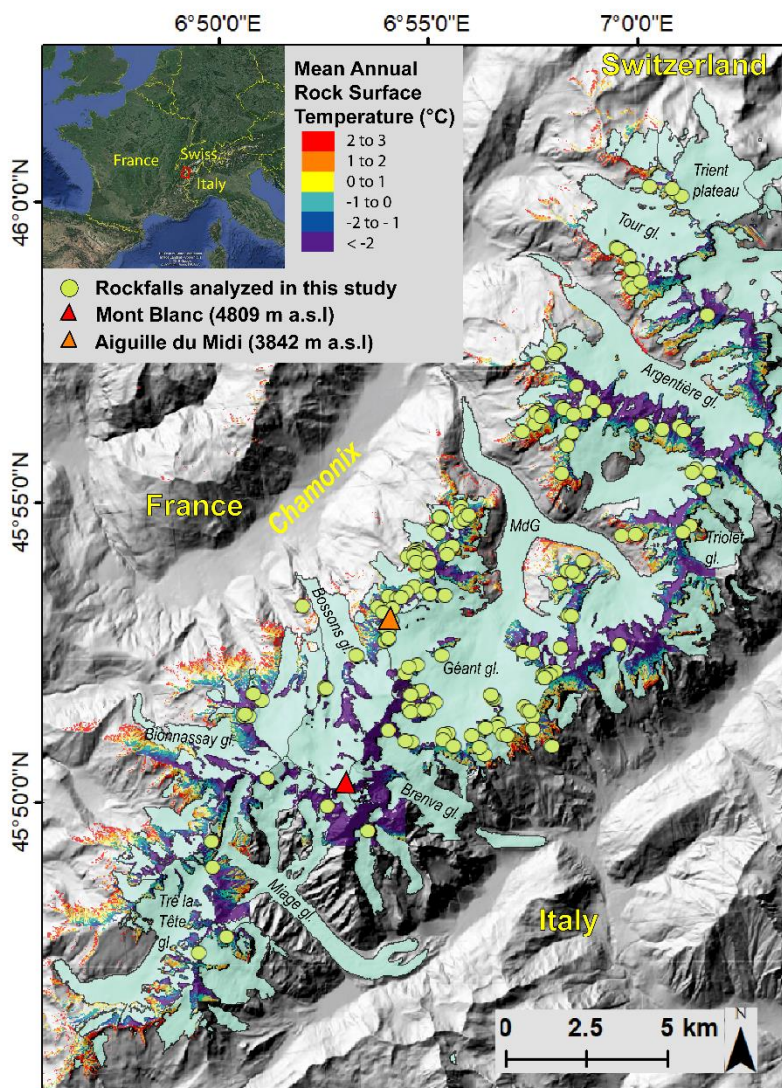
→ Rockwall temperature evolution is accurately simulated at depth > 8 m

→ What is the role of hydrological processes in permafrost dynamics ?

