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PREDISPOSING, TRIGGERING AND RUNOUT CONDITIONS OF TWO ROCK SLOPE FAILURES IN THE FRENCH ALPS: ÉTACHE VALLEY AND CRÊTE DES GRANGETTES

Maëva Cathala, Josué Bock, Laurent Astrade, Matan Ben-Asher, Xavier Bodin, Guillaume Chambon, Deline Philip, Thierry Faug, Kim Génuite, Stéphane Jaillet, et al.

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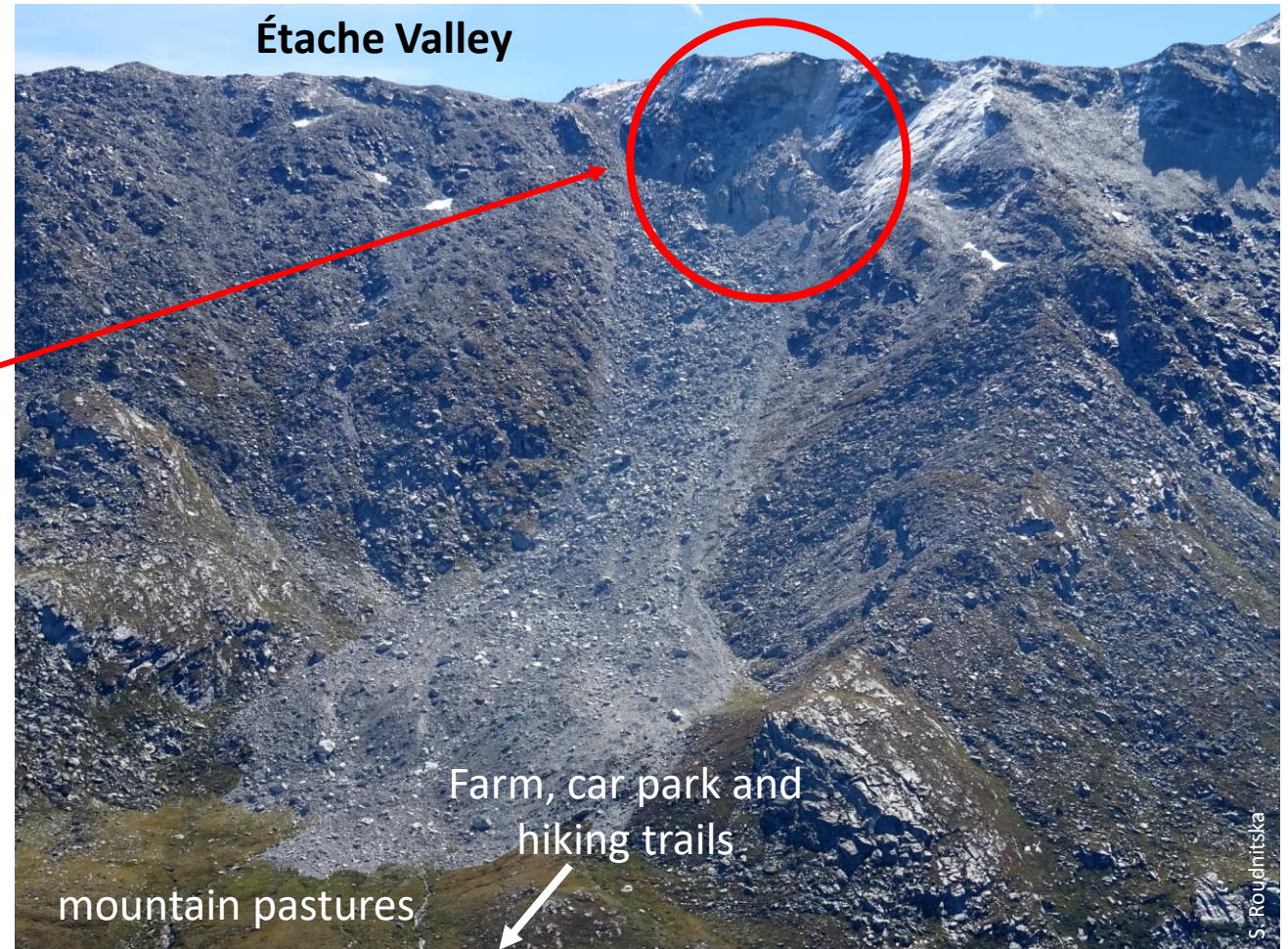
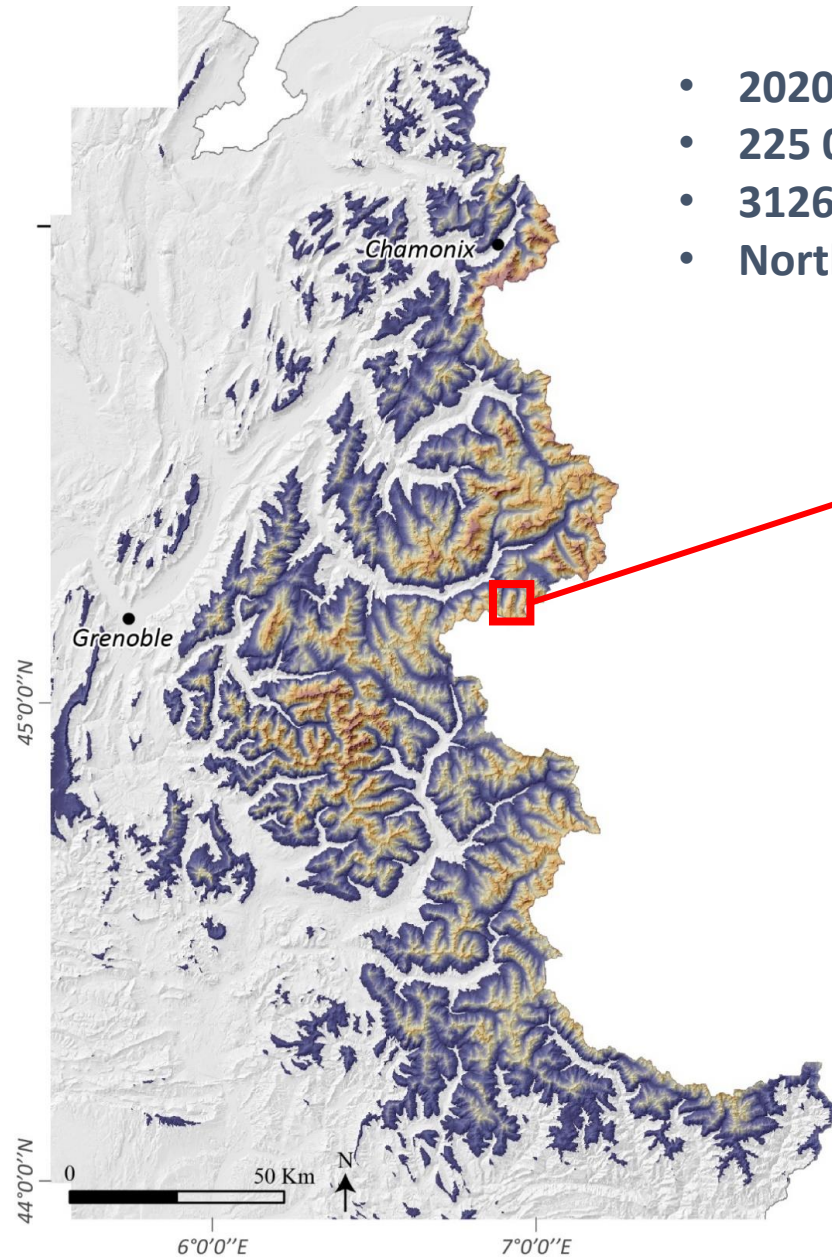
PREDISPOSING, TRIGGERING AND RUNOUT CONDITIONS OF TWO ROCK SLOPE FAILURES IN THE FRENCH ALPS: ÉTACHE VALLEY AND CRÊTE DES GRANGETTES



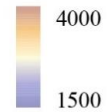
Authors: Cathala M., Bock J., Abdulsamad F., Astrade L., Ben Asher M., Bodin X., Chambon G., Deline P., Faug T., Génuite K., Jaillet S., Josnin J-Y., Ravanel L., Revil A., Richard J., Verroust F., Magnin F.

CONTEXT AND STUDY SITES

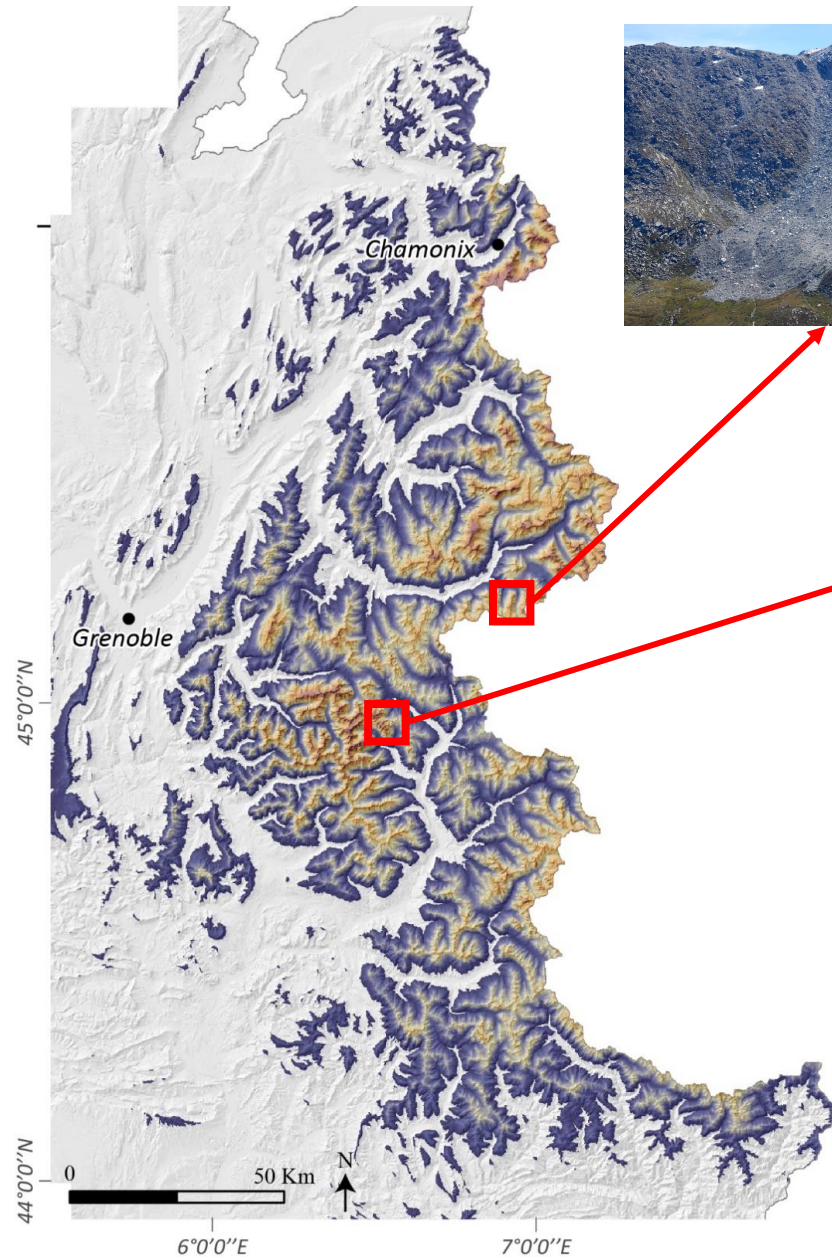
- 2020 June 18
- 225 000 m³
- 3126 m
- North West face



Altitude (m a.s.l.)



