

## *Modeling Hydrogeological Processes in Steep Permafrost-affected Rock Slopes*

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# Permafrost degradation favors rock slope failure

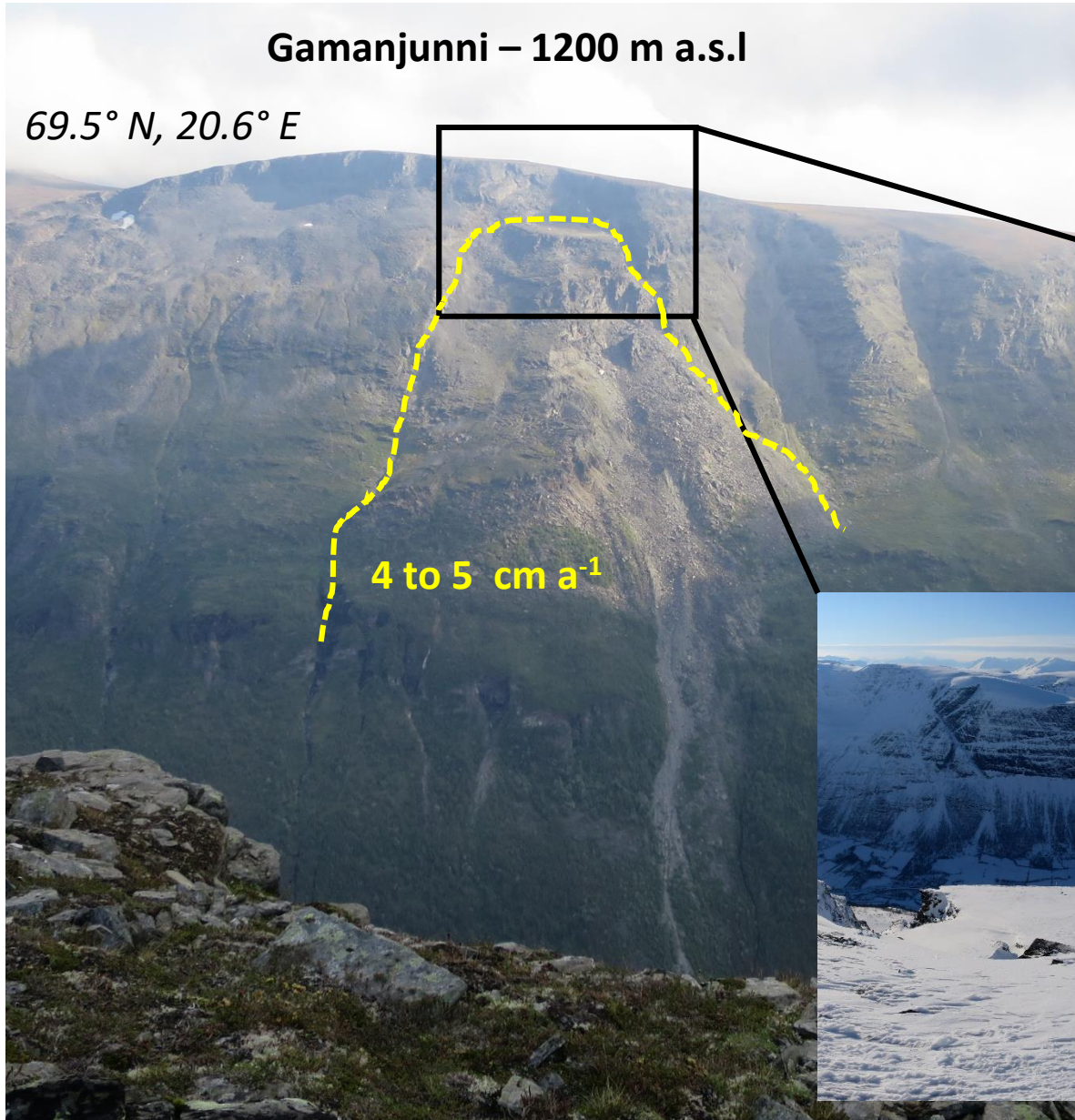
Etache – 3100 m a.s.l  
Occurred June 2020



# Permafrost degradation and rock slides

Gamanjunni – 1200 m a.s.l

69.5° N, 20.6° E



4 to 5 cm a<sup>-1</sup>

Continuous to discontinuous permafrost

Highest velocities recorded during spring  
(*Etzelmüller et al., 2022*)