Aiguille du Midi – 3842 m a.s.l

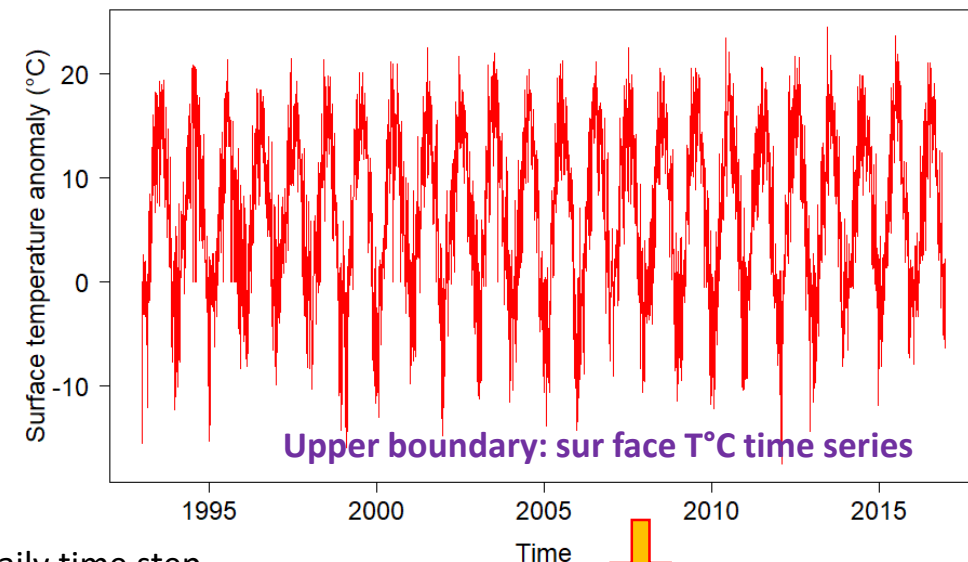


Approach for statistical analysis of rockwall temperature prior to failure



Data

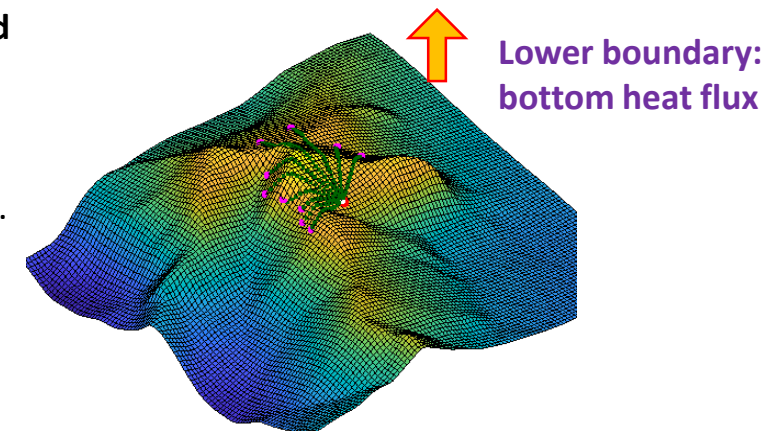
- **209 rockfall events** (100 to 60 000 m³) selected from an inventory collected in the Mont Blanc massif btw 2007- 2015
- Coordinates, date of occurrence, and detachment depths are known
- The Mean Annual Rock Surface Temperature for the period 1961-1990 is extracted from the map



Modeling approach

- Temperature profiles are simulated at a daily time step **for each event** from the surface to the depth of failure, from 1993 to 2016 with the **CRYOGRID2 transient diffusive thermal model** (Westermann *et al.*, 2013).
- **Rock surface temperature (RST) time series** are created from air temperature anomaly applied to the initial MARST to force transient thermal modeling.
- **A correction heat flux** is calculated to account for possible lateral heat fluxes from surrounding rock faces.
- **Uncertainties** for the initial MARST, RST time series and CRYOGRID2 parameters **are quantified**.