CONTEXT AND STUDY SITES

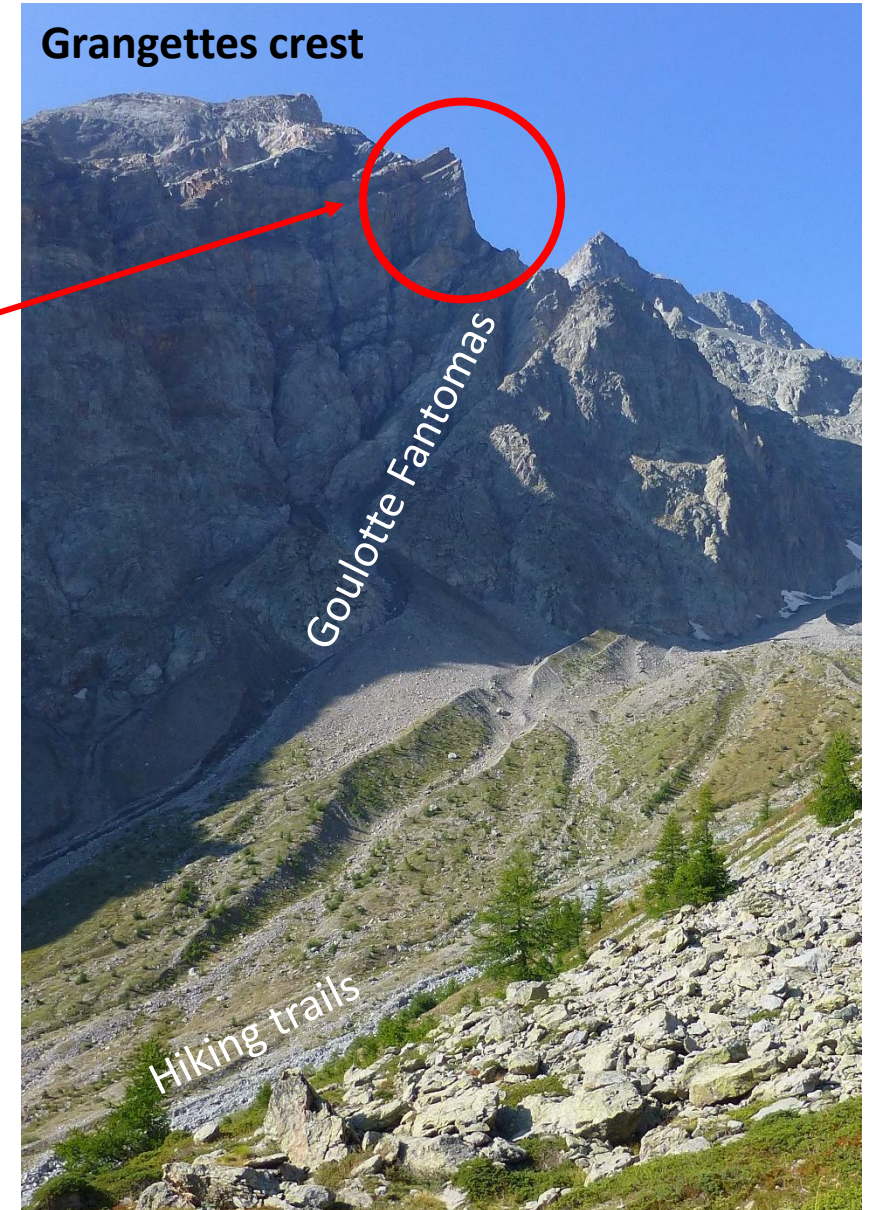


Étache Valley

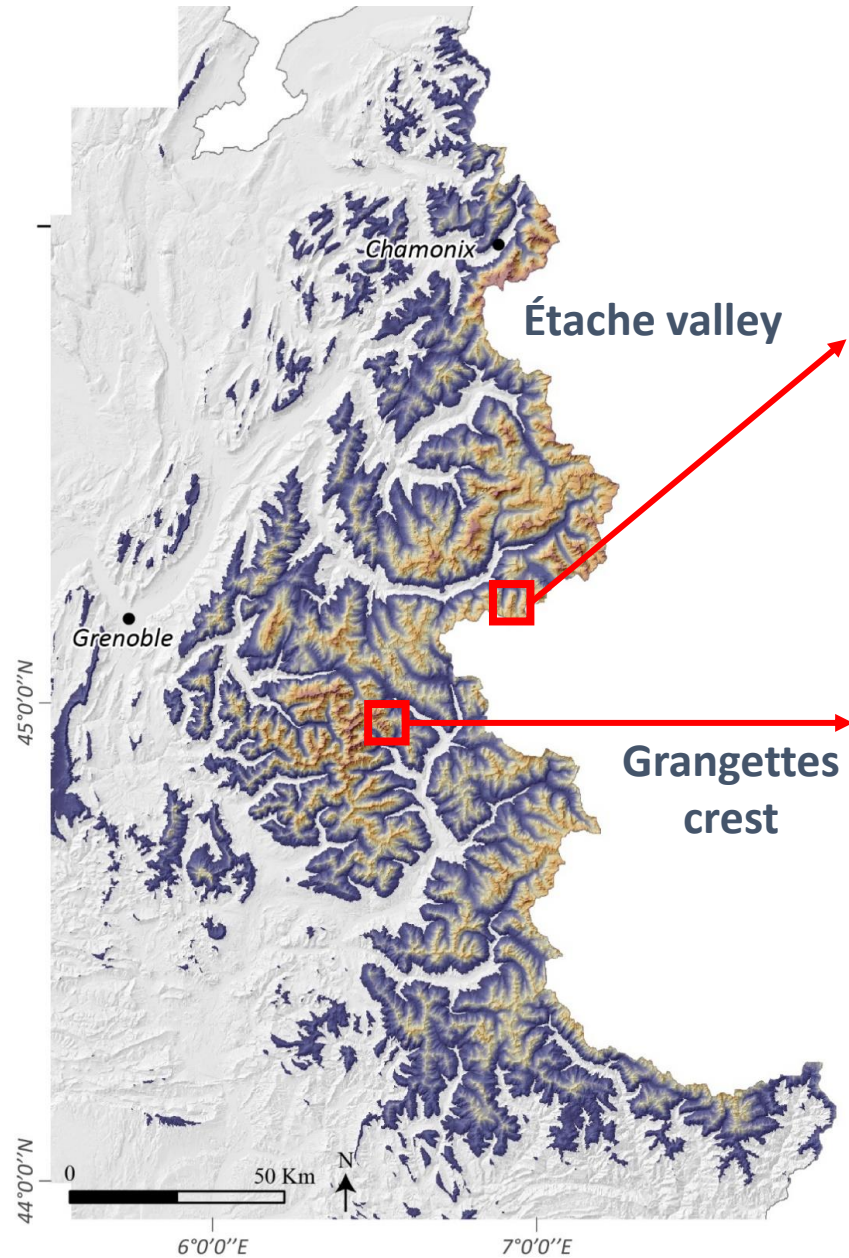


- **2020 September 17 (35 800 m³)**
- 2020 December 20 (220 000 m³)
- 2021 July 23 (unknow volume)
- 3080 m
- North face

Grangettes crest



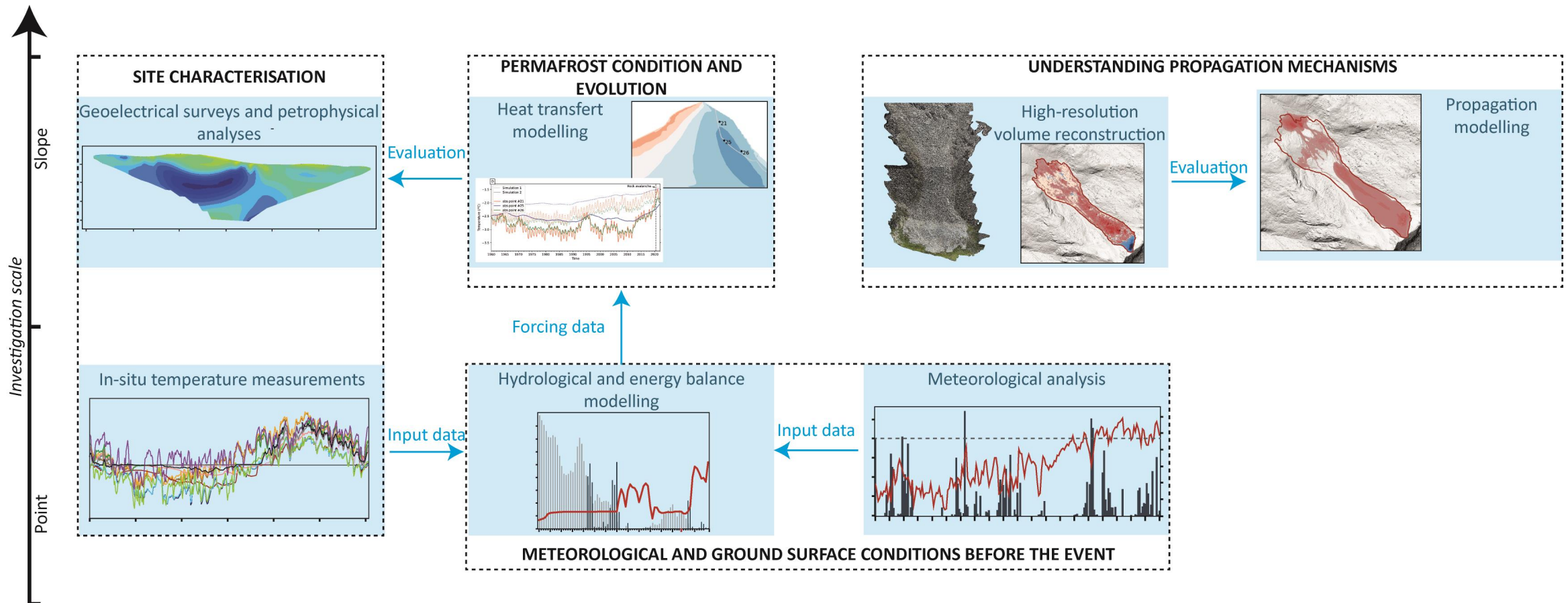
CONTEXT AND STUDY SITES



Role of permafrost in the triggering mechanisms?

METHODS

Combining methods to improve fundamental knowledge of the processes involved in the **predisposition**, **triggering** and **propagation** of rockfalls and rock avalanches in **permafrost-affected steep slopes**



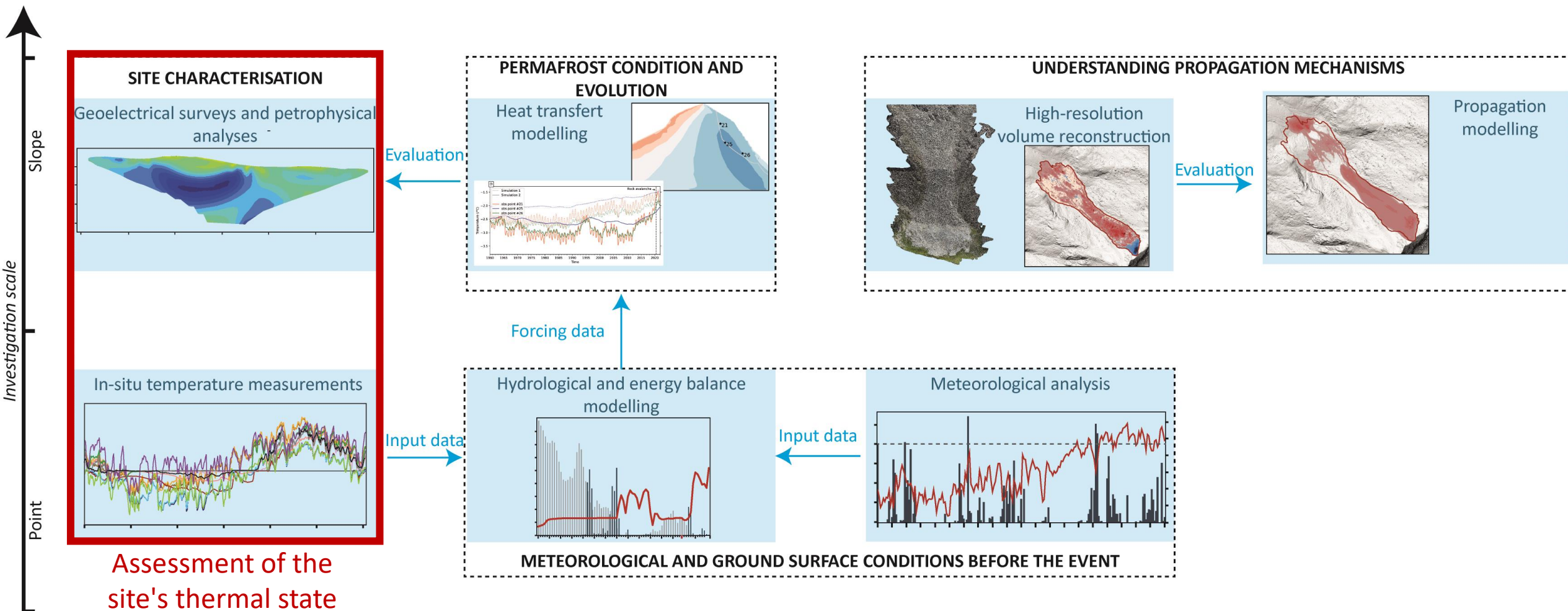
RESULTS & DISCUSSIONS

1) Thermal conditions

2) Meteorological / hydrological factors

3) Spatial and temporal evolution of permafrost

4) Propagation mechanisms



RESULTS & DISCUSSIONS

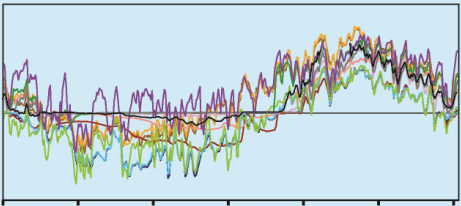
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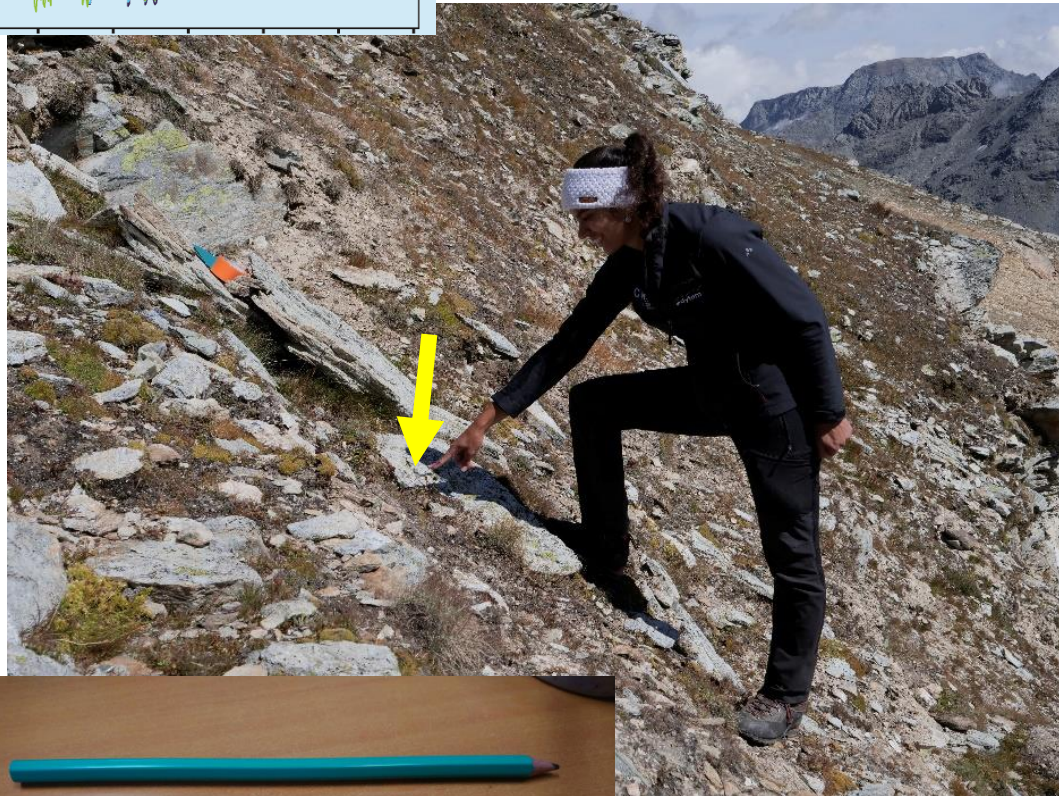
In-situ temperature measurements



ASSESSMENT OF THE SITE'S THERMAL STATE

Ground Surface Temperature - c. 10 cm depth – 1 measurement /hour

Gentle slope



Possible snow accumulation



Rockwall



Direct contact with the atmosphere

RESULTS & DISCUSSIONS

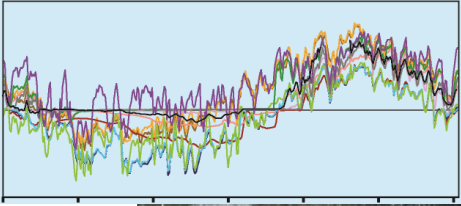
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In-situ temperature measurements



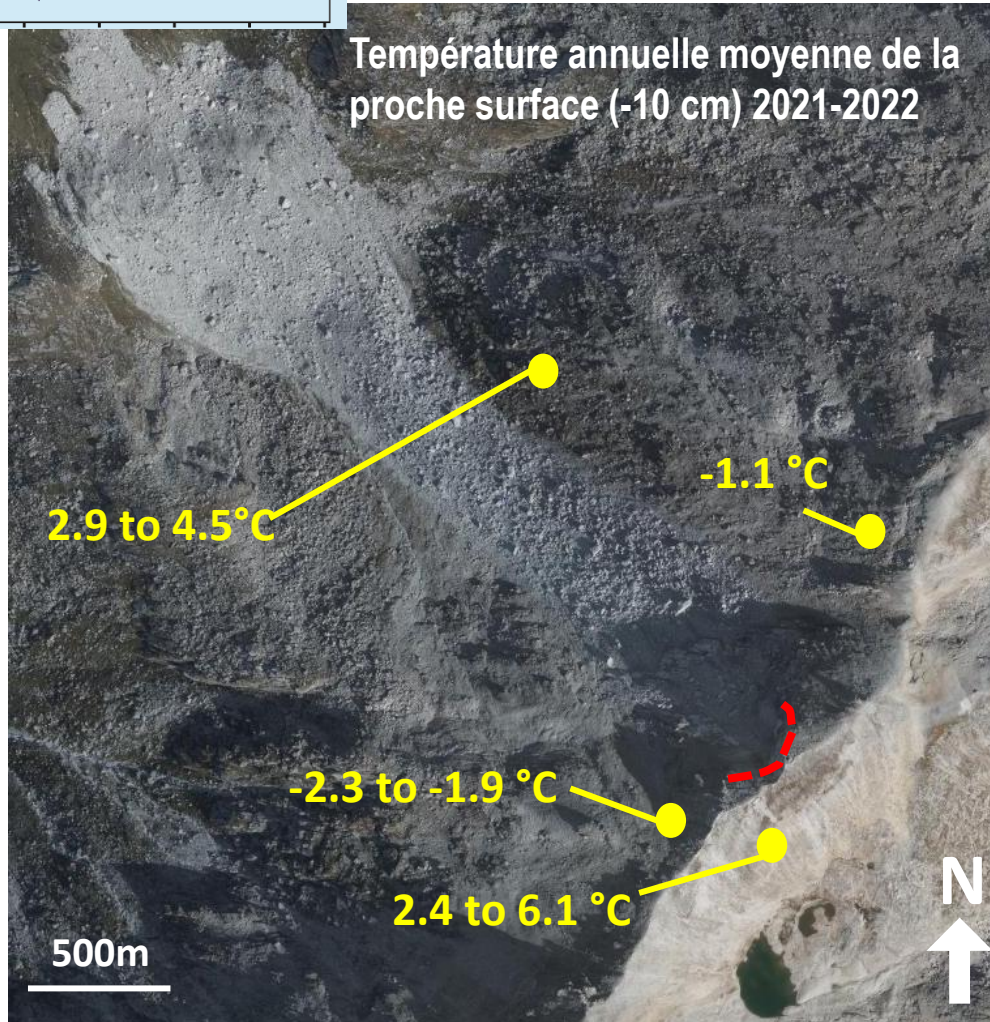
ASSESSMENT OF THE SITE'S THERMAL STATE

Ground Surface Temperature

Étache Valley



Température annuelle moyenne de la proche surface (-10 cm) 2021-2022



→ Favourable conditions for permafrost occurrence on the north face, ≠ south face