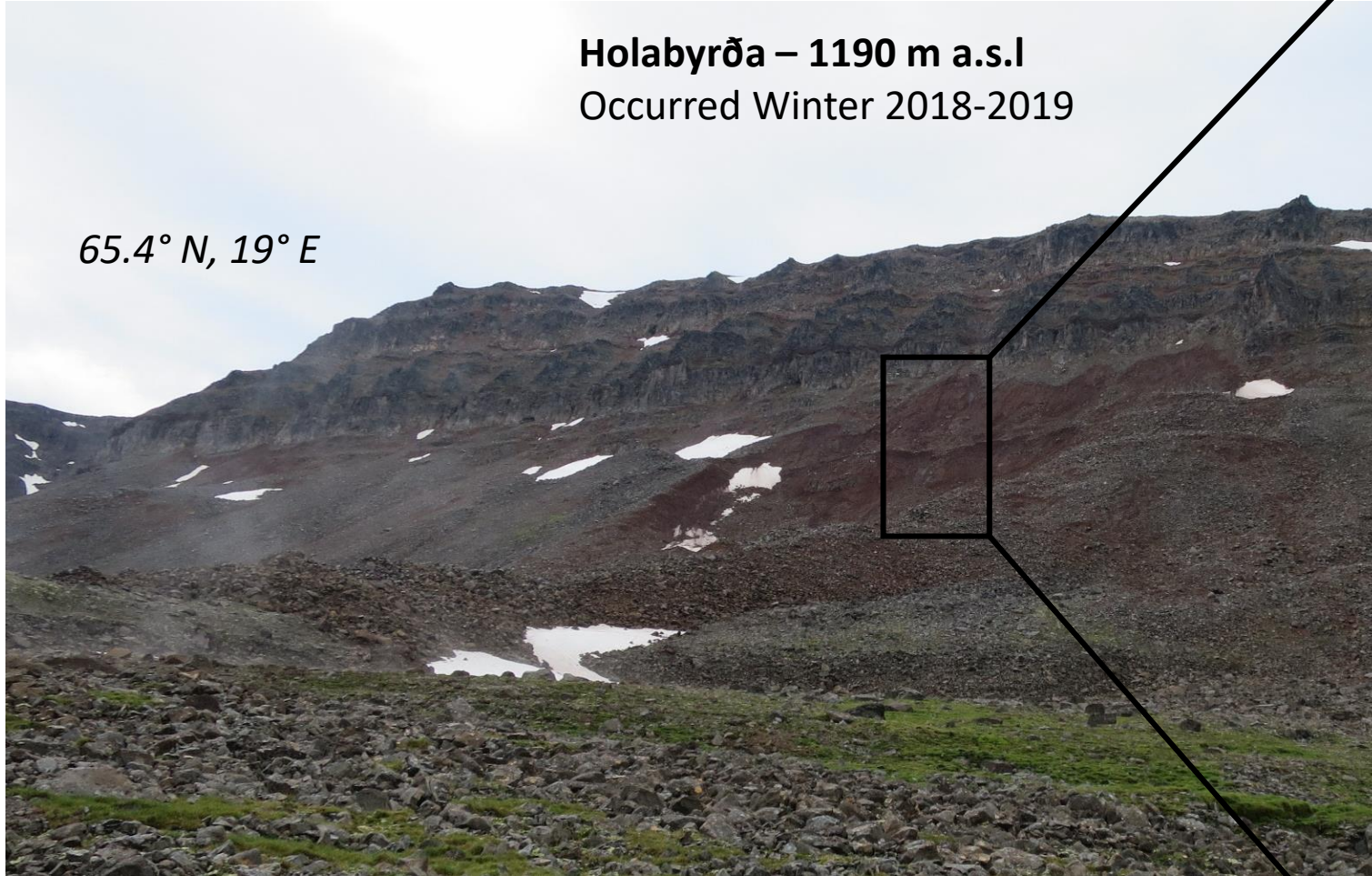


# Permafrost degradation and talus collapse

Above the regional limit of permafrost

Holabyrða – 1190 m a.s.l  
Occurred Winter 2018-2019

65.4° N, 19° E



# *Hypothesis and research question driving this study*

## **Hypothesis**

Water infiltration accelerates permafrost degradation and ice-joints erosion and/or provokes high hydrostatic pressures

## **Research question**

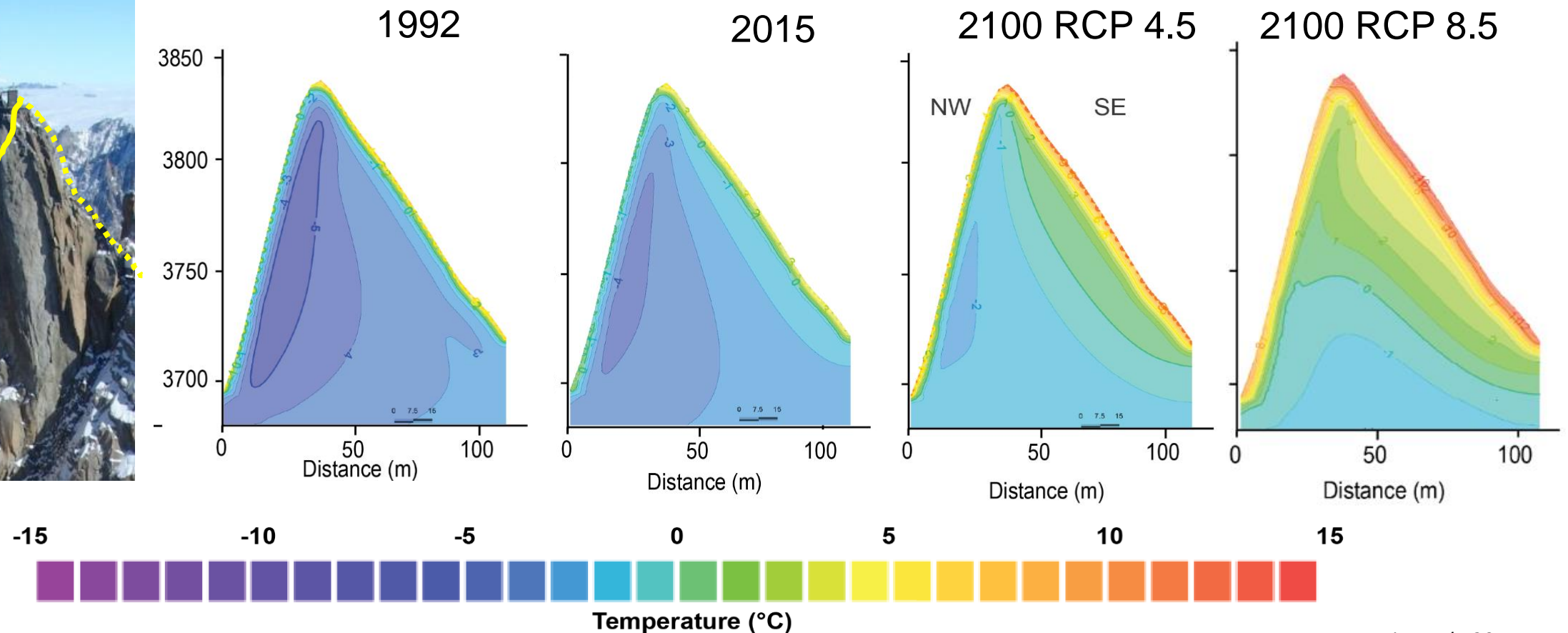
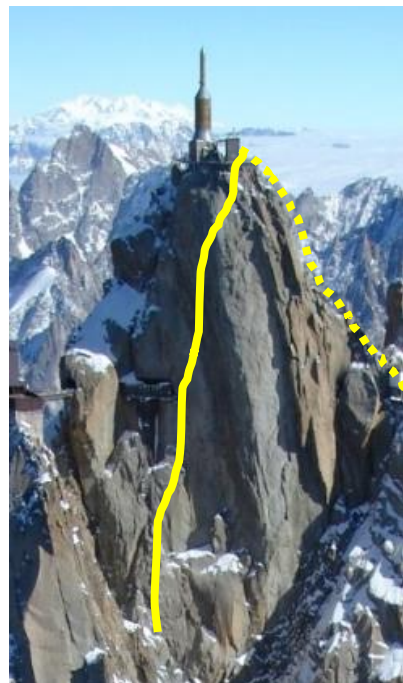
What is the thermal and mechanical implications of water infiltration and circulation in steep permafrost-affected rock slope ?



# Thermal modeling of steep rock permafrost affected rock slopes: background

1. Creating surface temperature time series
2. Simulating conductive heat transfer and latent heat exchanges in a homogeneous, saturated and isotropic rock medium

→ How to introduce water flows in this approach ?