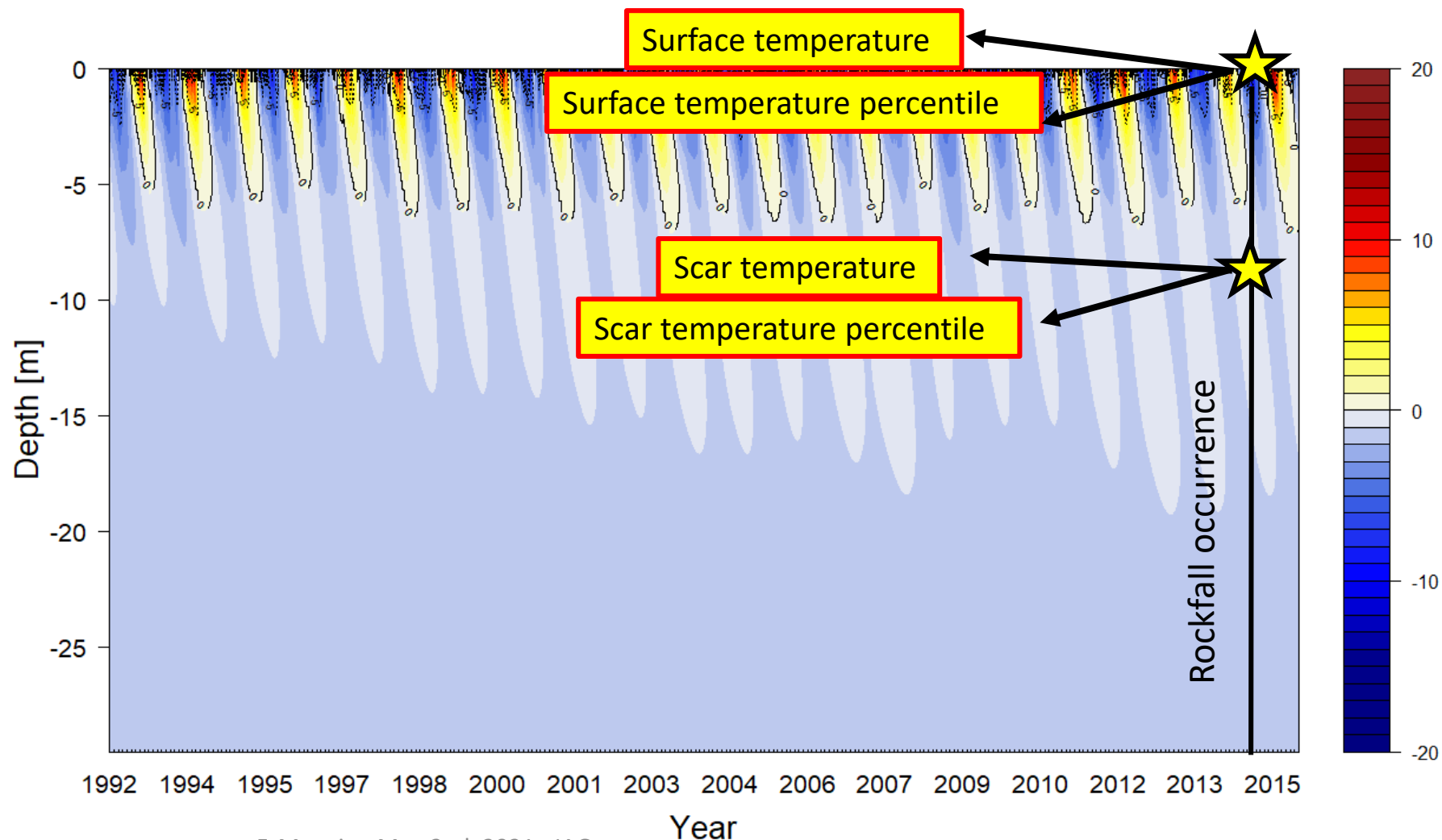
CryoGRID2: 1D transient thermal model



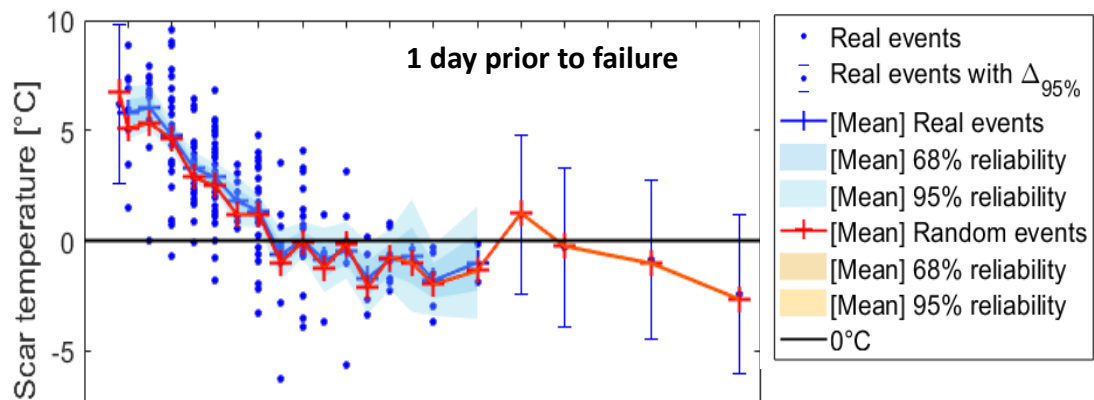
Approach for statistical analysis of rockwall temperature prior to failure

Results analysis

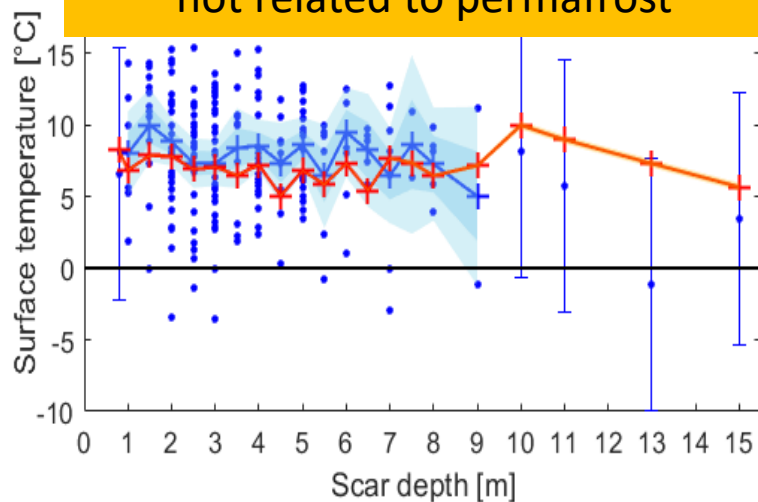
- **4 temperature variables** are considered to analyze temperature conditions and dynamics prior to failure
- **Various temporalities prior to failure ranging from the day of occurrence to 2 months before** are considered
- **1000 random events at each rock fall location** (209 000 in total) drawn according to the statistics of rockfall timing (distribution over the year)