RESULTS & DISCUSSIONS

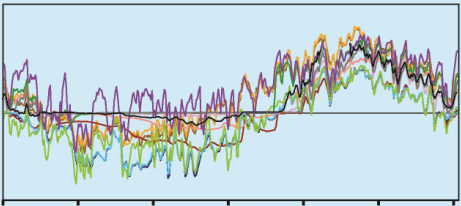
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In-situ temperature measurements



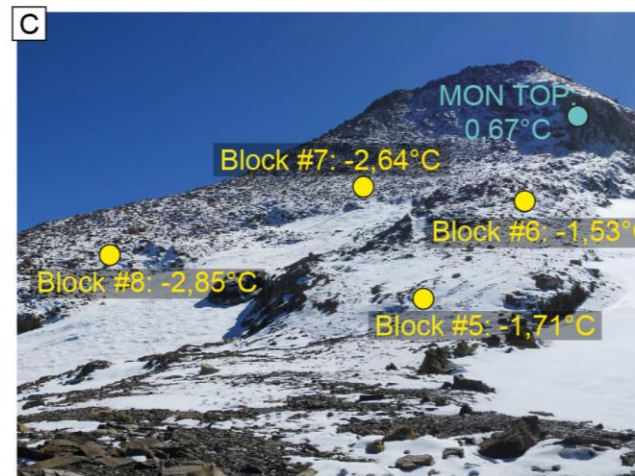
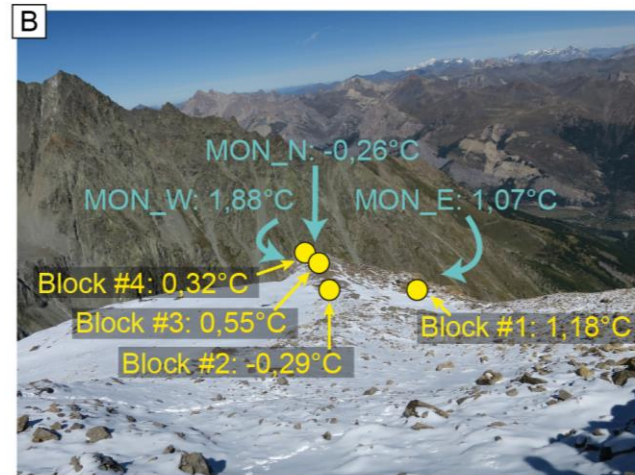
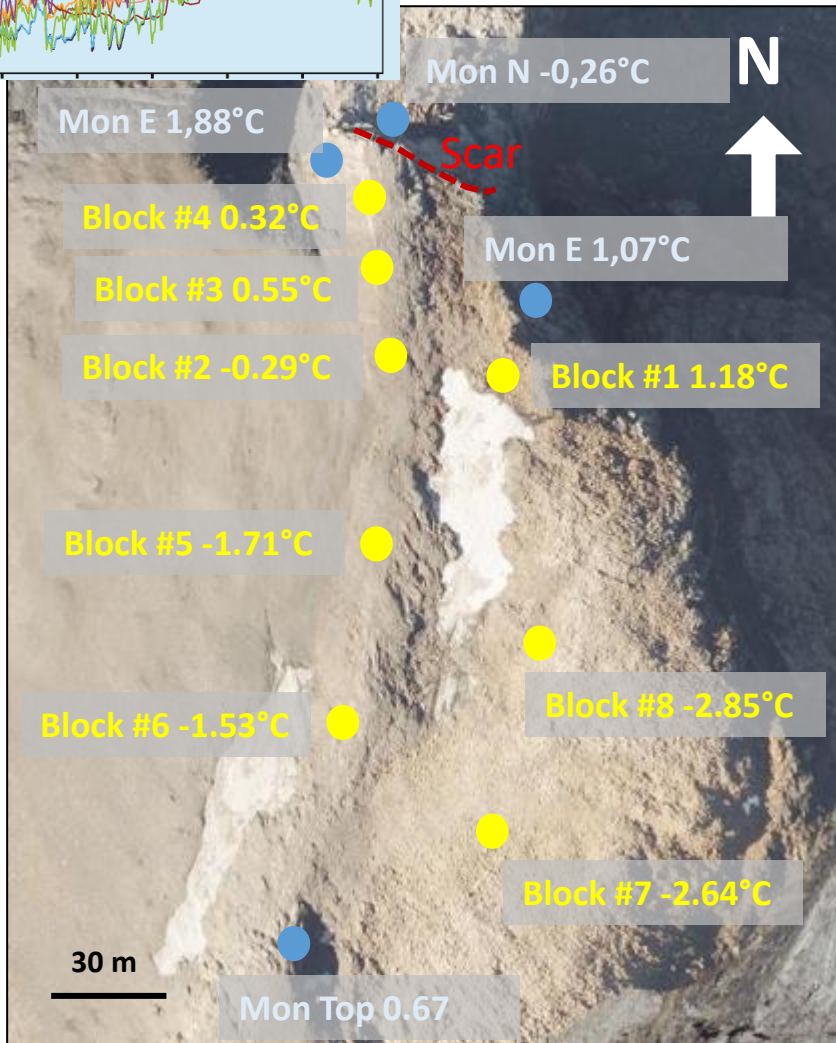
ASSESSMENT OF THE SITE'S THERMAL STATE

Ground Surface Temperature

Grangettes crest



Grangettes



→ Conditions favourable for permafrost occurrence on the north face and the crest (in superficial formations)

RESULTS & DISCUSSIONS

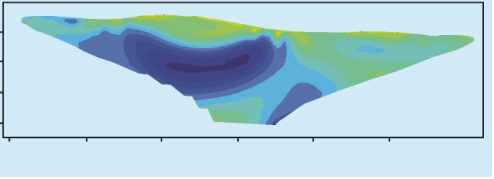
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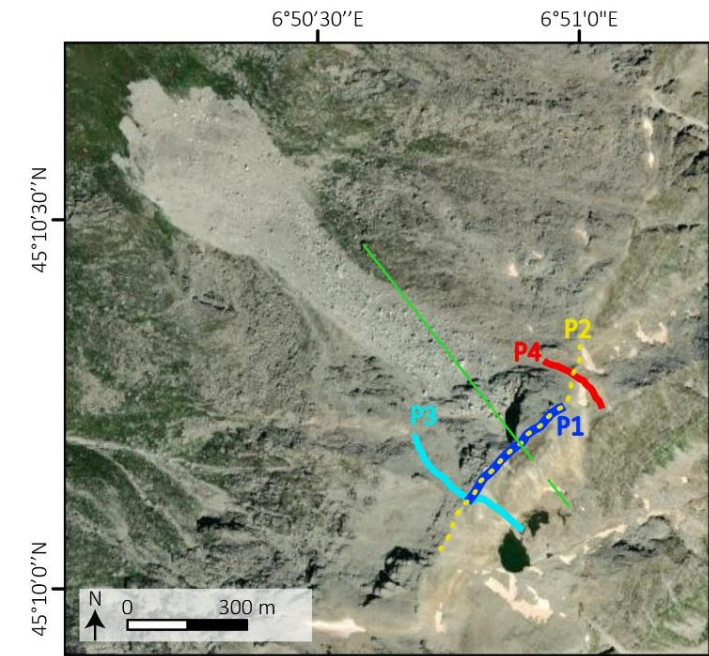
4) Propagation mechanisms

Goelectrical surveys and petrophysical analyses



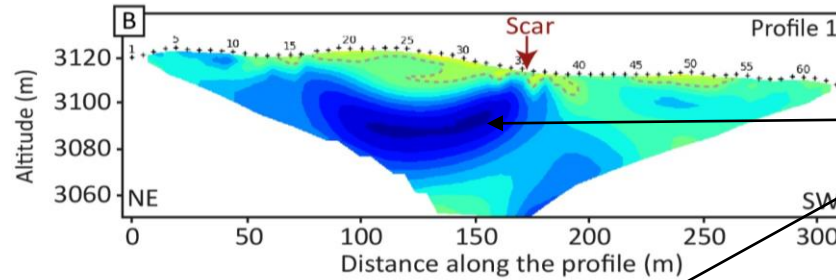
ASSESSMENT OF THE SITE'S THERMAL STATE

Geophysical survey Étache Valley

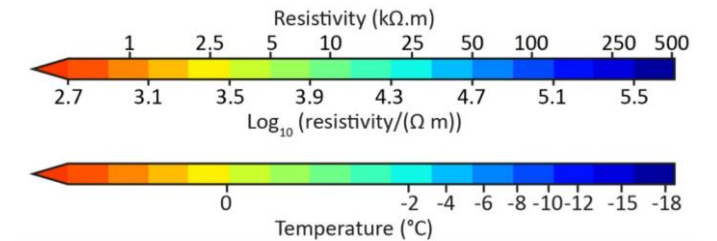
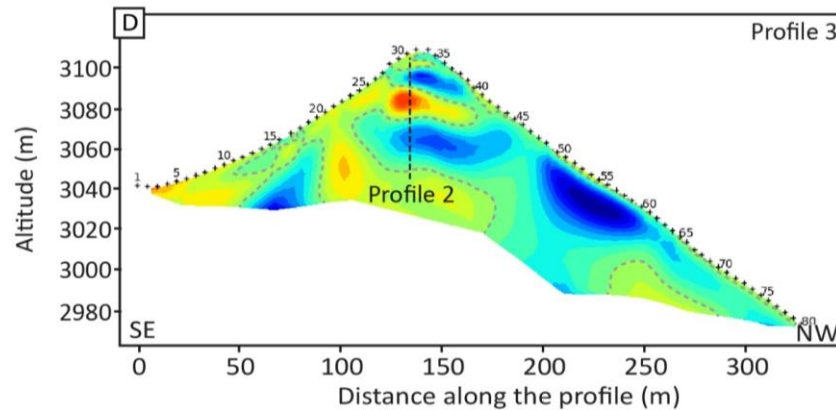
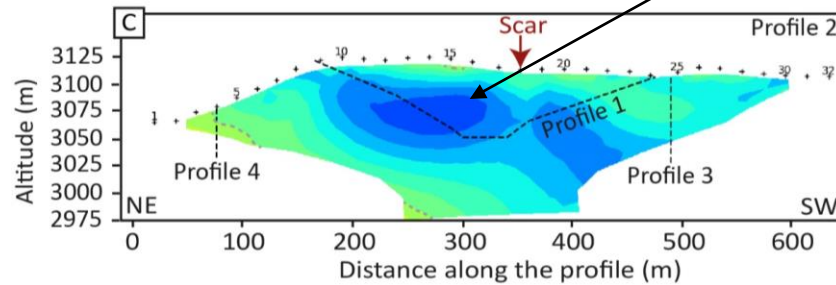


Profile P1-P3-P4 : 5m spacing between the electrodes

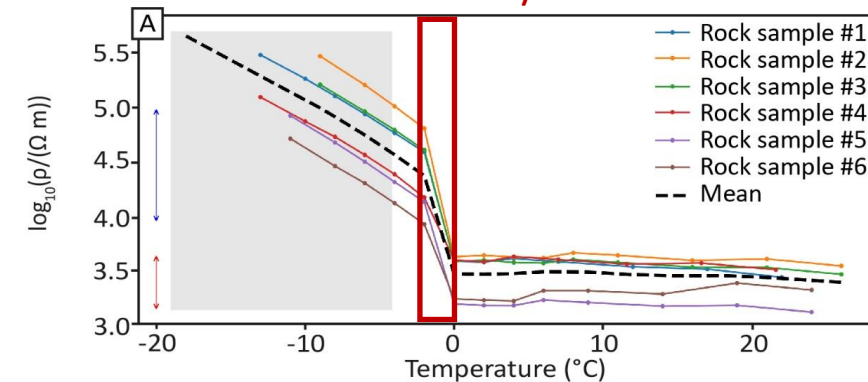
Profile P2 : 20m spacing between the electrodes



Permafrost



Transition freeze/no freeze



RESULTS & DISCUSSIONS

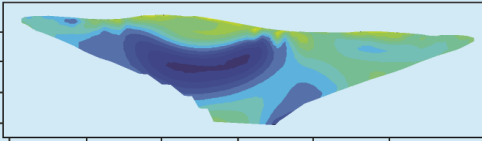
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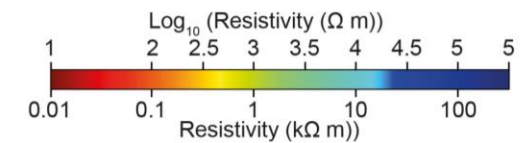
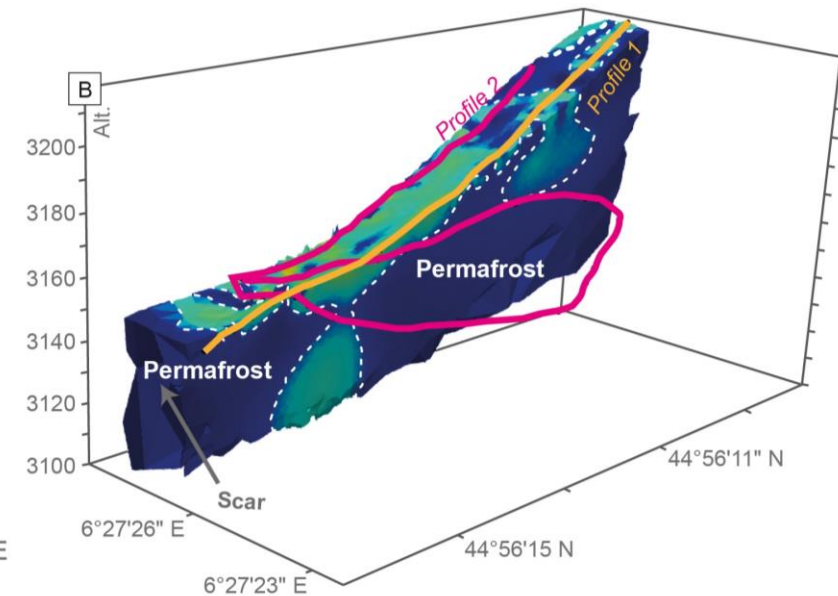
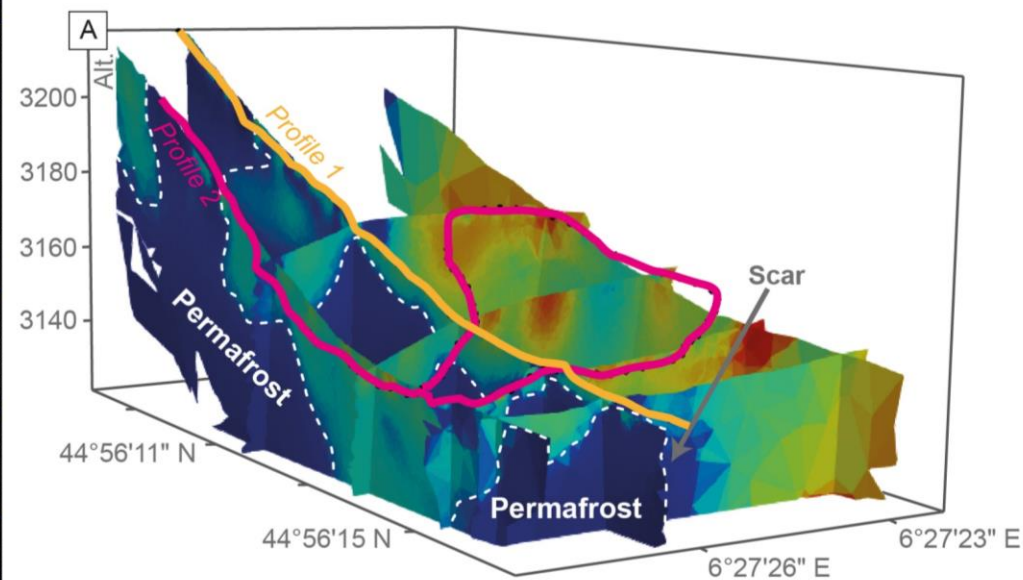
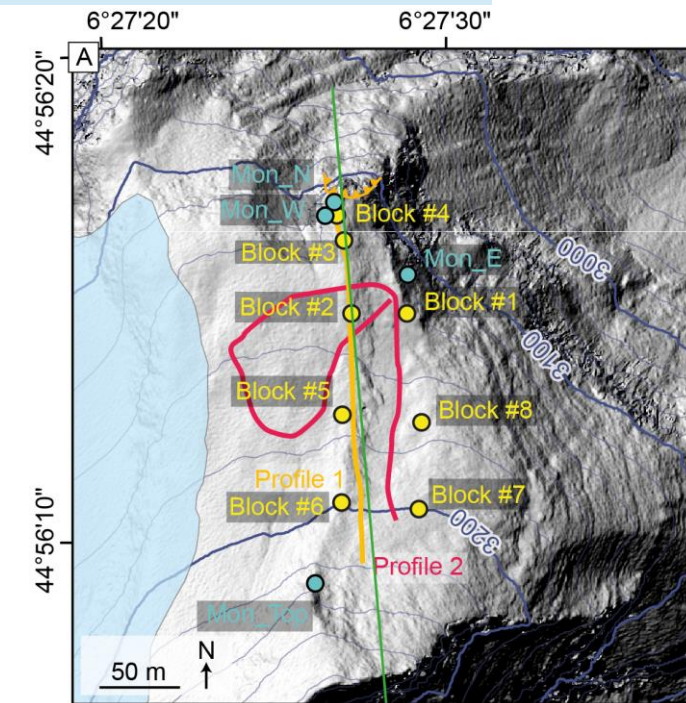
Goelectrical surveys and petrophysical analyses