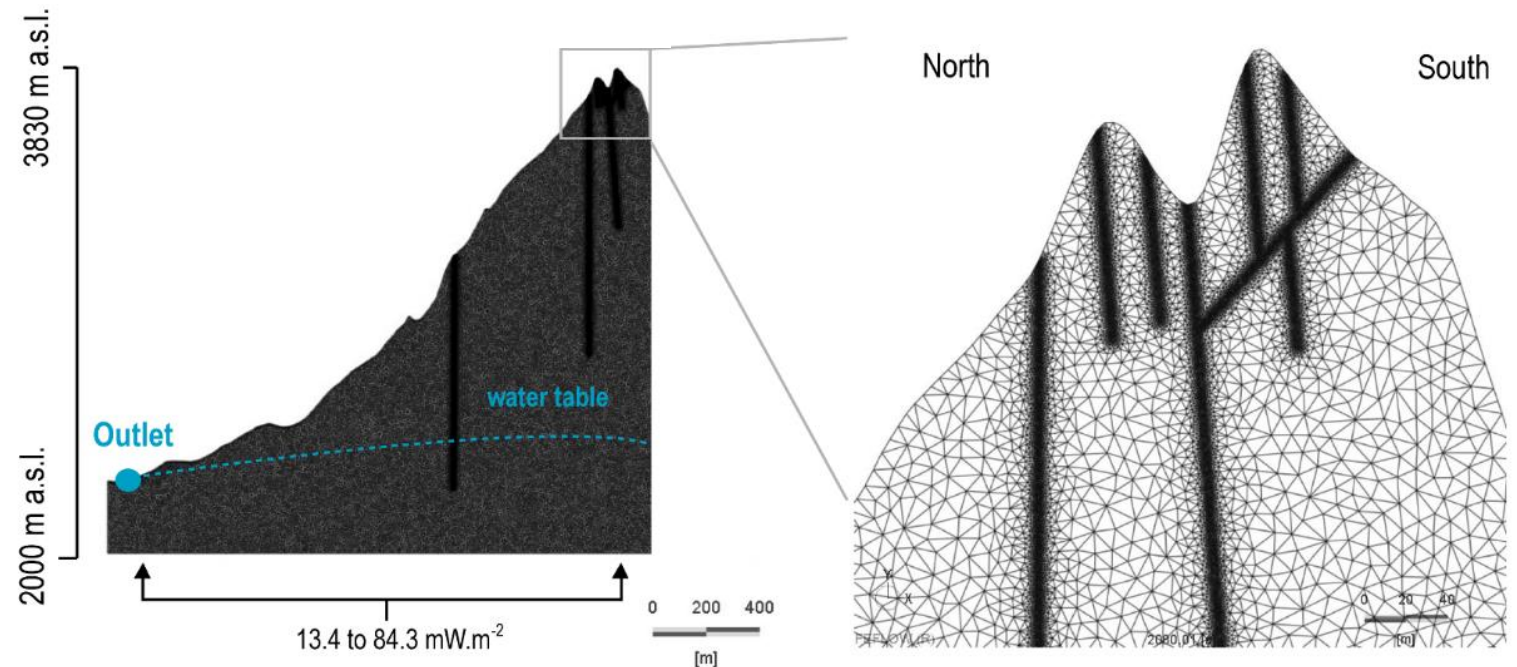
# Coupling thermal and hydrological processes

1. Extending the model down to a water outlet
2. Designing main water pathways
3. Initializing the water table (unfrozen conditions) for unsaturated cases-studies
4. Simulating water and heat transfers using the Darcy law calculating first water flow velocity that is then integrated in the dispersive-diffusive the heat transport equation
5. Simulating laminar water flows in fractures (Hagen-Poiseuille law)



Simulations are run using the Feflow<sup>®</sup> program

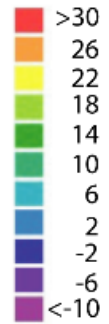
*Magnin and Josnin, 2021*



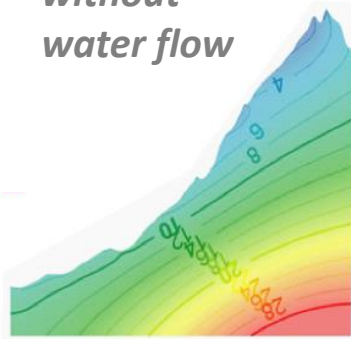
# Thermal implications of water flows in frozen bedrock: 4 cases-studies

After initialization  
(thawed conditions)

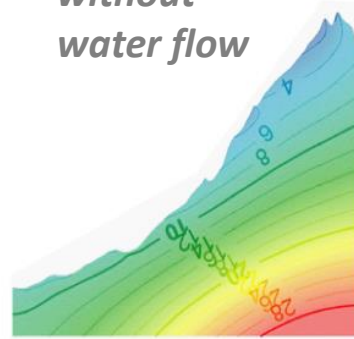
Temperature (°C)



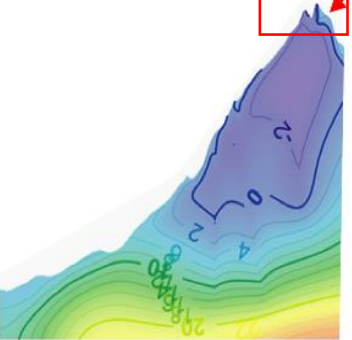
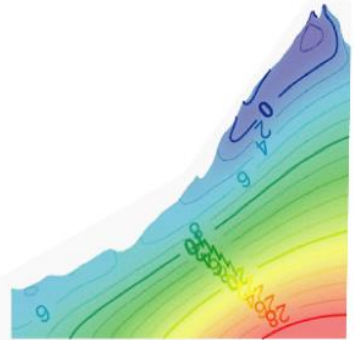
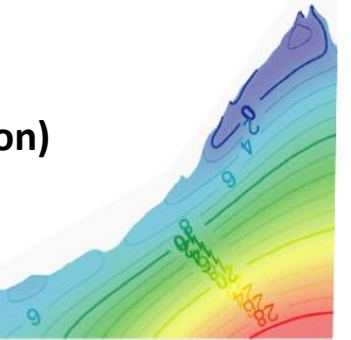
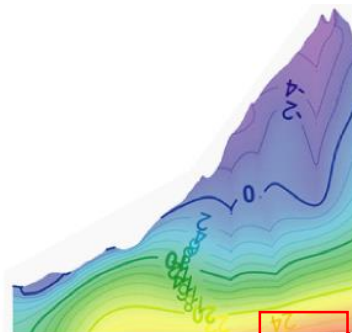
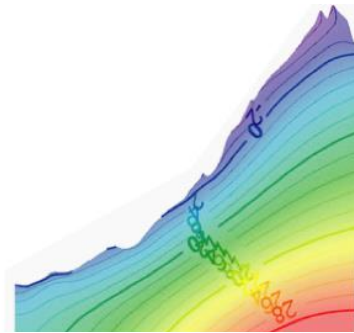
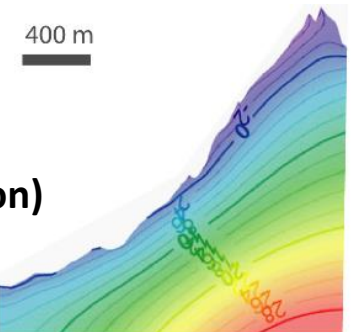
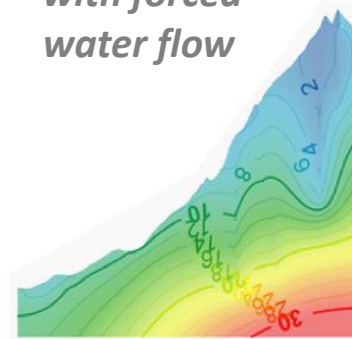
1. Saturated without water flow



2. Unsaturated without water flow



3. Saturated with forced water flow



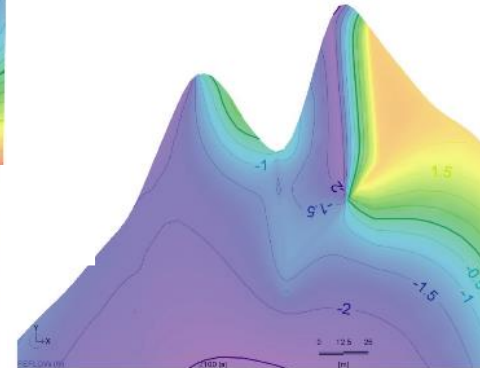
Water flows into rockwall fractures strongly affect the freezing and thawing patterns:

→ Temperature gradients are greater

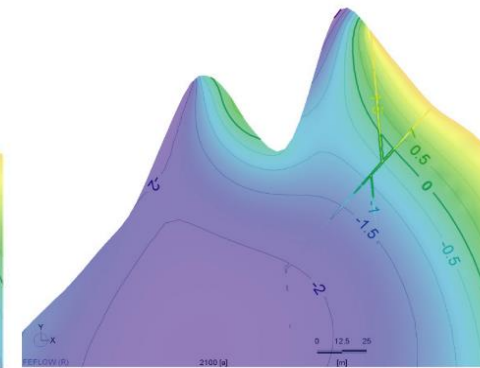
→ Permafrost forms deeper

→ Thawing is enhanced in saturated fractures (thawing corridors) and surrounding saturated rock medium (thawing wedges)

3. Saturated with forced water flow



4. Unsaturated with forced water flows in saturated fractures



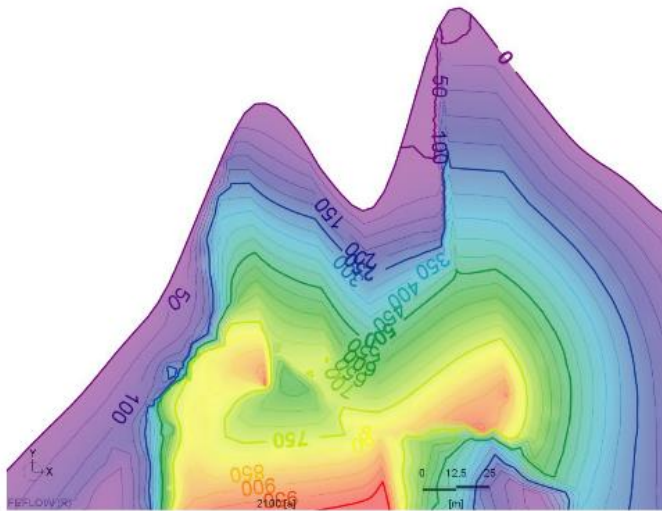
Temperature (°C)



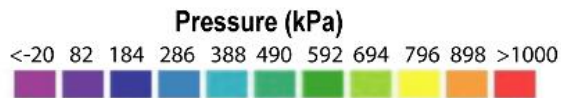
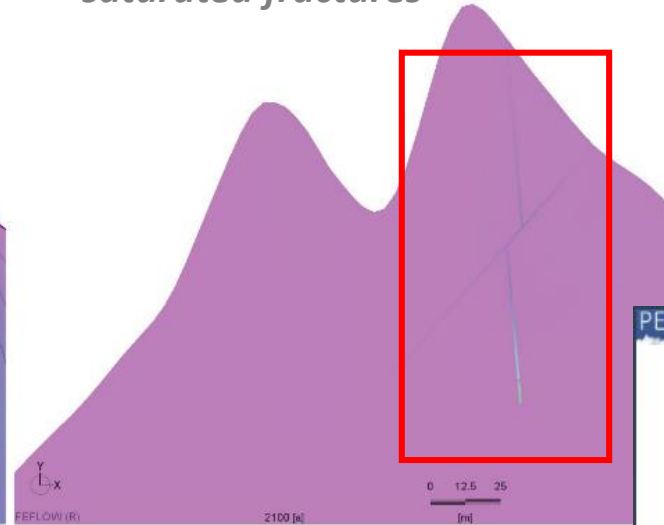


# Mechanical implications of water flows in frozen bedrock: 4 cases-studies

3. Saturated with forced water flow



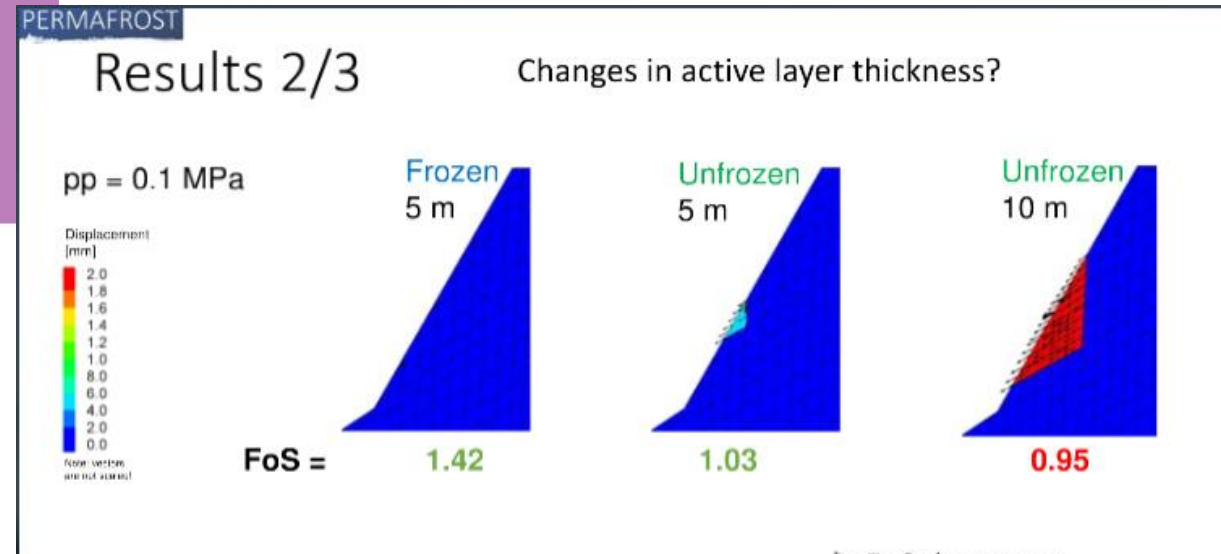
4. Unsaturated with forced water flows in saturated fractures