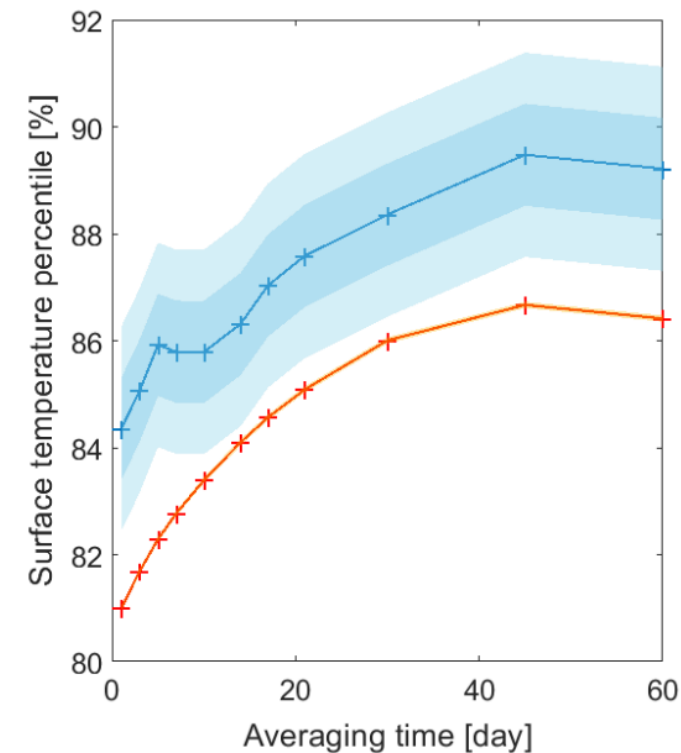
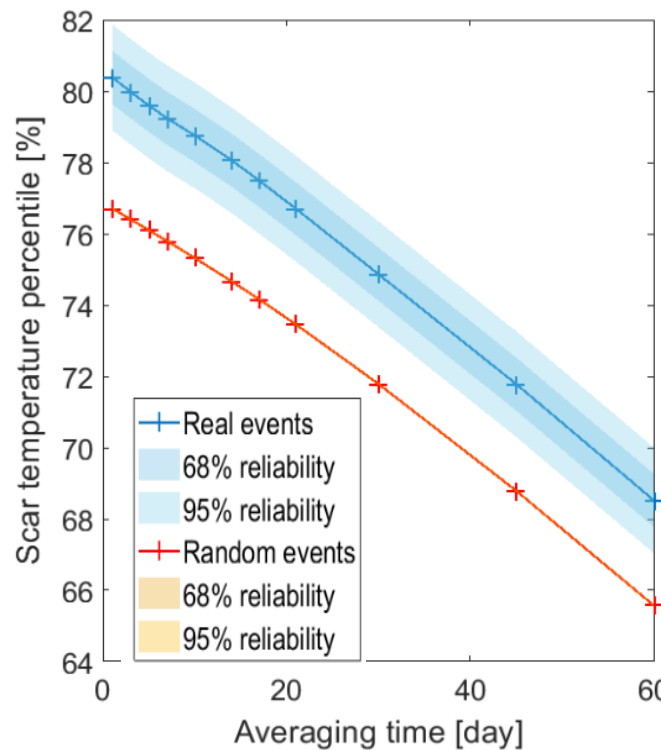
Rockwall temperature conditions and dynamics prior to failure



Permafrost-related rockfalls may generally concern events > 6 m and most events < 4 m depth are not related to permafrost

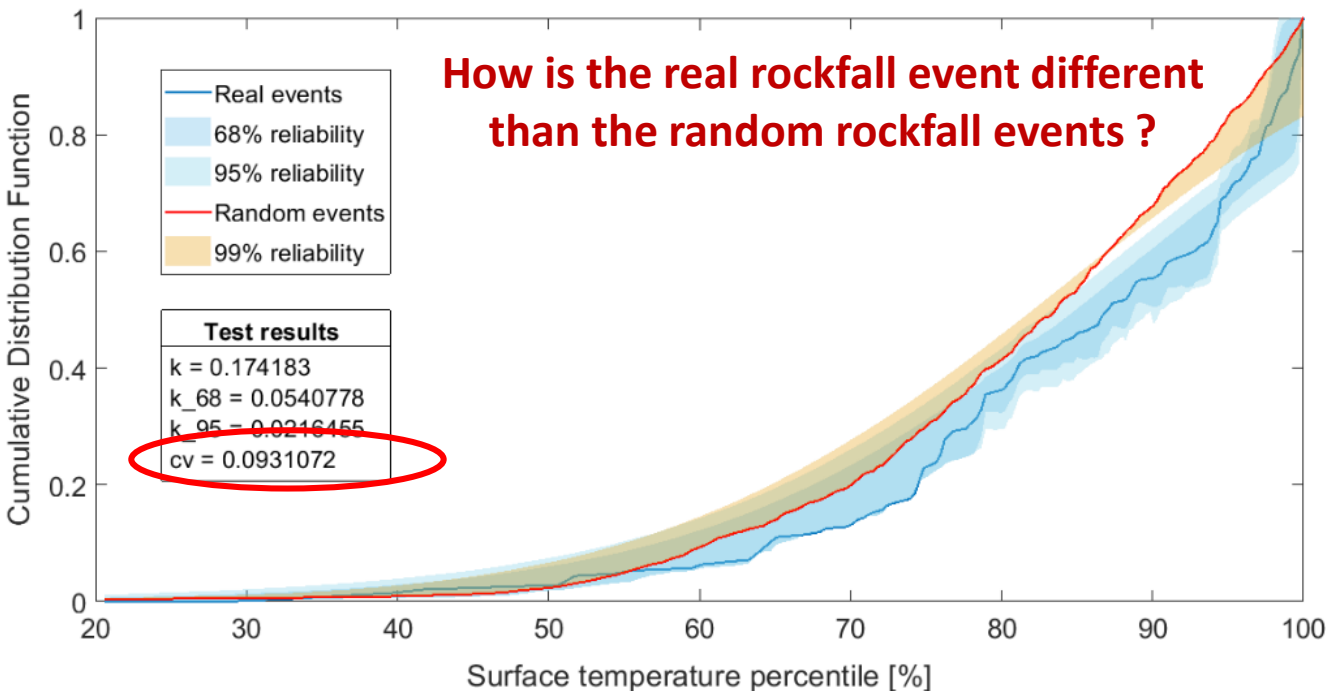


Extraordinary high temperature is a common triggering factor of rockfall for both frozen and non-frozen rockwalls.