ASSESSMENT OF THE SITE'S THERMAL STATE

Geophysical survey

Grangettes crest



Profile P1 : 240m - 5m spacing between the electrodes

Profile P2 : 400m - 20m spacing between the electrodes

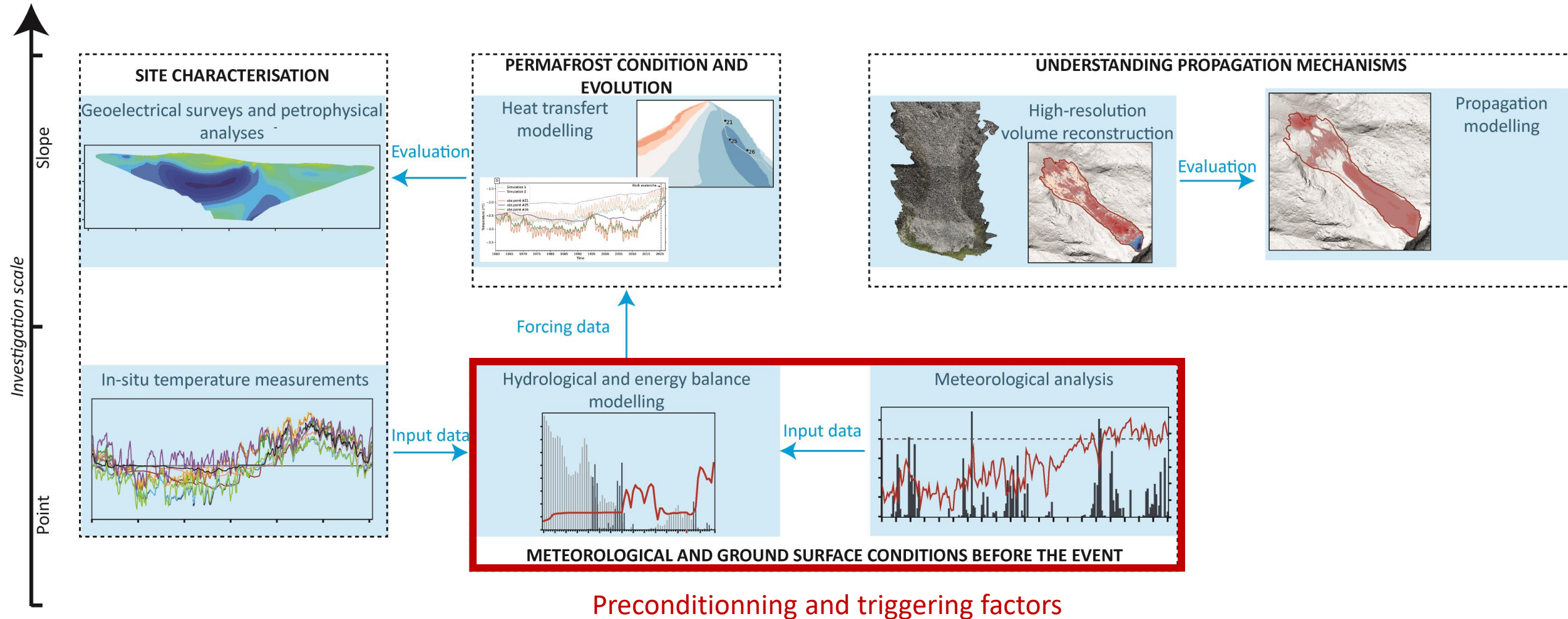
RESULTS & DISCUSSIONS

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RESULTS & DISCUSSIONS

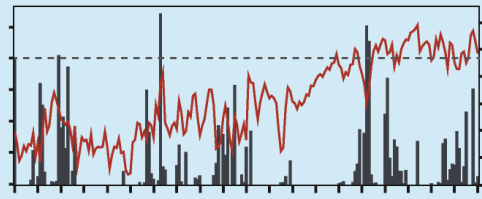
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Meteorological analysis



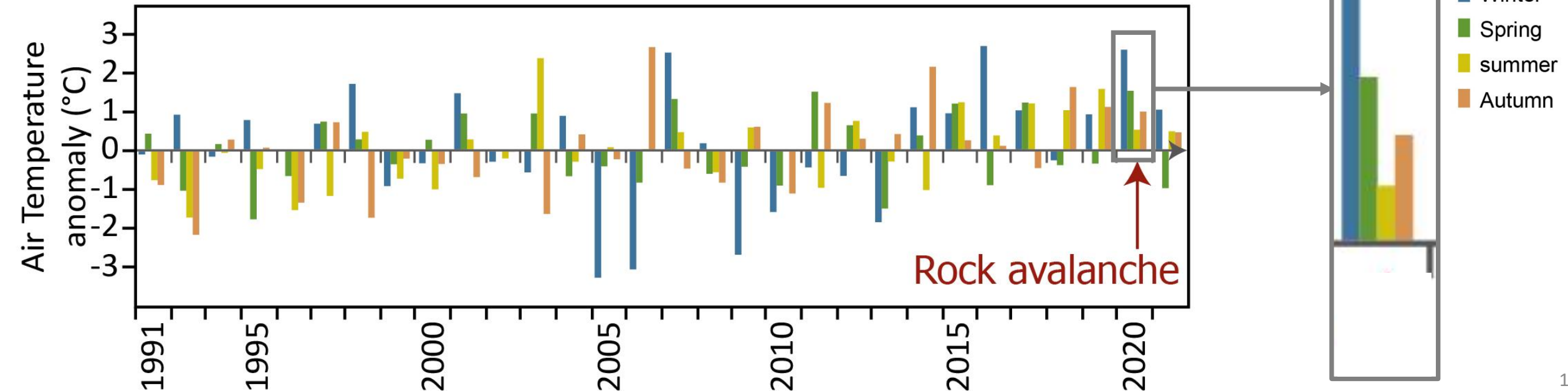
METEOROLOGICAL ANALYSIS

Étache Valley



Positive air temperature anomalies compared to 1991-2020:

- **Summer 2019** : +2.1°C (The 2nd warmest)
- **Winter 2020** : +2.9°C (The 2nd warmest)
- **Spring 2020** : +1.9°C (The warmest)



RESULTS & DISCUSSIONS

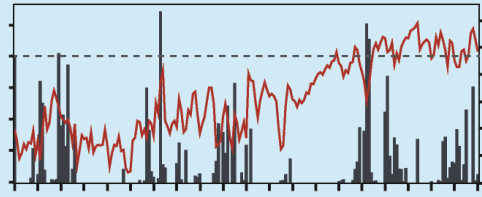
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Meteorological analysis



METEOROLOGICAL ANALYSIS

Étache Valley



Étache

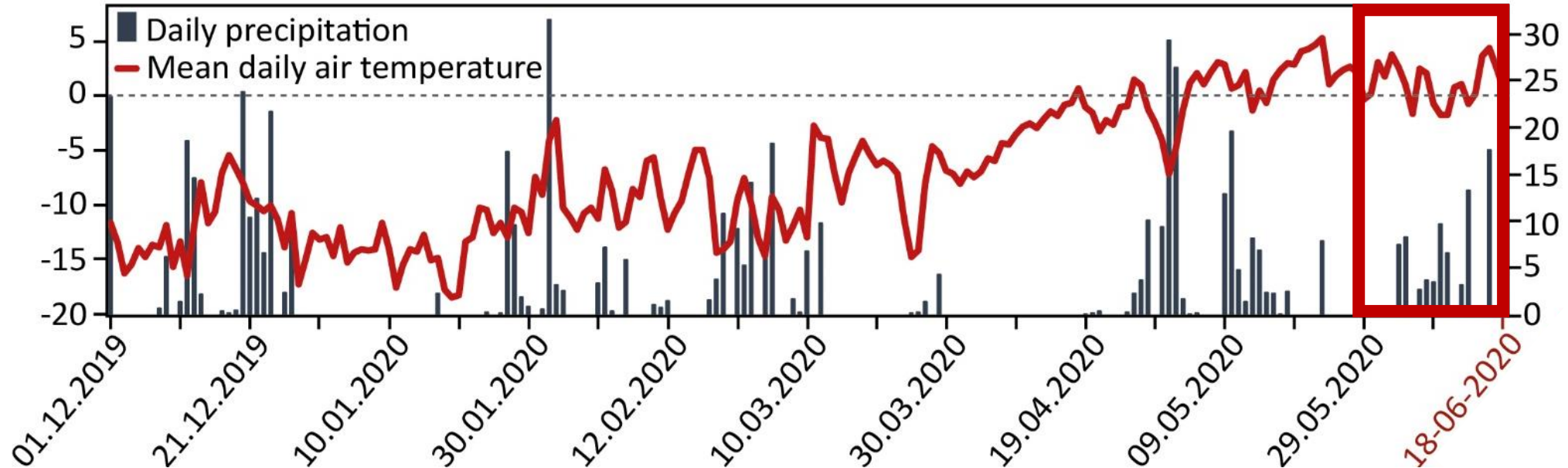
Significant precipitation in winter and spring 2020

Air temperature

(°C)

Daily precipitation

(mm)



→ Heavy rainfalls the week prior to the event

→ Water supply

RESULTS & DISCUSSIONS

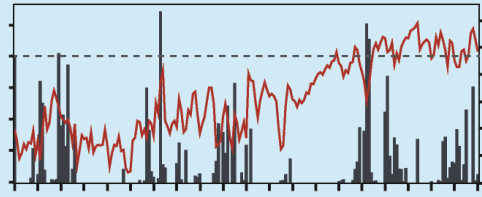
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Meteorological analysis



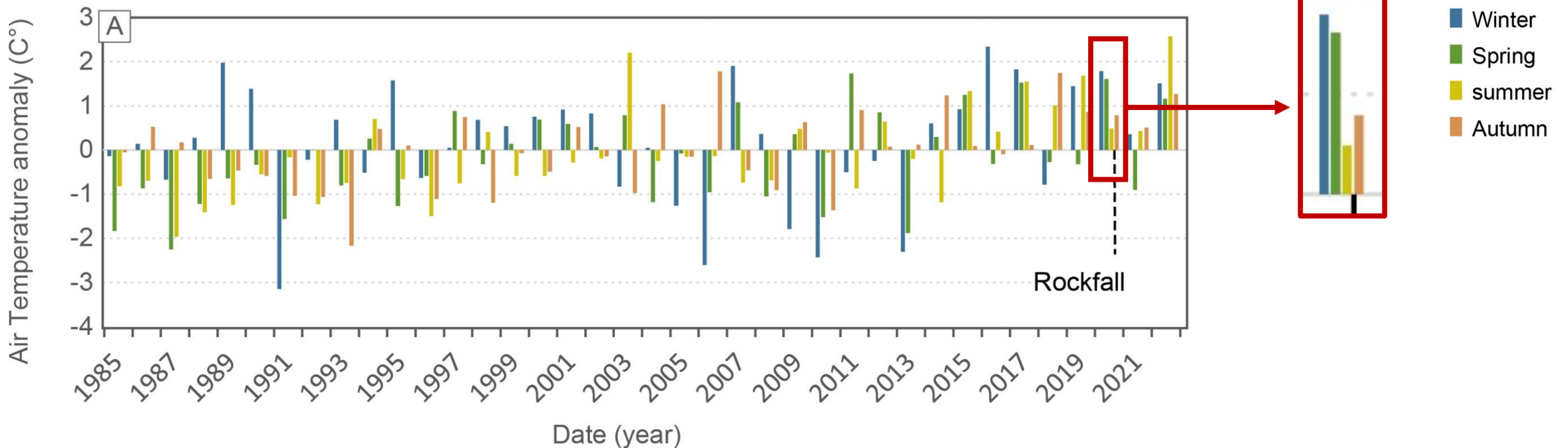
METEOROLOGICAL ANALYSIS

Grangettes Crest



Springs and summers exceptionally warm since 2015

- **Winter 2020** : the 4th warmest
- **Spring 2020** : the warmest
- **Summers 2015-2020** : the warmer summers since 2003



RESULTS & DISCUSSIONS

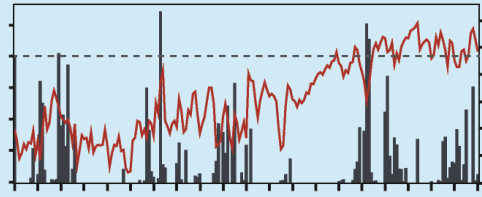
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Meteorological analysis

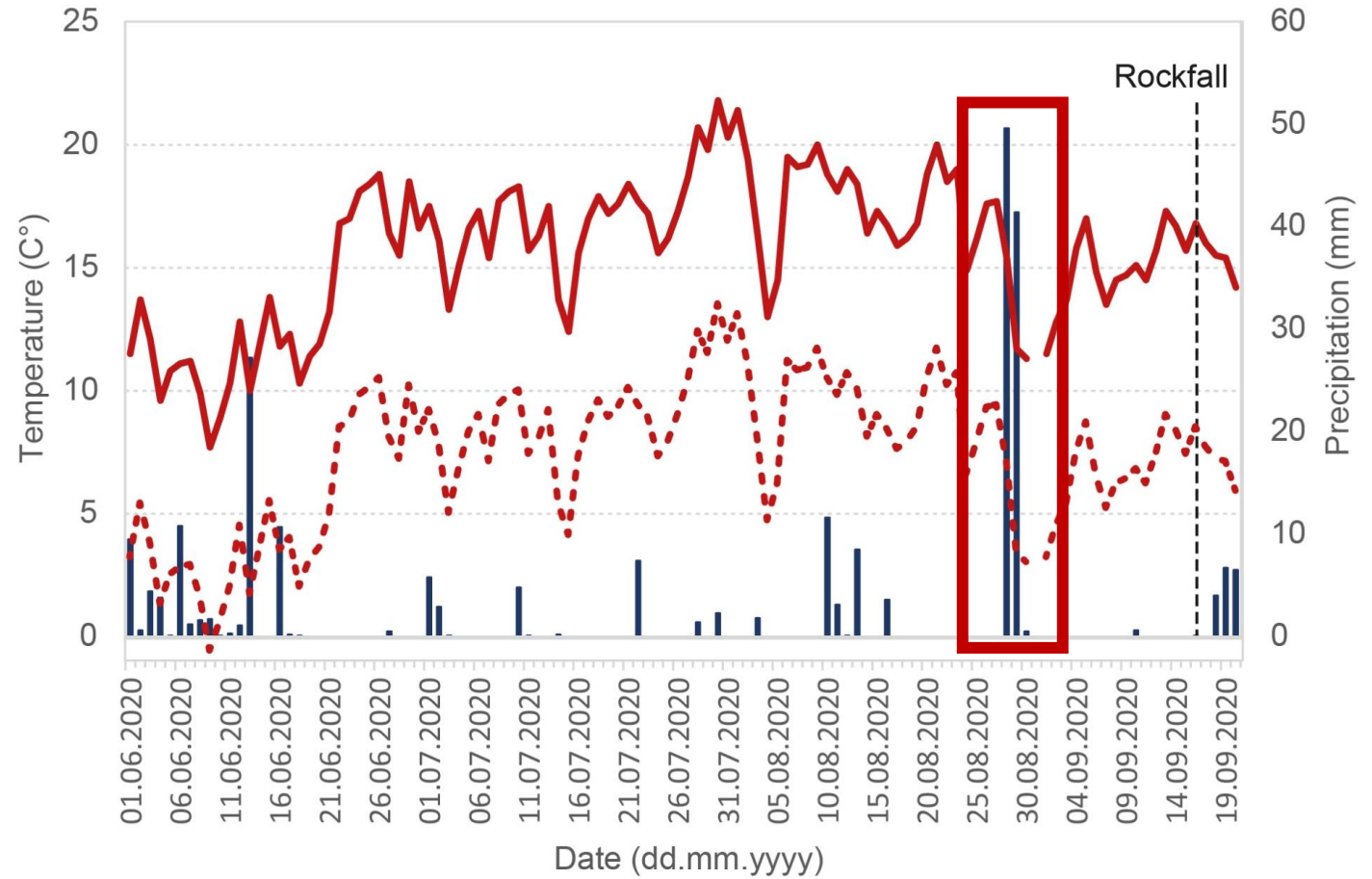


Heavy (but not exceptional) precipitations 20 days prior to the event

→ Triggering factor?