Magnin and Josnin, 2021

➔ Towards a coupling with mechanical models

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



- FoS decreases
- Unstable area grows

\*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>

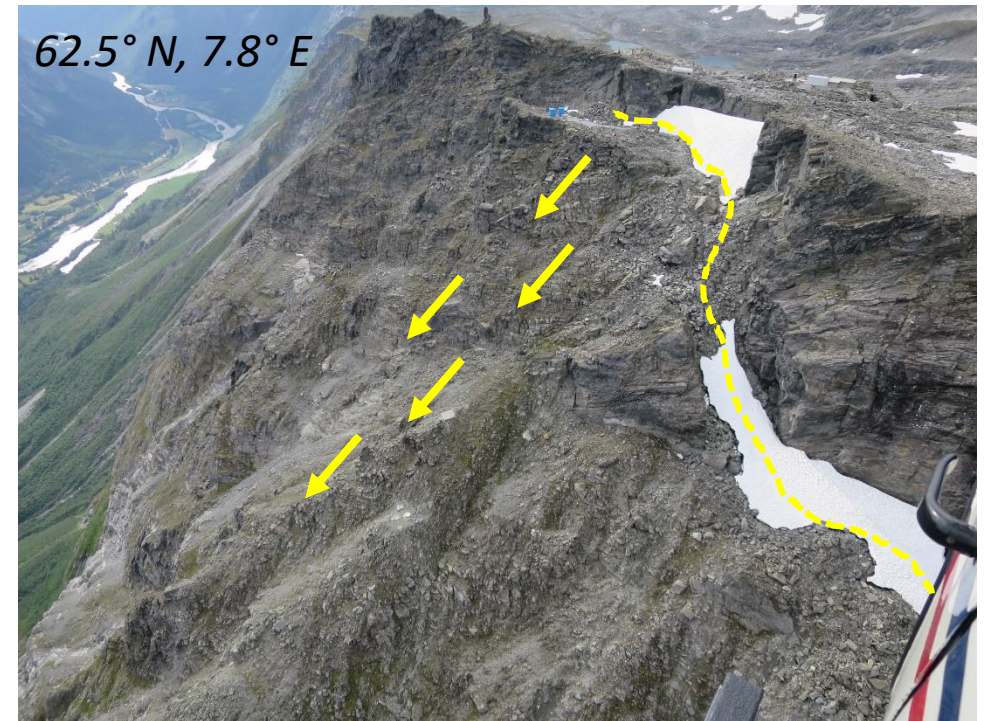
# Conclusions

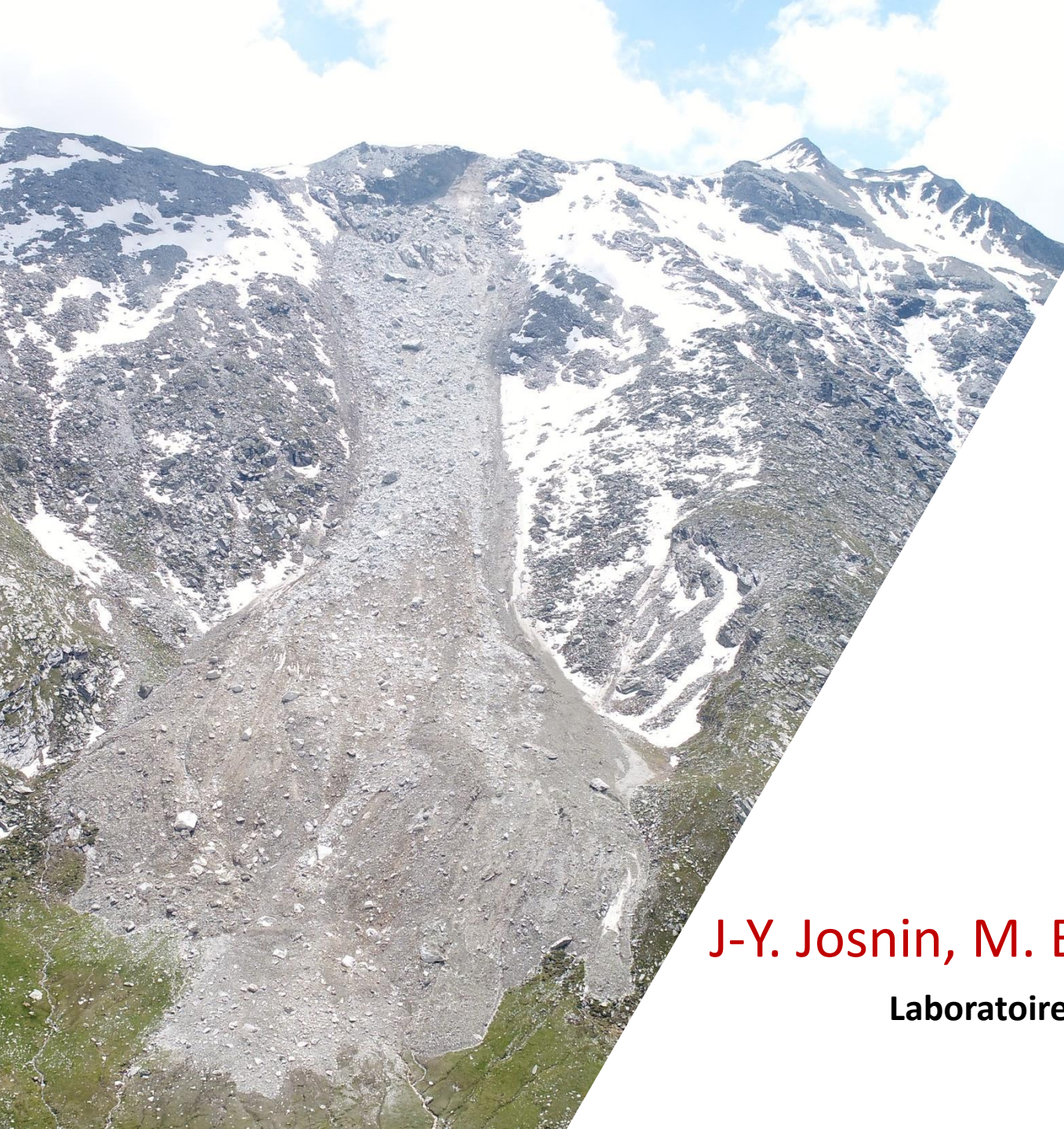
- We set up a numerical approach to couple thermal and hydrogeological processes in steep permafrost-affected rock slopes
- Results first invite to rethink our understanding of permafrost distribution and evolution
- Results confirm that water infiltration may accelerate permafrost degradation in the fractures (when saturated) and in the surrounding rock mass (when saturated as well)
- Results are highly promising to couple these thermo-hydro-geological models with mechanical models and improve our understanding of steep periglacial rock slope failure processes

## On-going work

- Running simulation at finer spatial and temporal scale (seasonal, active layer dynamics)
- Testing the sensitivity to fracture geometry (aperture, dipping...)
- Estimating realistic water quantities for infiltration (collaboration with University of Oslo using the Cryogrid 3 model).

**Sporadic to no-permafrost**  
**Mannen – 1300 m a.s.l** *(Etzelmüller et al., 2022)*





*Thank you for your attention*

*Any Questions ?*

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# Permafrost degradation and rock slides