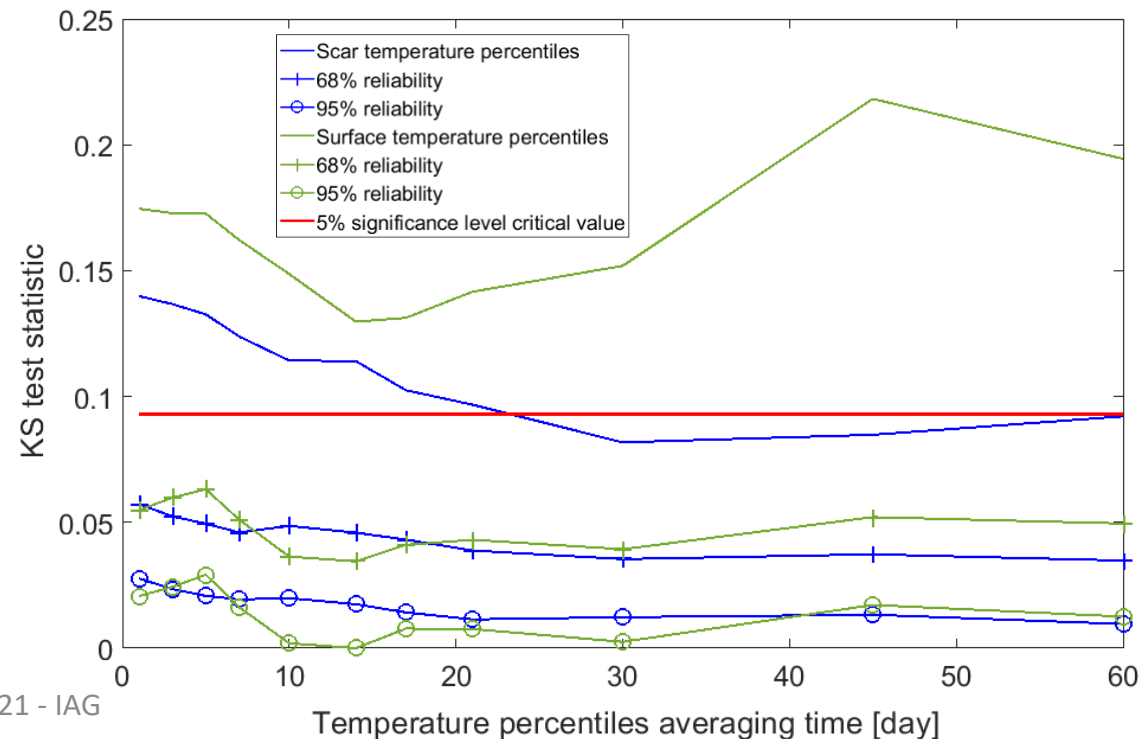
Determination of the statistical significance of rockwall temperature prior to failure

- Results of the real events simulations are compared to those of the random events in a Kolmogorov-Smirnov test (KS) to determine their statistical significance



➔ Such statistics could support the development of a rockfall susceptibility index using weather forecast

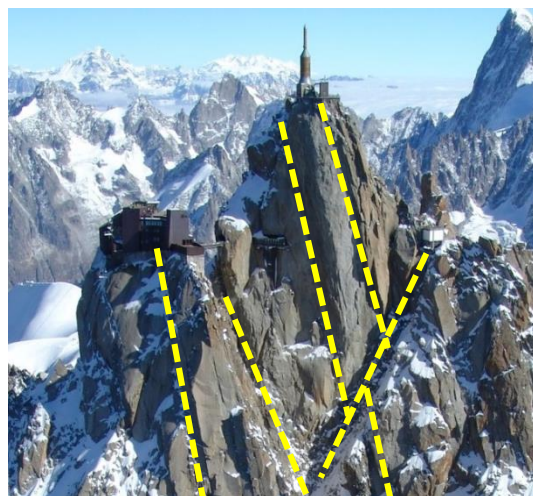
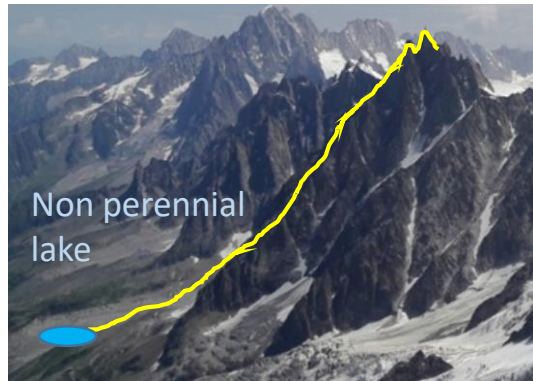
- Hot periods lasting at least 1.5 month combined with 1-5 days hot spell are particularly prone to rockfalls.
- Rockfalls are a direct reaction to extraordinary high temperature at depth.