METEOROLOGICAL ANALYSIS

Grangettes Crest



Grangettes

- Temperature at LMLB AWS
- - - Temperature extrapolated at the scar elevation
- Precipitation

RESULTS & DISCUSSIONS

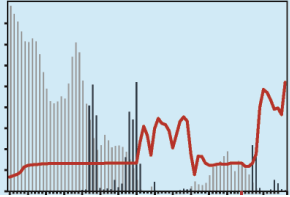
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Hydrological and energy balance modelling

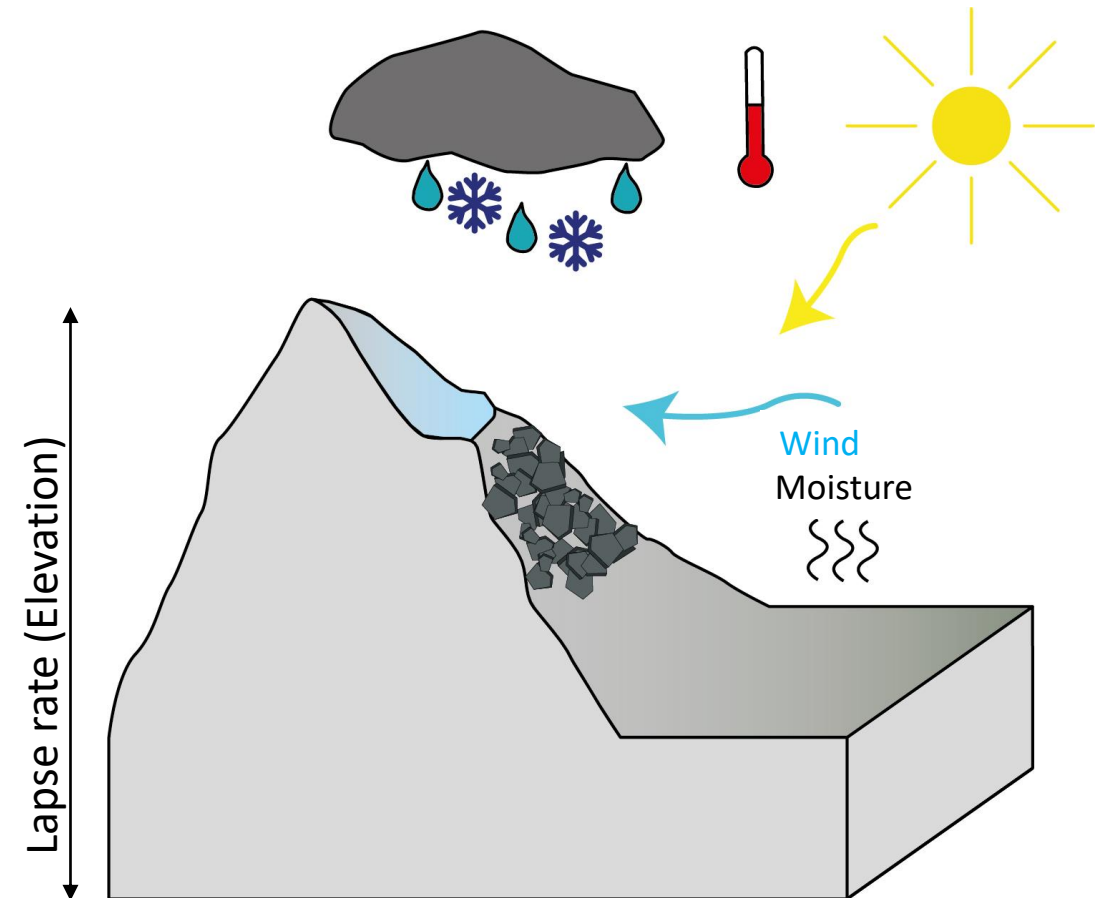


THERMAL AND HYDROLOGICAL CONDITIONS OF THE GROUND BEFORE THE EVENT

ENERGY AND HYDROLOGICAL BALANCE MODELLING

(CRYOGRID; WESTERMAN ET AL., 2013)

- **Atmospheric data:** air temperature, precipitation + snow, wind, humidity, solar radiation
→ *Météo France data/ Safran + Crocus models*
- **Surface data:** evolution of snow cover → Crocus model
→ Ben Asher et al., 2023 (set for steep slopes)
- **Model outputs:**
→ Surface temperature
→ Water supply (available for infiltration)
→ **At the point scale (1D)**



RESULTS & DISCUSSIONS

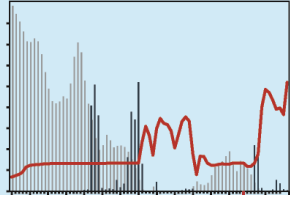
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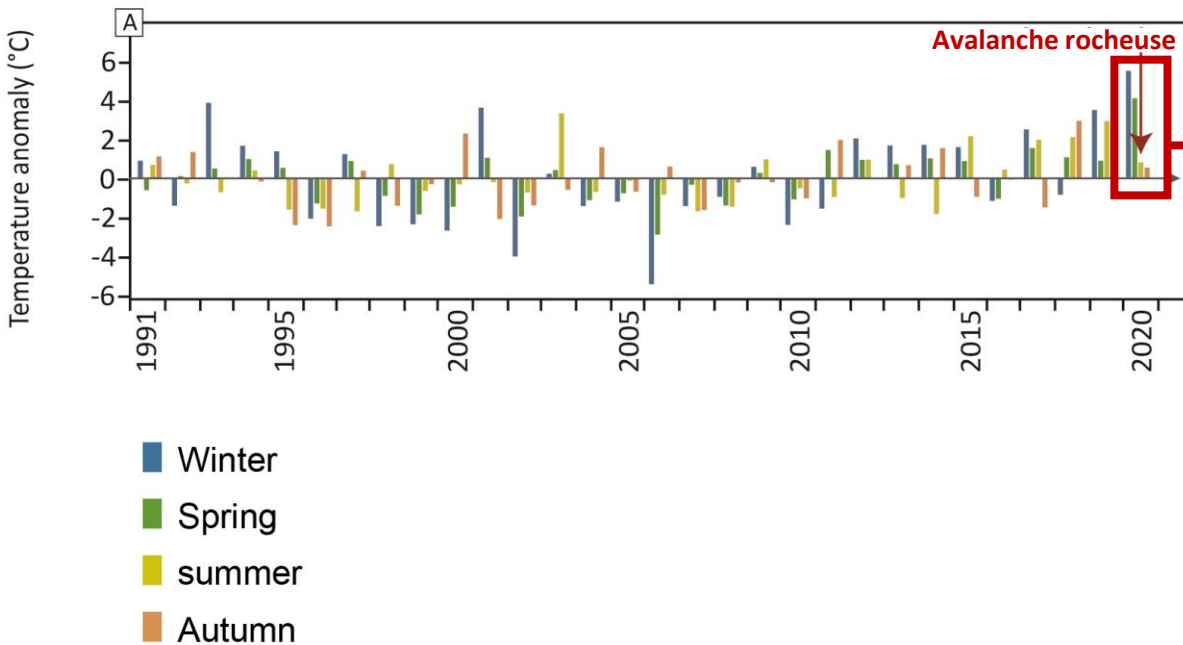


THERMAL AND HYDROLOGICAL CONDITIONS OF THE GROUND BEFORE THE EVENT

Étache valley



Étache



Exceptionally High Ground Temperatures (significantly exceeding air temperatures)

- Winter 2020 : +5.5 °C (2.9°C > air temperature anomaly)
- Spring 2020 : +4.1 °C (2.6°C > air temperature anomaly)

→ Ground surface temperature are **unprecedented since the start of the modeled record (1958)**

→ **Permafrost warming:** A preconditioning factor for slope instability

RESULTS & DISCUSSIONS

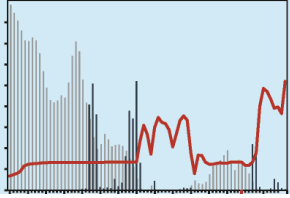
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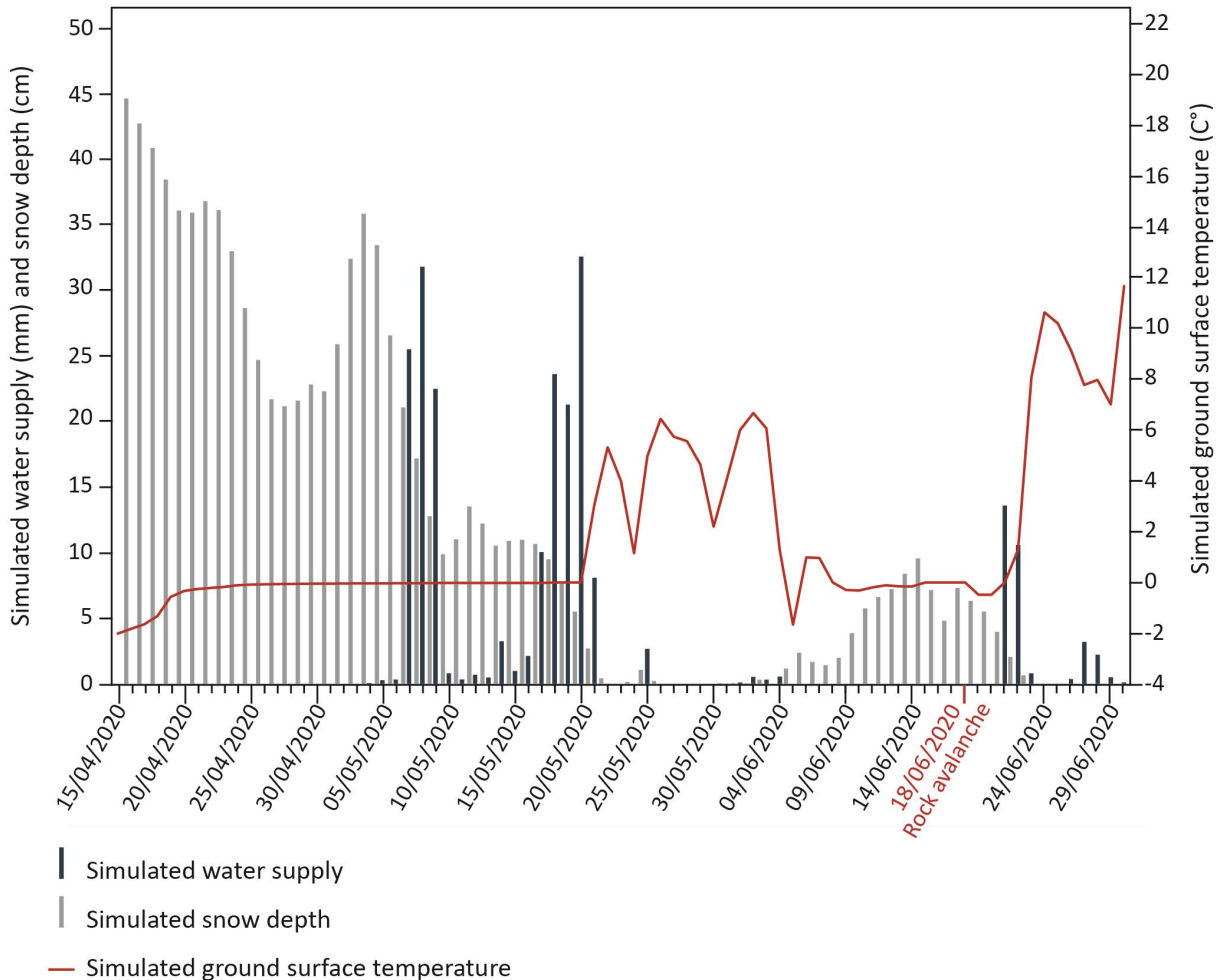
3) Spatial and temporal evolution of permafrost

4) Propagation mechanisms

Hydrological and energy balance modelling



THERMAL AND HYDROLOGICAL CONDITIONS OF THE GROUND BEFORE THE EVENT Étache valley



Spring 2020 : the highest water supply available for infiltration since 1958 (+120 mm)

→ Heavy precipitation and snow melt

→ **Role of water infiltration:**

- **Increase hydrostatic pressures**
- **Erosion of ice-filled fractures**

RESULTS & DISCUSSIONS

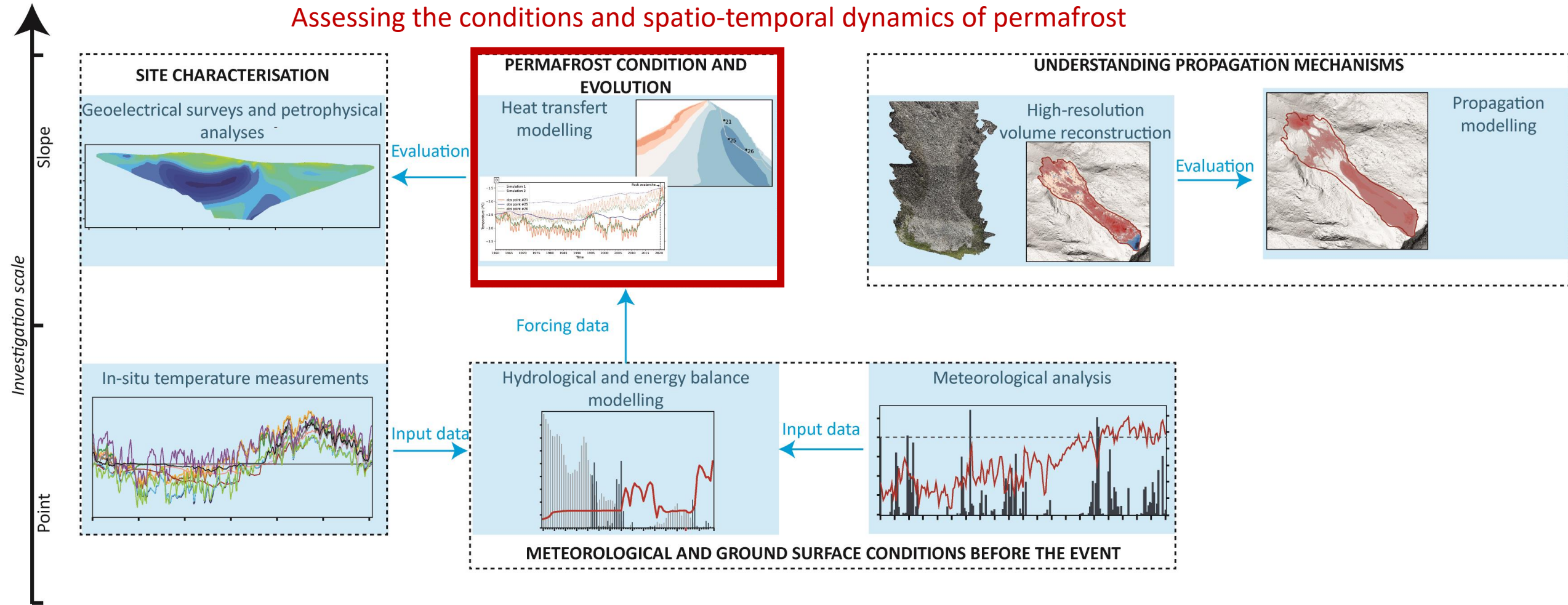
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Assessing the conditions and spatio-temporal dynamics of permafrost