Mannen – 1300 m a.s.l

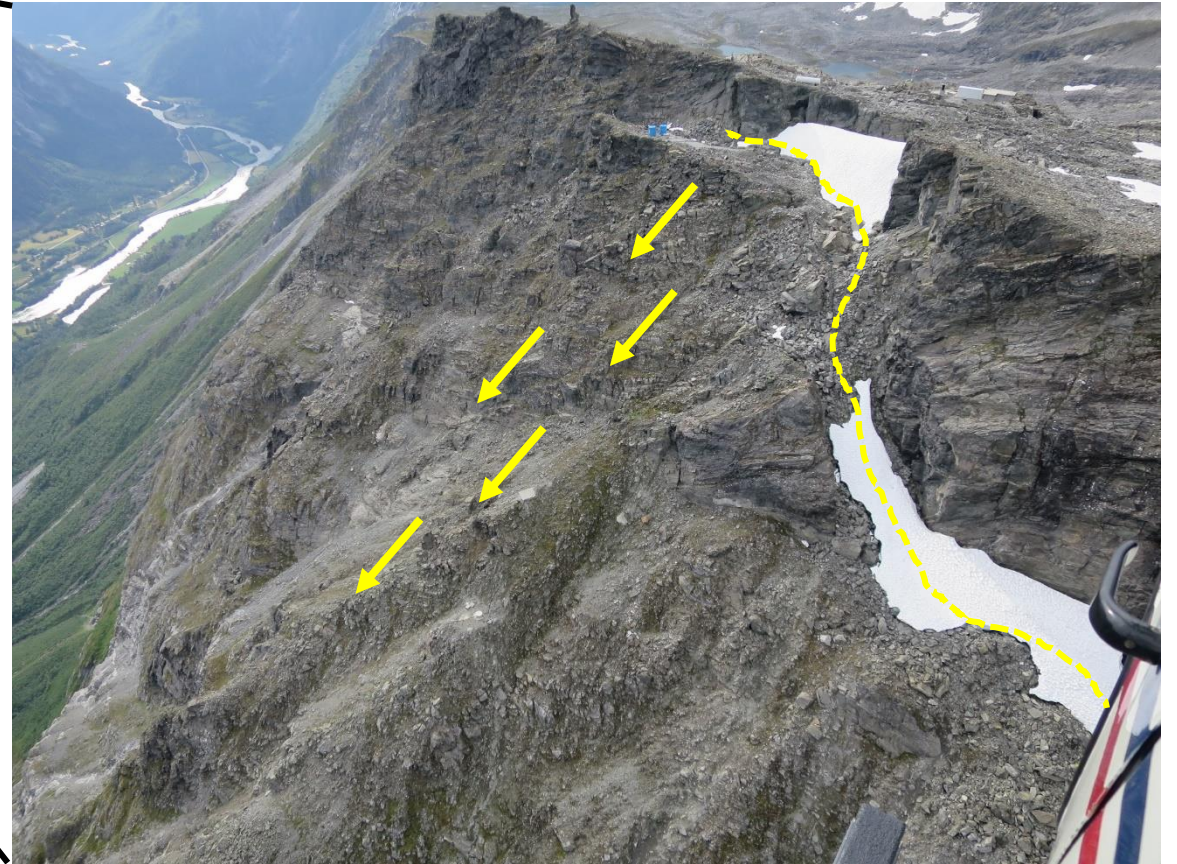
62.5° N, 7.8° E

Fell in Sept. 2019

2.5 mm a<sup>-1</sup>

5 mm a<sup>-1</sup>

Sporadic to no-permafrost  
(Etzelmüller et al., 2022)



**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?**

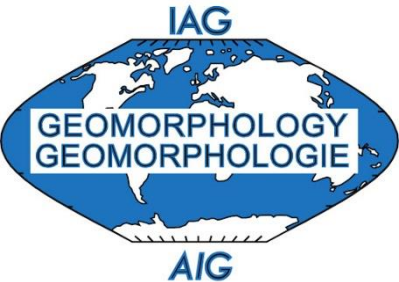
- A significant statistical relationship was clearly established between rock temperature dynamics and rockfall occurrence.
- The high uncertainty in the simulated temperature field points out the need to use a greater rockfall sample
- The little temperature difference between real rockfalls and random 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**



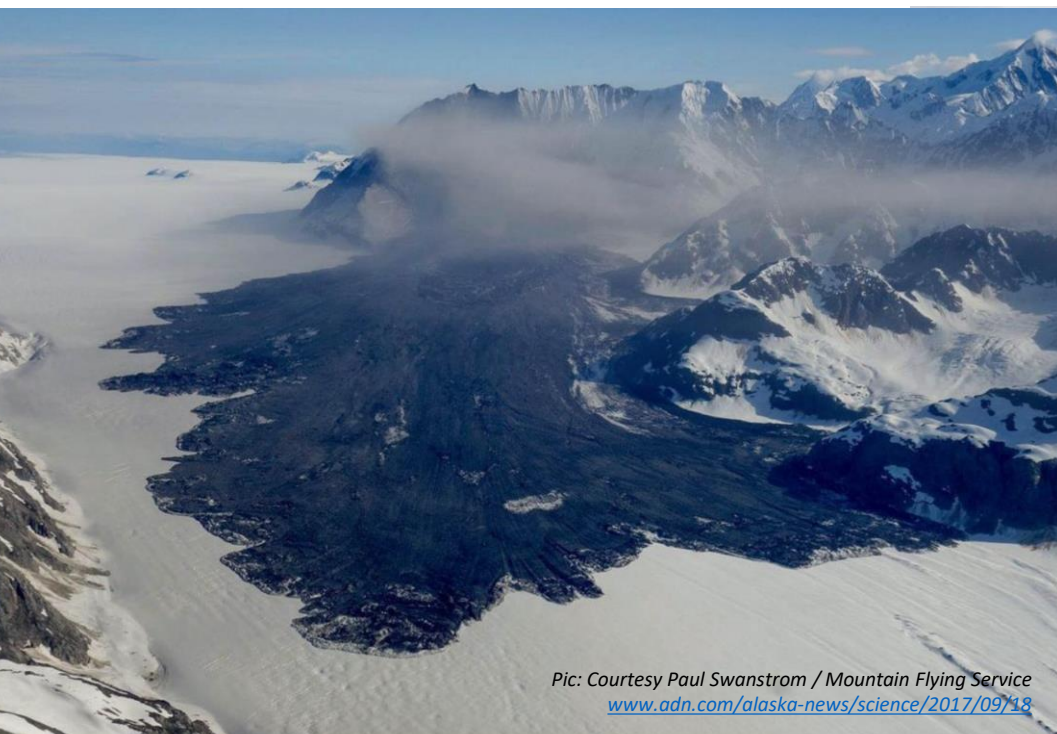
## ***Modeling Rockwall Permafrost to Understand Periglacial Rock Slope Failures***