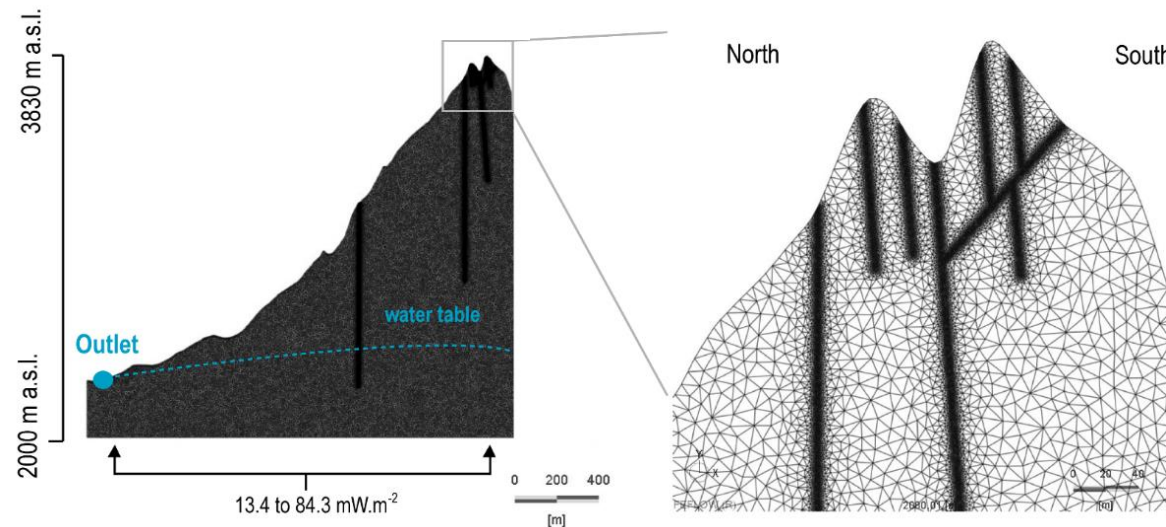
Modeling approach to couple thermal and hydrological processes

Model set up and modeling approach

- Model domain according to hydrogeological settings for non-frozen conditions (water table and fractures as preferential flow paths)
- Fully coupled thermal and hydrological simulations with Feflow®

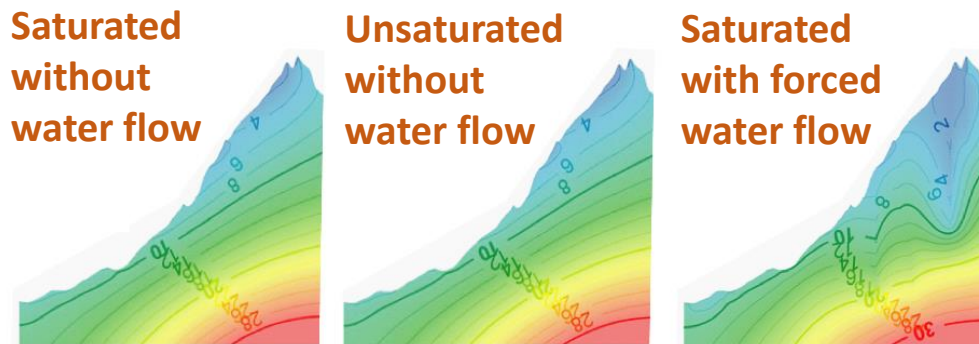


- Darcy law plugged into the continuity equation
- Hydraulic conductivity determined through the van Genuchten – Mualem relationship
- Flow velocity integrated into the dispersive-diffusive heat transport equation
- Water discharge in the fractures is calculated through the Hagen-Poiseuille linear flow formulation

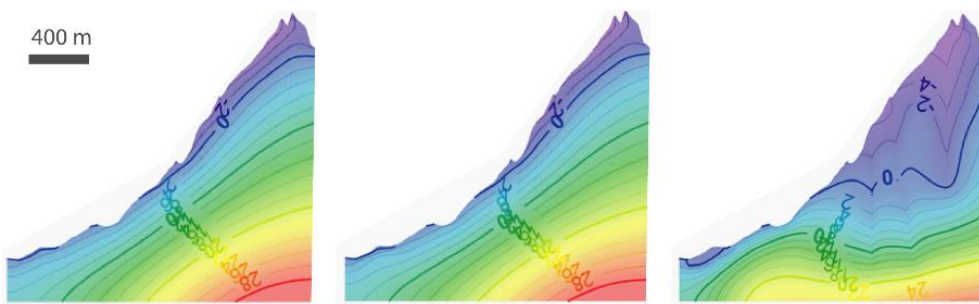
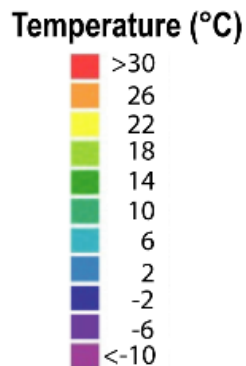


Output of hydrothermal models for different saturation level and water flow forcing