RESULTS & DISCUSSIONS

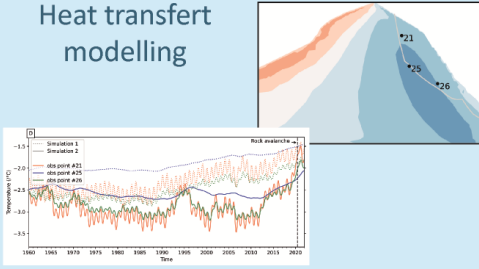
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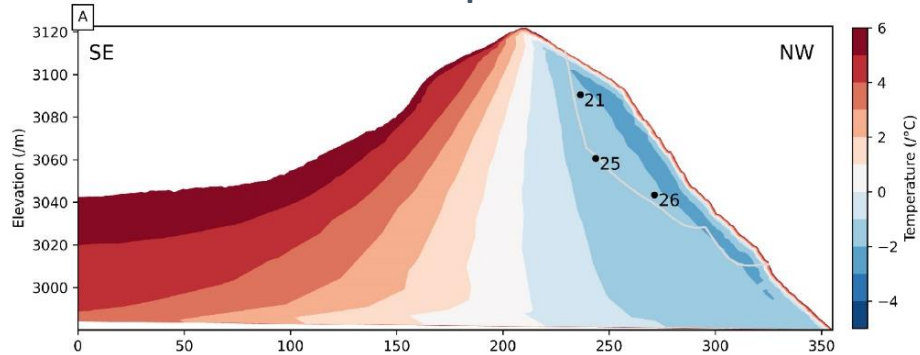
Heat transfert modelling



ASSESSING THE CONDITIONS AND SPATIO-TEMPORAL DYNAMICS OF PERMAFROST Étache Valley

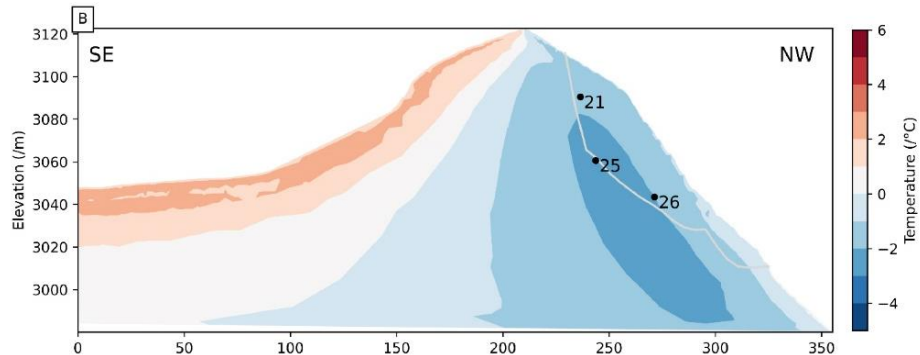


Simulation 1 : Forced with rock surface temperature deduced from
air temperature



→ = **Strong horizontal gradient of temperature**
(~7/8 °C difference between the SE and NW aspects)

Simulation 2 : Forced with rock surface temperature modelled with *CryoGrid* (energy balance modeling)



→ = **Smoother pattern:**
(~4/5 °C difference between the SE and NW aspects)

- **SE : cooling effect**
- **NW : warming effect**

RESULTS & DISCUSSIONS

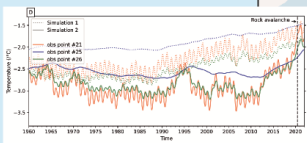
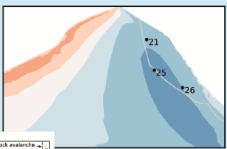
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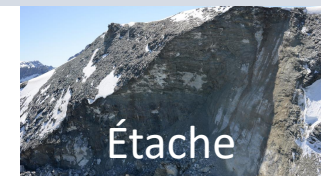
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Heat transfert
modelling

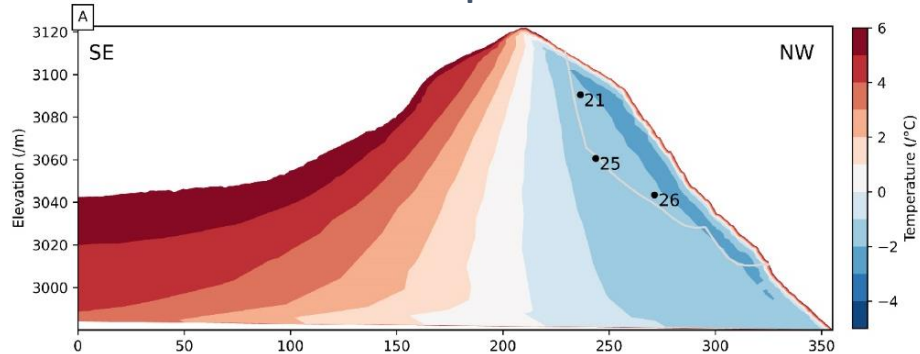


ASSESSING THE CONDITIONS AND SPATIO-TEMPORAL DYNAMICS OF PERMAFROST Étache Valley

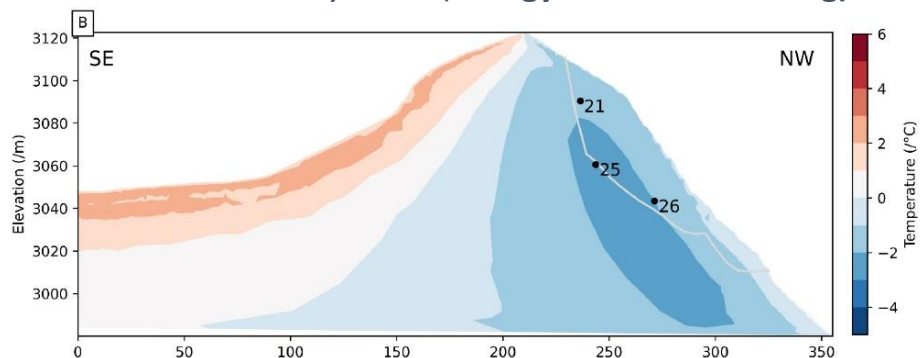


Étache

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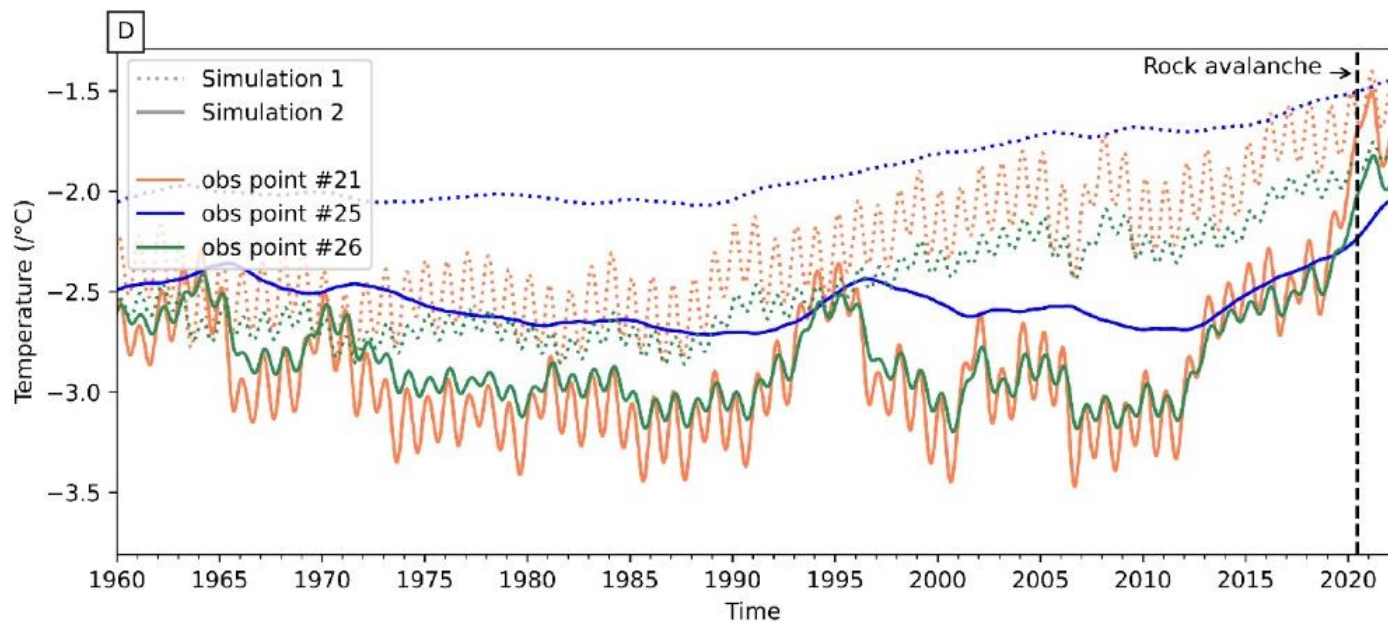


Simulation 2 : Forced with rock surface temperature
modelled with *CryoGrid* (energy balance modeling)



→ **Warming permafrost**

- Progressive since the 1990's and very sharp after 2012
- Transition from cold to warm permafrost



RESULTS & DISCUSSIONS

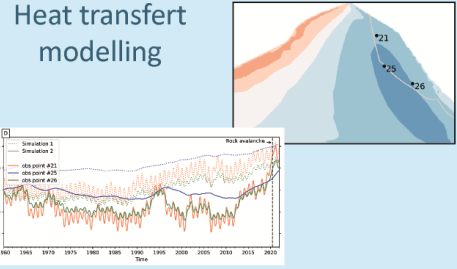
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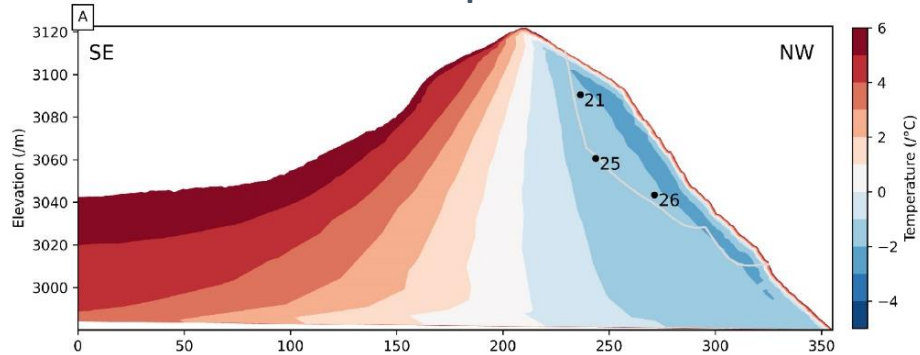
Heat transfert modelling



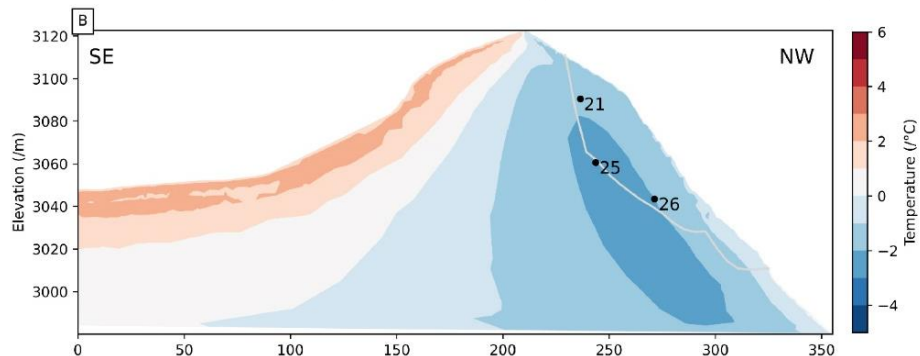
ASSESSING THE CONDITIONS AND SPATIO-TEMPORAL DYNAMICS OF PERMAFROST Étache Valley



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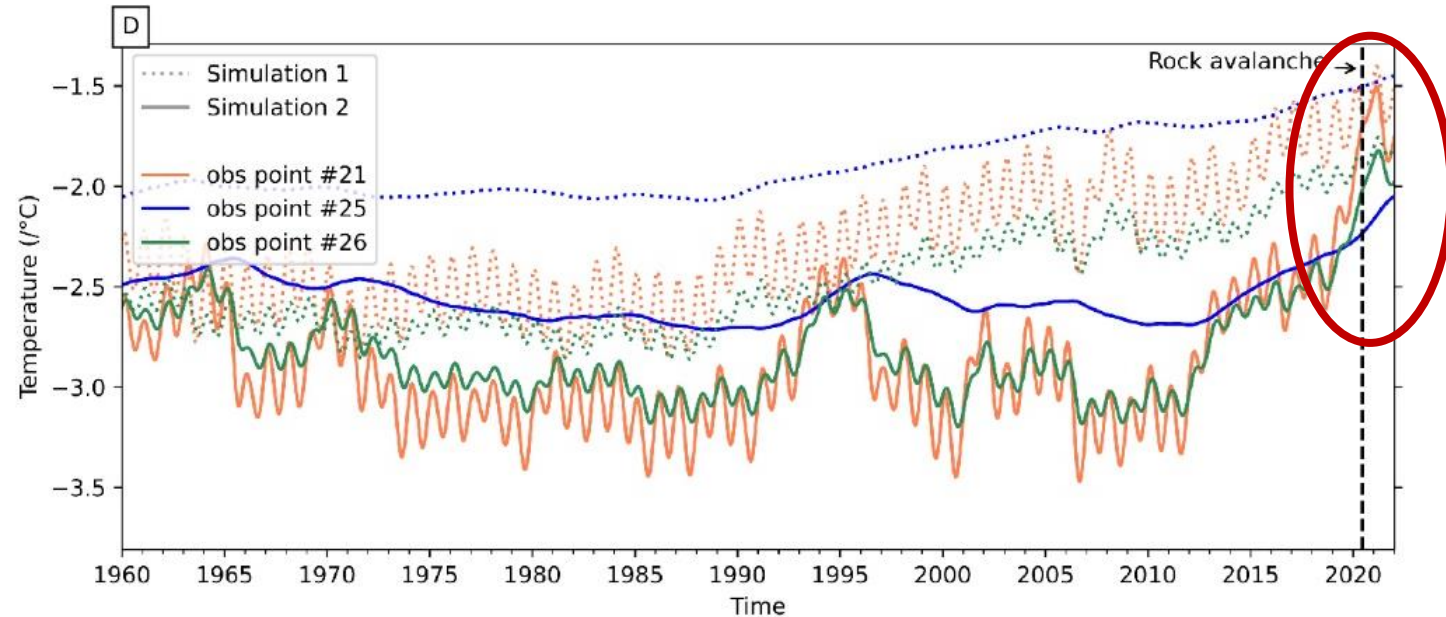


Simulation 2 : Forced with rock surface temperature modelled with *CryoGrid* (energy balance modeling)



→ Warming permafrost

- Progressive since the 1990's and very sharp after 2012
- Transition from cold to warm permafrost