**Thank you for your attention!**  
**AG, March, 2<sup>nd</sup>, 2021**

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

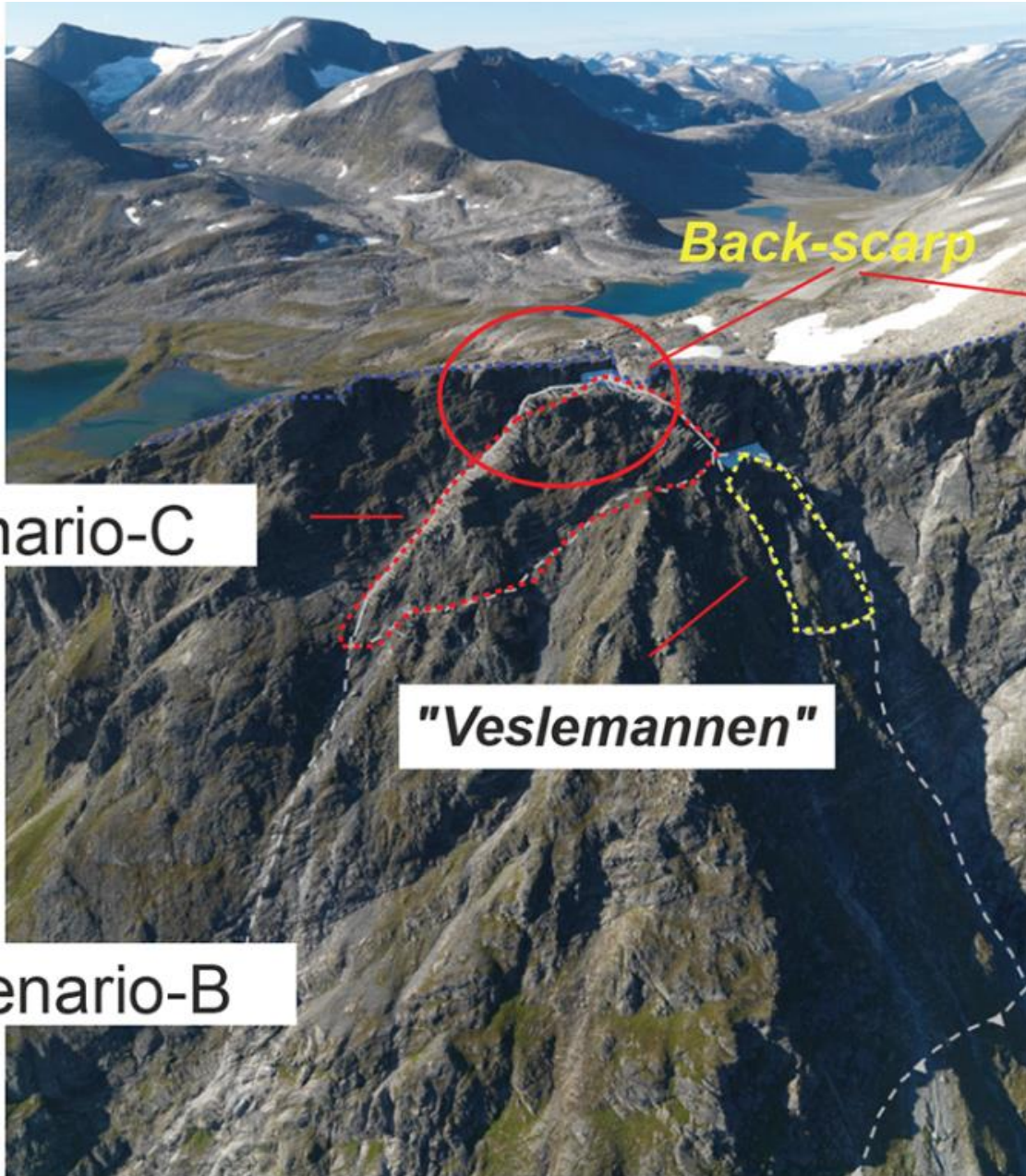


Pic : J-C Bèche



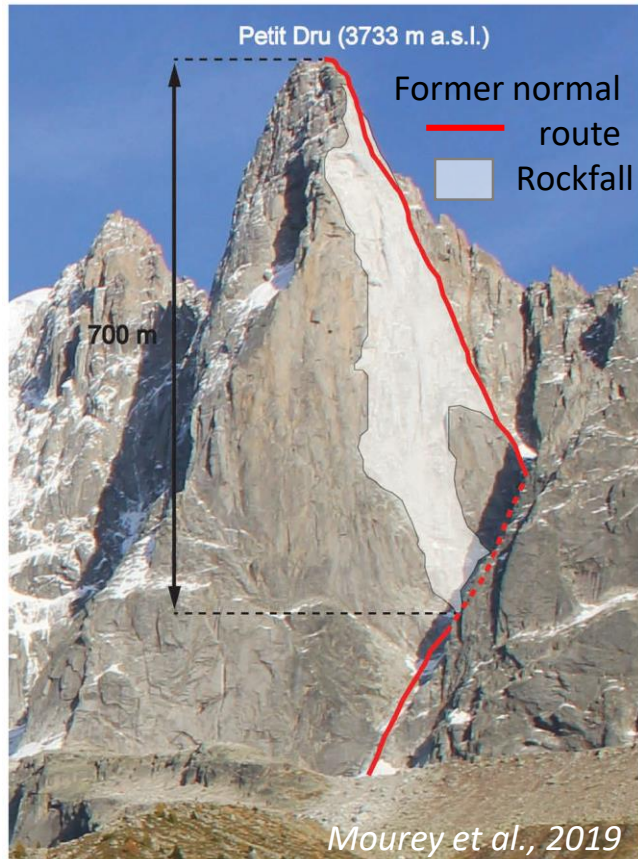
[www.geopraevent.ch](http://www.geopraevent.ch)  
Source : Scoria hut

*The same hypotheses might be true for rock slides and talus failure*



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

## Change in mountain practices and professional guiding activities

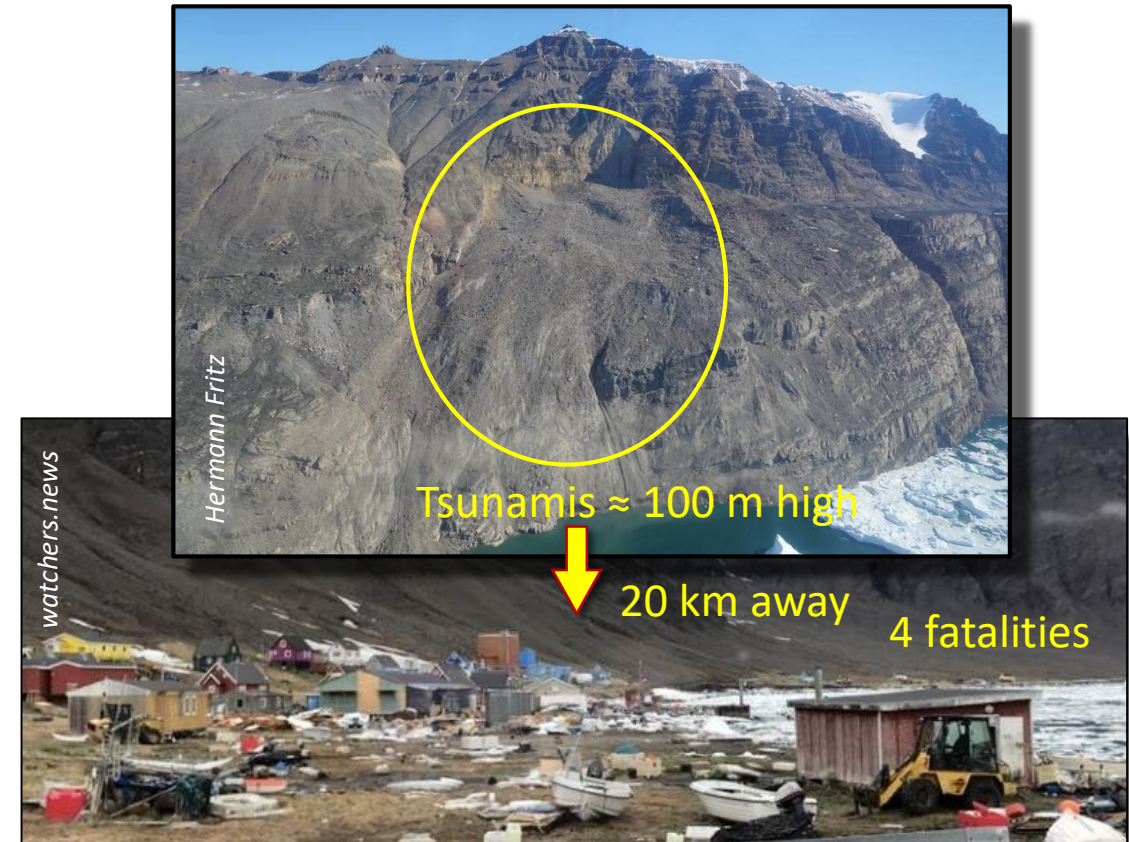


## Piz Cengalo rock avalanche Switzerland- August 2017



## Chain reaction processes with far-reaching impacts

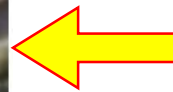
### Rock avalanche in Karrat Fjord - Greenland – June 2017