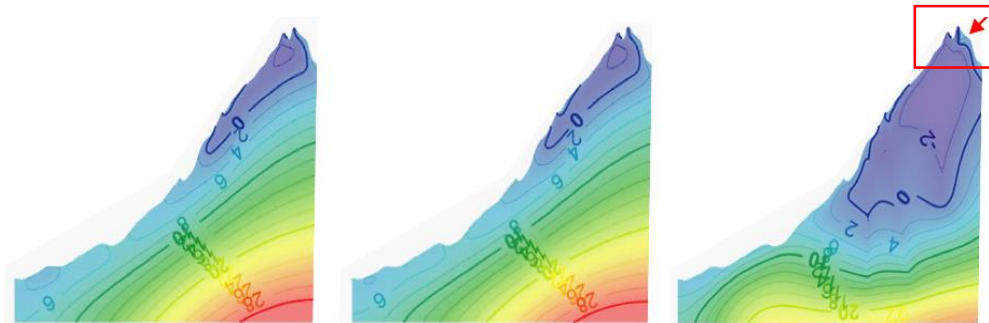
0 AD:
 After initialization
 (thawed conditions)



1850 AD:
 After steady freezing



2100 AD:
 After steady thawing

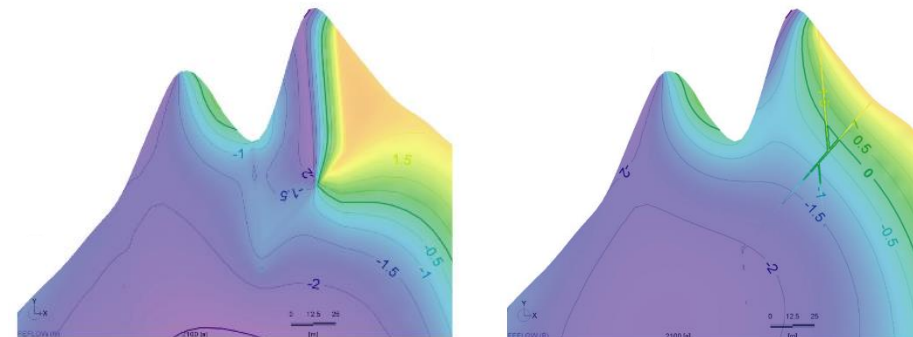


Water flows into rockwall fractures strongly affect the freezing and thawing patterns:

- Temperature gradients are greater than in no flow conditions
- Thawing is enhanced in saturated fractures (thawing corridors) and surrounding saturated rock medium (thawing wedges)

Saturated with forced water flow

Unsaturated with forced water flows in saturated fractures



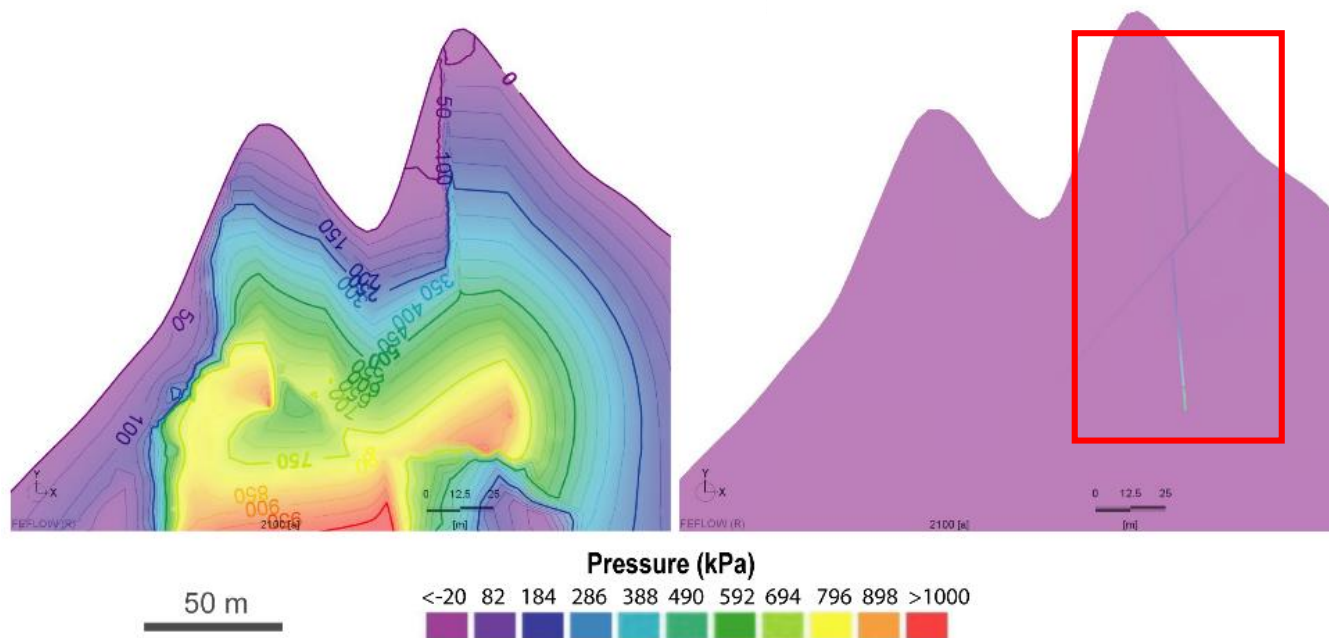
Temperature (°C)