→ The rock avalanche occurred under the warmest modeled conditions

RESULTS & DISCUSSIONS

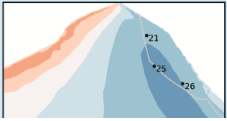
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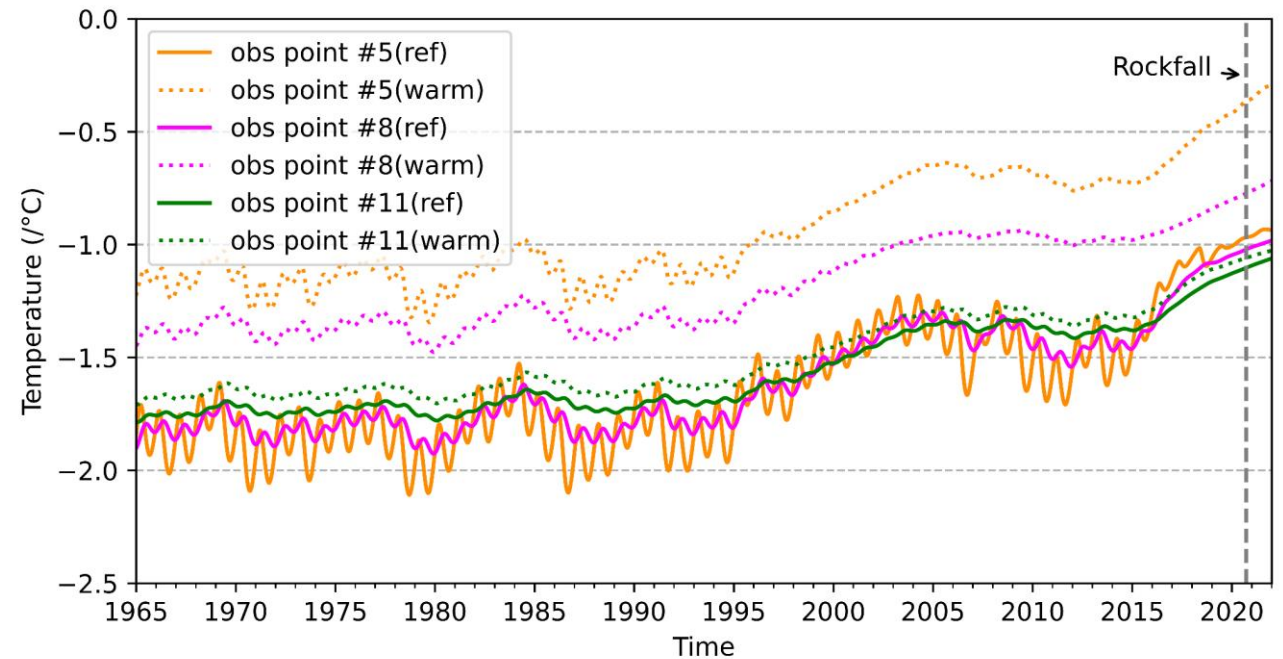
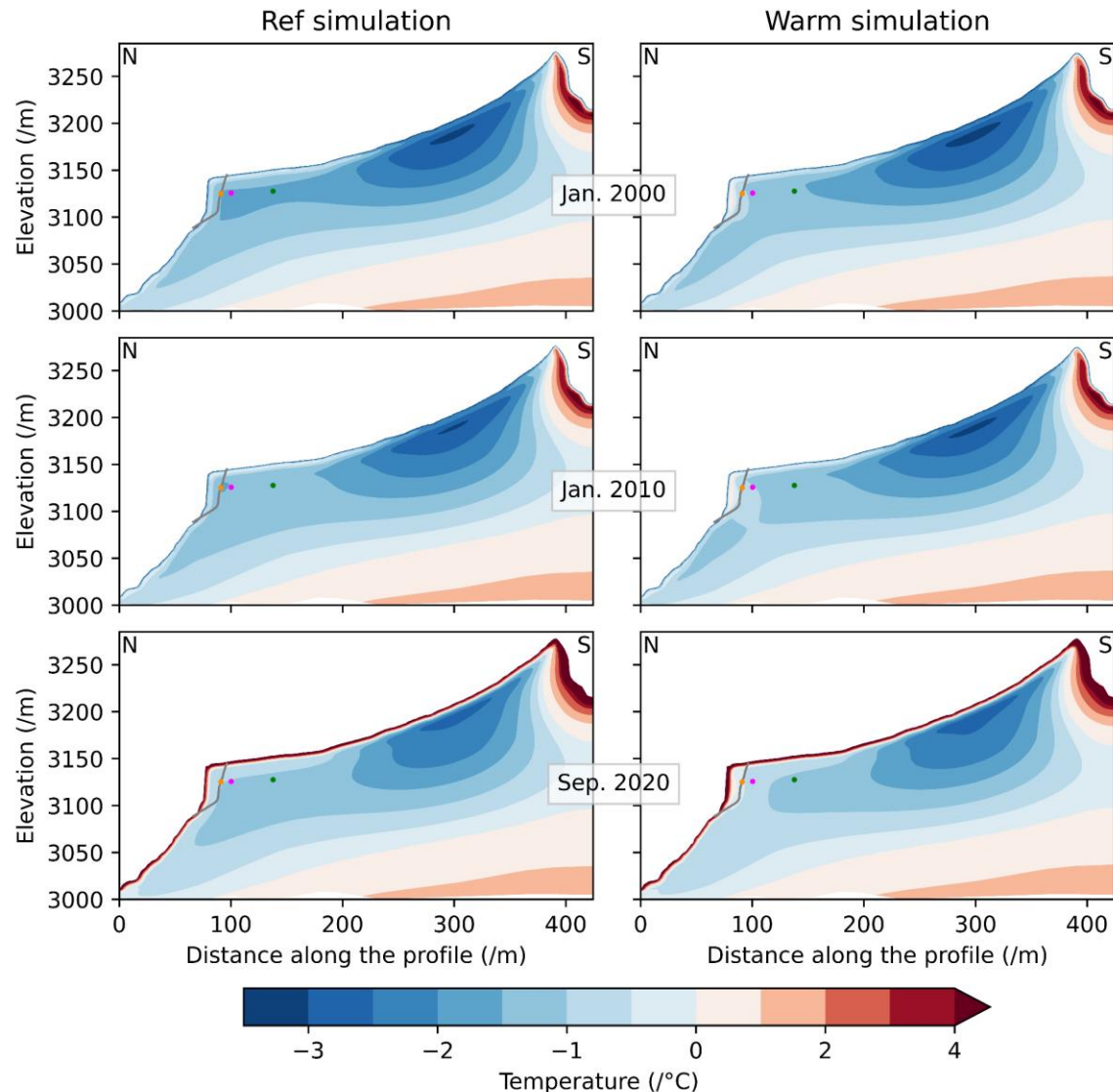


ASSESSING THE CONDITIONS AND SPATIO-TEMPORAL DYNAMICS OF PERMAFROST

Grangettes crest



Grangettes



- Progressive warming permafrost since the 1990's

RESULTS & DISCUSSIONS

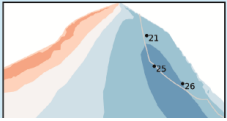
1) Thermal conditions

2) Meteorological / hydrological factors

3) Spatial and temporal evolution of permafrost

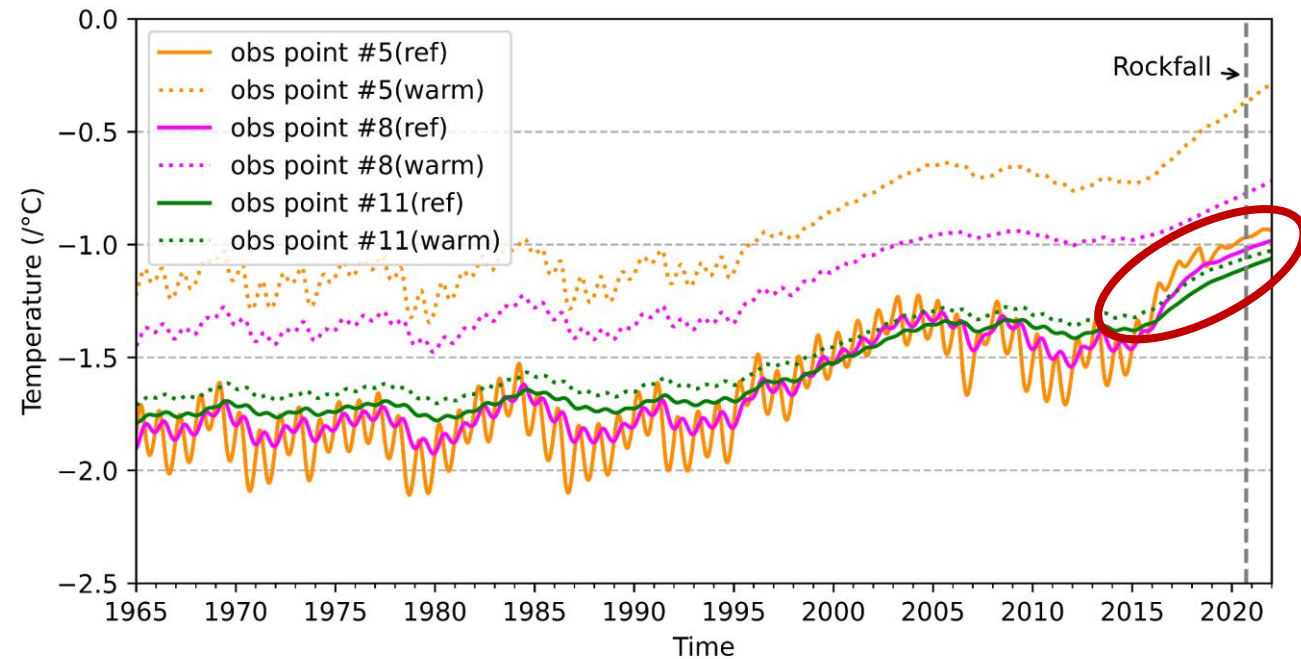
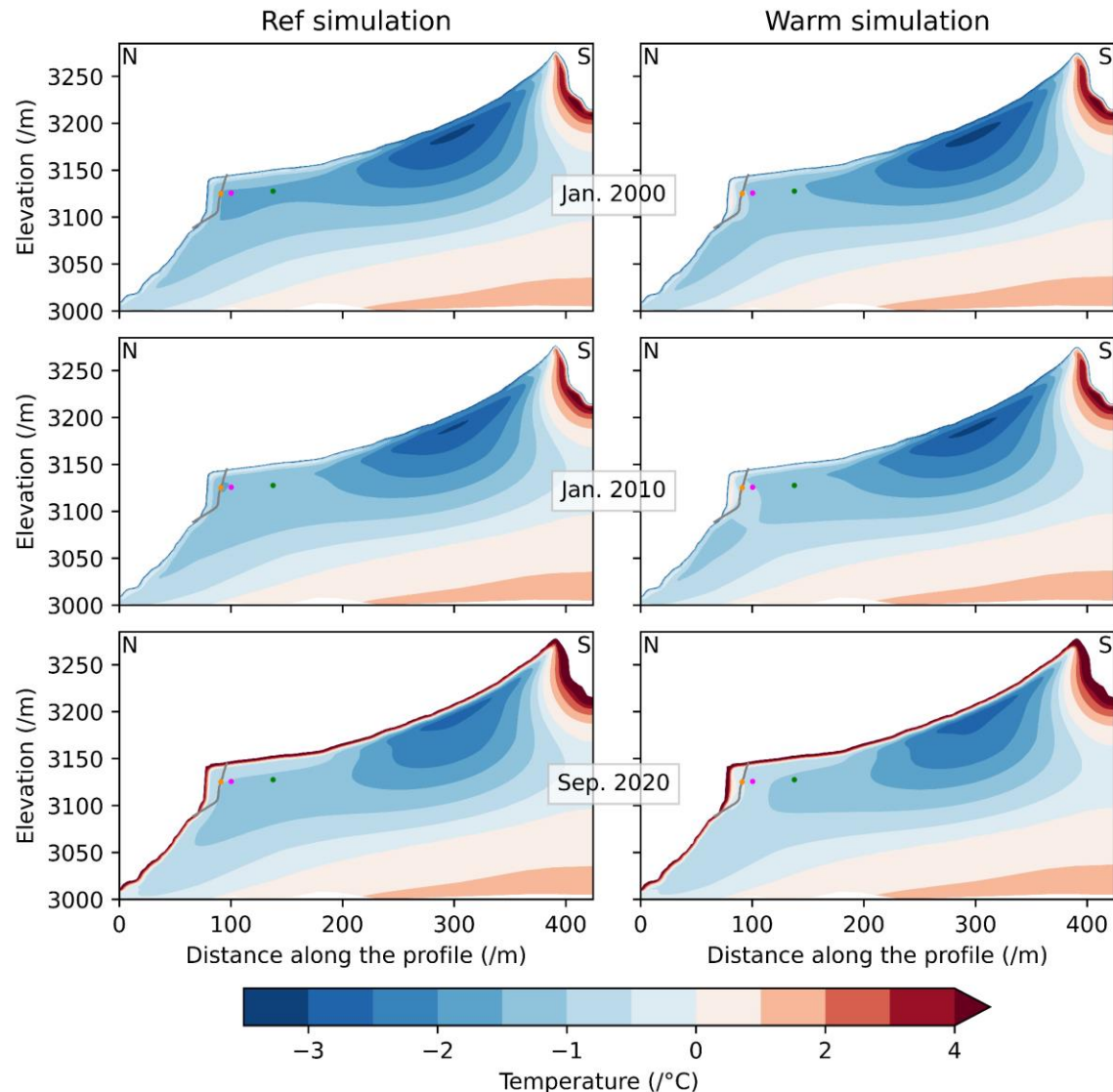
4) Propagation mechanisms