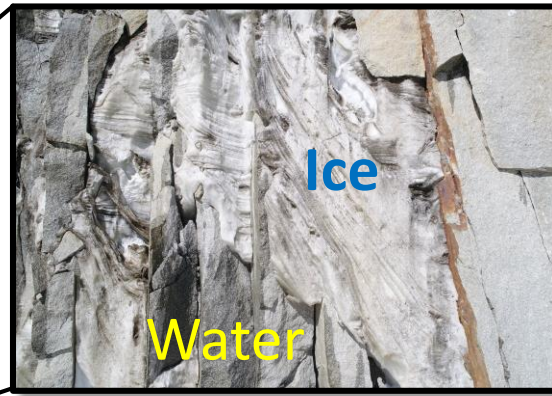
# Periglacial rock slope failures are increasing and impact Alpine and Arctic communities

Chamoli rock-ice avalanche—  
February 2021

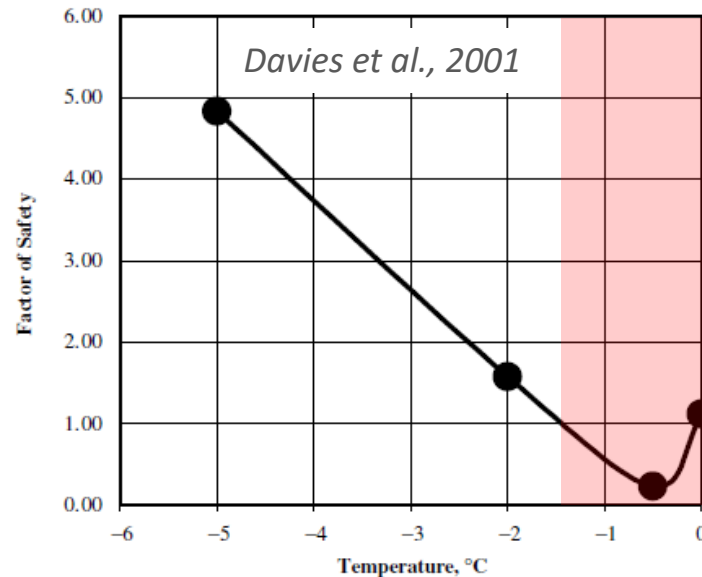


# Permafrost degradation is most likely responsible for these increasing destabilisations

The Trident du Tacul rock fall  
sep. 26<sup>th</sup>, 2018

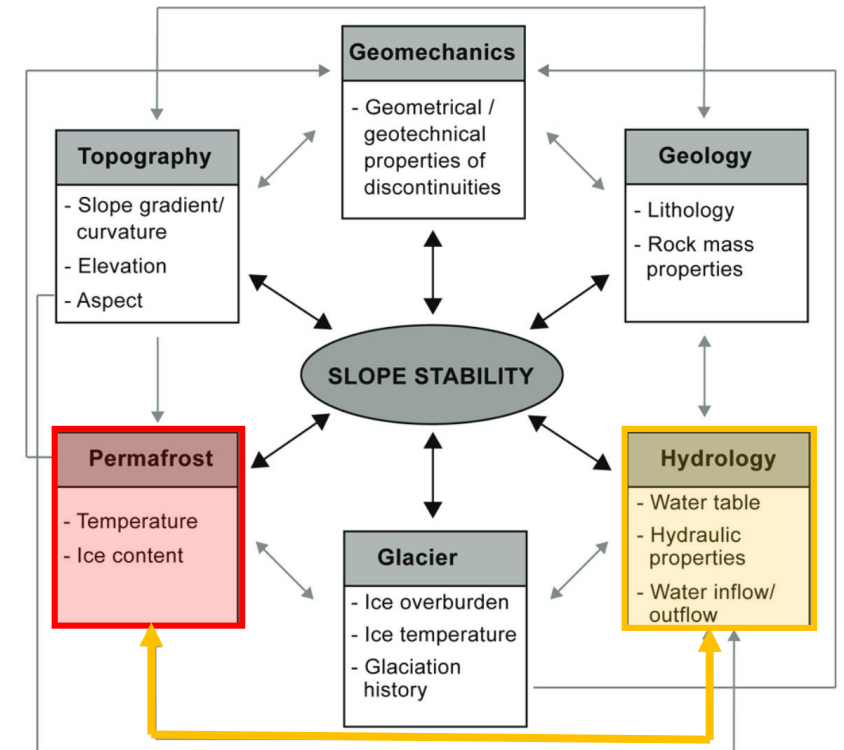


Shear resistance of an ice-filled joint  
between bedrock compartments



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

# Permafrost degradation favors rock slope failure

Etache – 3100 m a.s.l  
Occurred June 2020



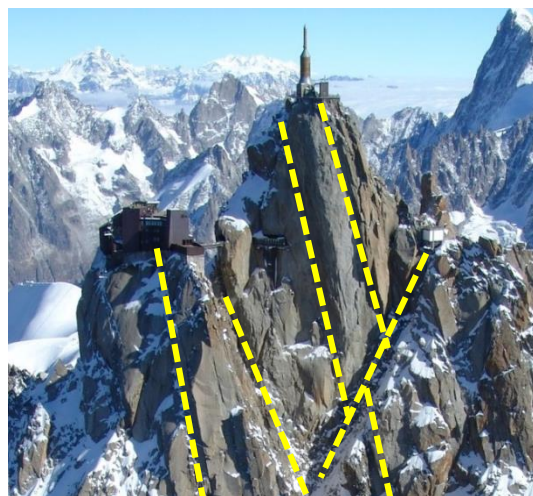
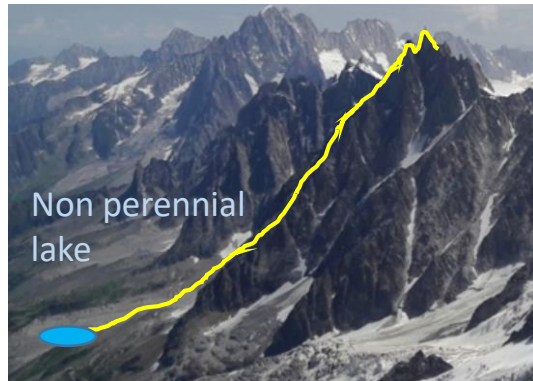
**Main hypothesis:** The warming and melting of ice-filled fracture triggers rock slope failure (decreasing shear resistance, loss of ice-rock bonding).

**Additional hypothesis:** Water infiltration accelerates permafrost degradation and ice-joints erosion and/or provokes high hydrostatic pressures

# 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