Towards thermo-hydro-mechanical models to simulate rockwall destabilizations

Saturated with forced water flow

Unsaturated with forced water flows in saturated fractures



Hydrostatic pressures have complex patterns under fully saturated conditions

Critical values of 0.1 Mpa as determined by Stoll et al. 2020* may be easily reached in thawing fractures and surrounding rock mass

→ Such data could be integrated into discrete element models describing the mechanical behaviour of frozen rockwalls to better assess hydrothermal conditions prone to rockwall failures

*Stoll, V., Scandroglio, R., Krautblatter, M., 2020. *Modelling rock walls destabilization caused by hydrostatic pressure in frozen/unfrozen bedrock (Hochvogel & Zugspitze, Germany)*. Presented at the EGU General Assembly, Vienna, Austria. <https://doi.org/doi.org/10.5194/egusphere-egu2020-14338>

There is a need for a better understanding of periglacial rockwall destabilization processes in order to support Alpine and Arctic communities in their adaptation strategy to a changing cryosphere

1. Is there a statistical relationship rockwall temperature and rockfall occurrence?

- A significant statistical relationship was clearly established between rock temperature dynamics and rockfall occurrence.
- The high uncertainty in the simulated temperature field points out the need to use a greater rockfall sample
- The little temperature difference between real rockfalls and random rockfalls suggest to draw a random sample for other locations than those of observed rockfalls.

➔ **A first step towards the determination of rockfall susceptibility index according to weather forecast**

2. What is the role of hydrological processes in permafrost dynamics and frozen rockwall mechanics ?

- Favors a deep reaching of the permafrost body when forming
- Enhance thawing in saturated fractures and in the surrounding saturated rock medium (thawing corridors and wedges)
- Results in complex fluid pressure fields that may reach critical values leading to destabilization.
- Implementation at various time and space scale is required.

➔ **A first step towards fully coupled thermo-hydro-mechanical models to analyze frozen rockwall destabilization**



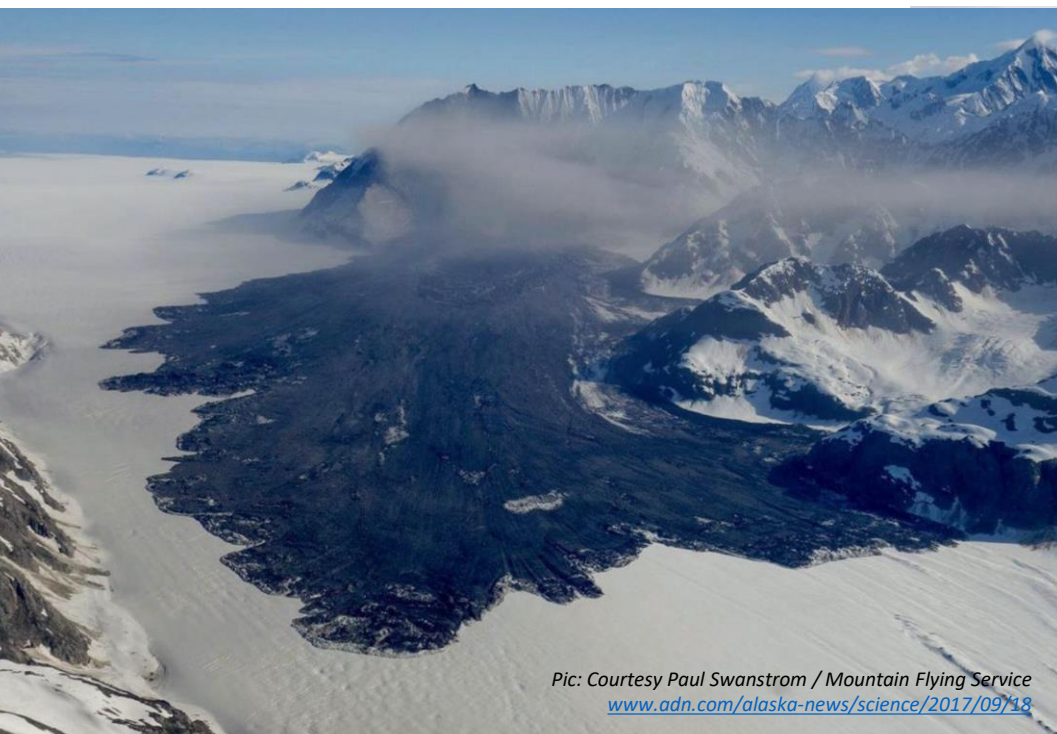
Modeling Rockwall Permafrost to Understand Periglacial Rock Slope Failures

Thank you for your attention!
AGU, March, 2nd, 2021

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Pic: Courtesy Paul Swanstrom / Mountain Flying Service
www.adn.com/alaska-news/science/2017/09/18



Pic : J-C Bèche



www.geopraevent.ch
Source : Scoria hut