Heat transfert
modelling



ASSESSING THE CONDITIONS AND SPATIO-TEMPORAL DYNAMICS OF PERMAFROST

Grangettes crest



- Progressive warming permafrost since the 1990's
- Sharp increase since 2015

RESULTS & DISCUSSIONS

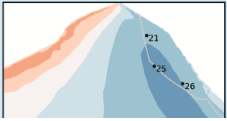
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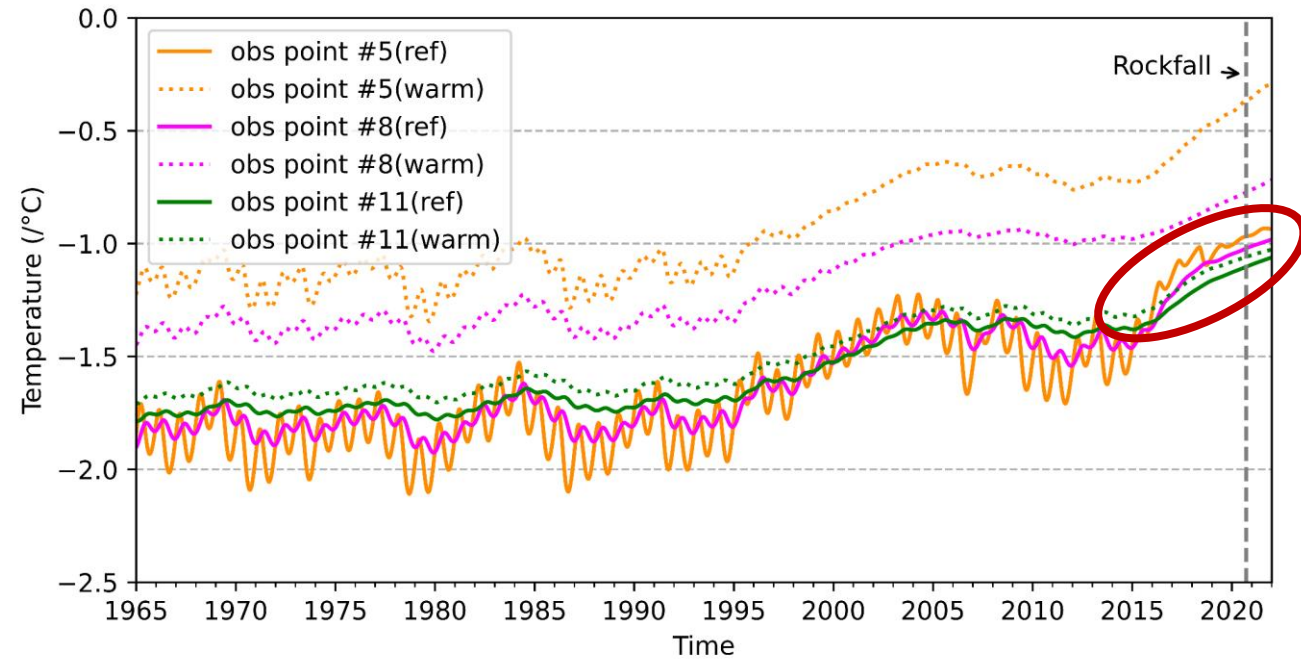
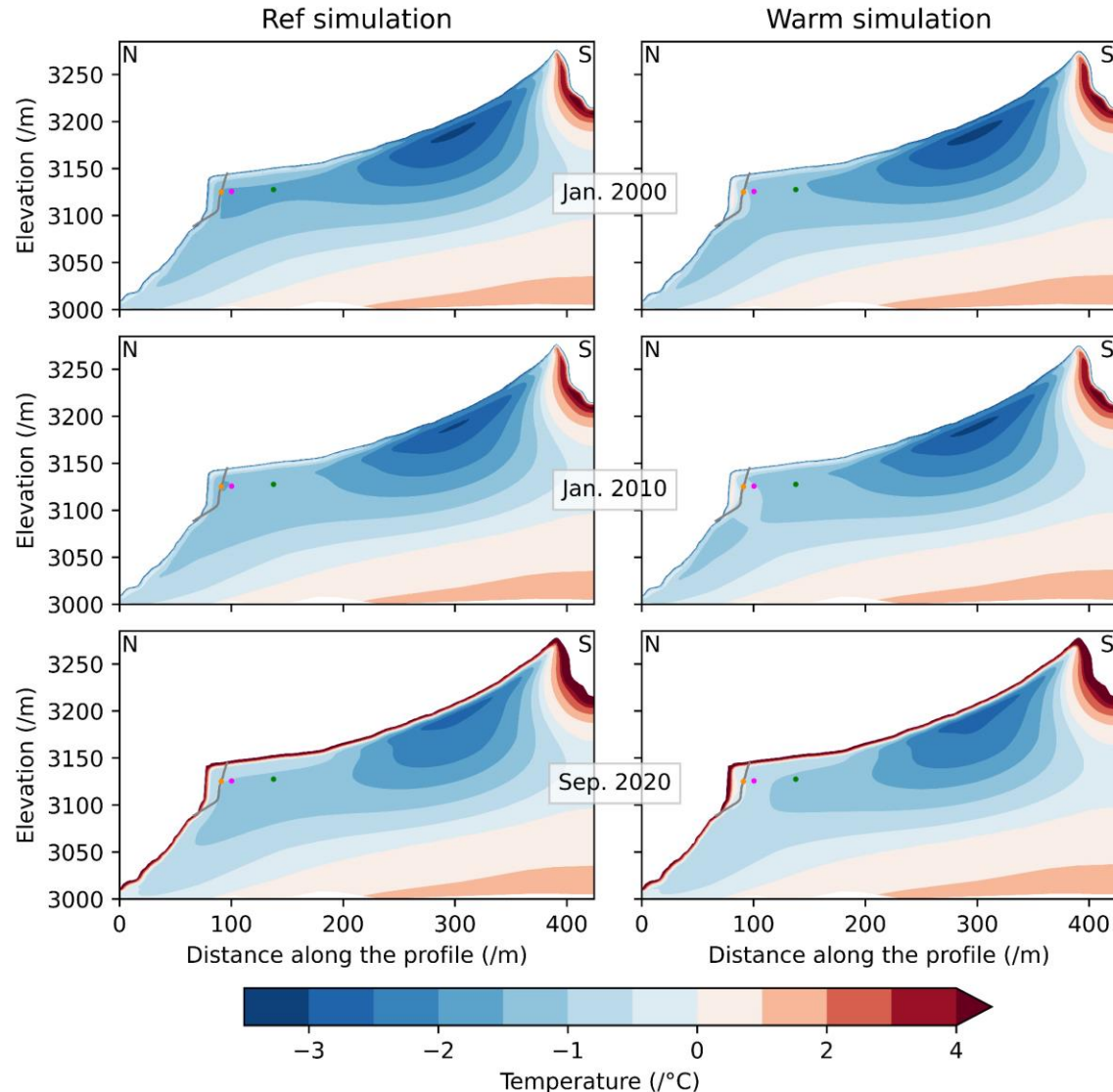
4) Propagation mechanisms

Heat transfert
modelling



ASSESSING THE CONDITIONS AND SPATIO-TEMPORAL DYNAMICS OF PERMAFROST

Grangettes crest



- Progressive warming permafrost since the 1990's
- Sharp increase since 2015
- Warm permafrost approaching 0°C

RESULTS & DISCUSSIONS

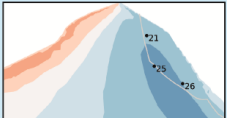
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3) Spatial and temporal evolution of permafrost

4) Propagation mechanisms

Heat transfert
modelling

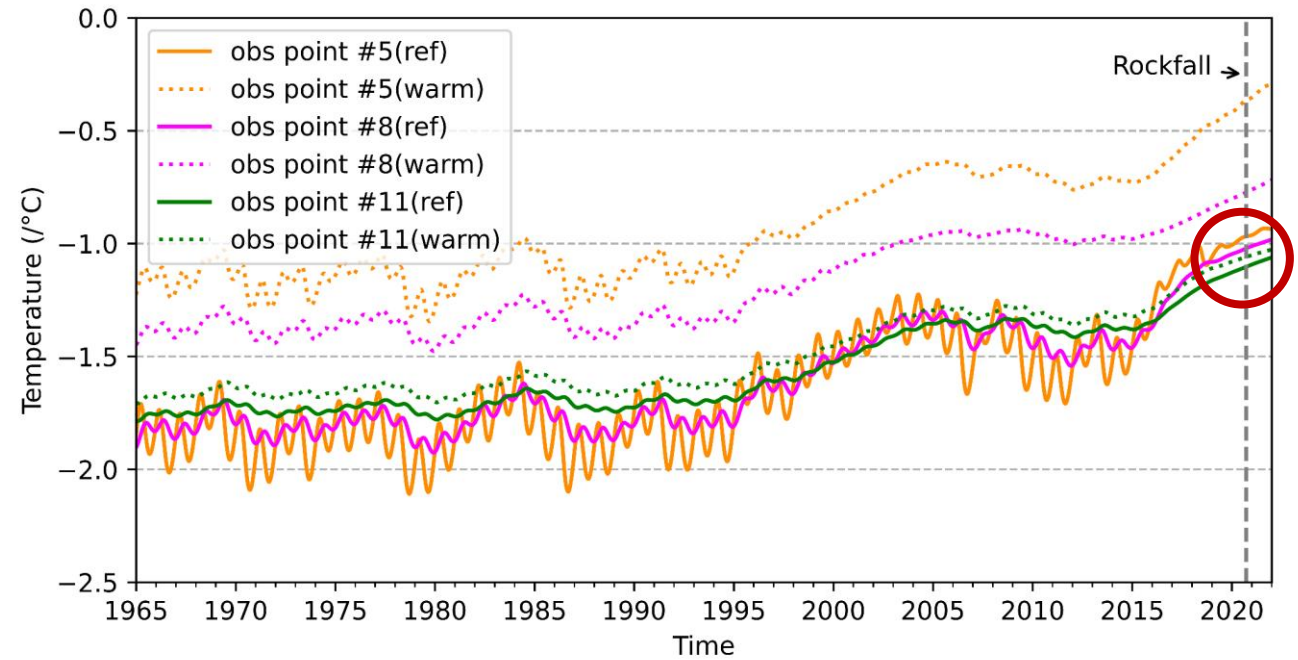
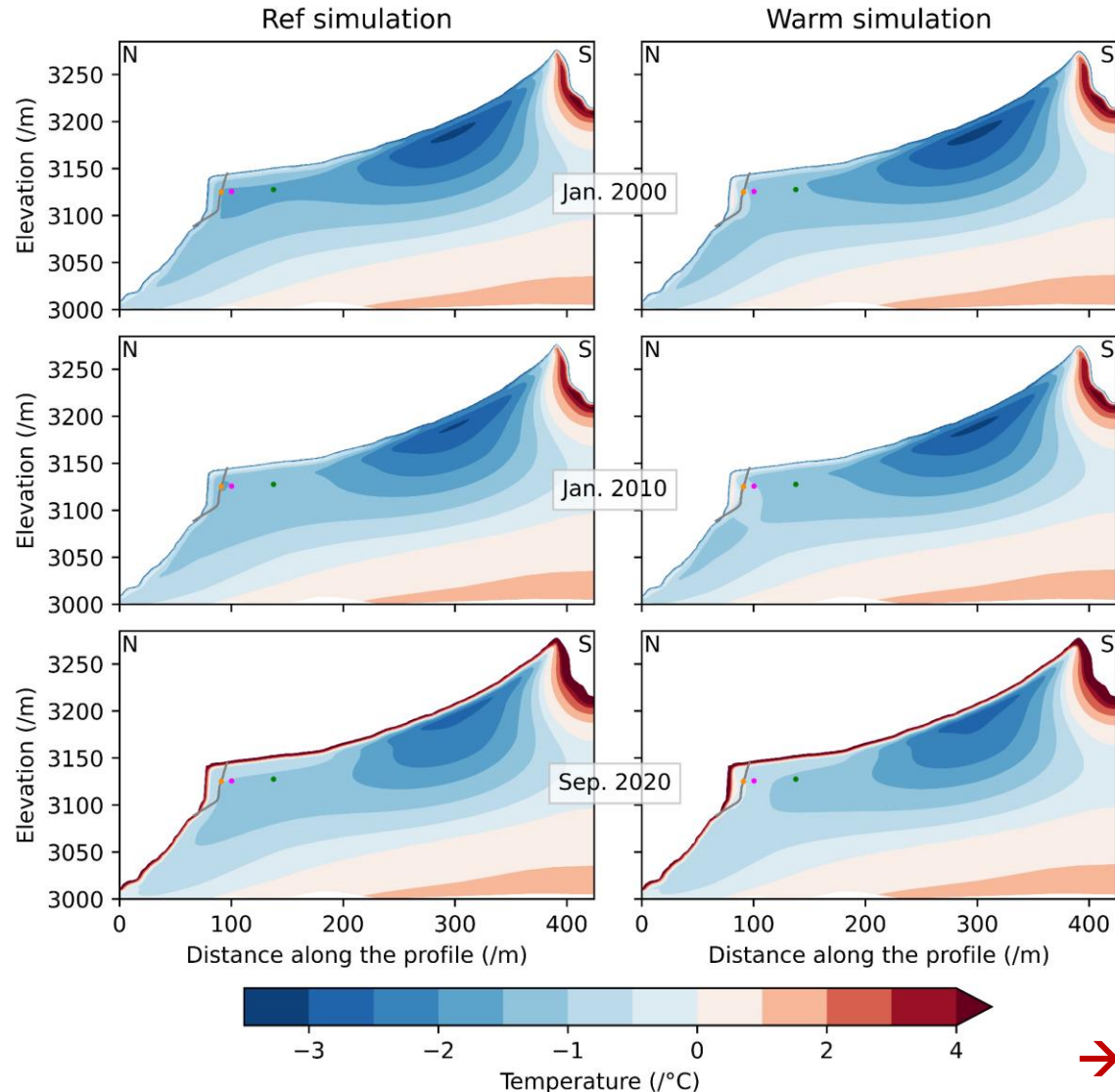


ASSESSING THE CONDITIONS AND SPATIO-TEMPORAL DYNAMICS OF PERMAFROST

Grangettes crest



Grangettes



- Progressive warming permafrost since the 1990's
- Sharp increase since 2015
- Warm permafrost approaching 0°C

→ The rockfall occurred under the warmest modeled conditions

RESULTS & DISCUSSIONS

1) Thermal conditions

2) Meteorological / hydrological factors

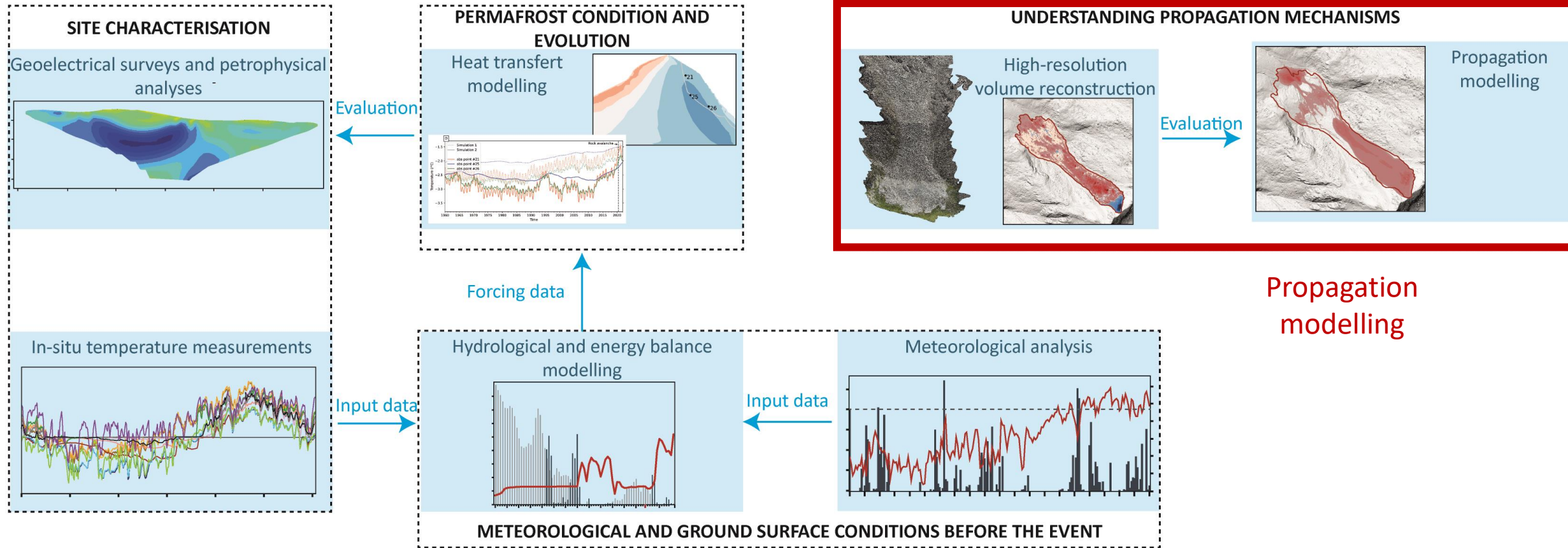
3) Spatial and temporal evolution of permafrost

4) Propagation mechanisms

Investigation scale

Slope

Point



Propagation modelling

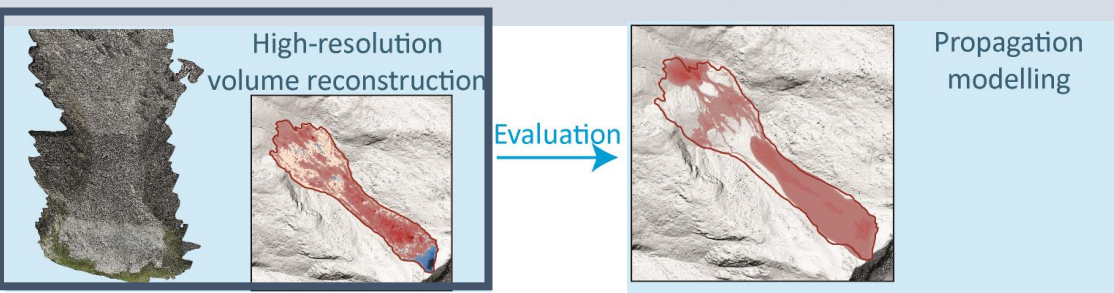
RESULTS & DISCUSSIONS

1) Thermal conditions

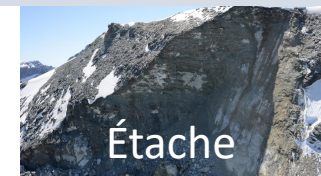
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4) Propagation mechanisms

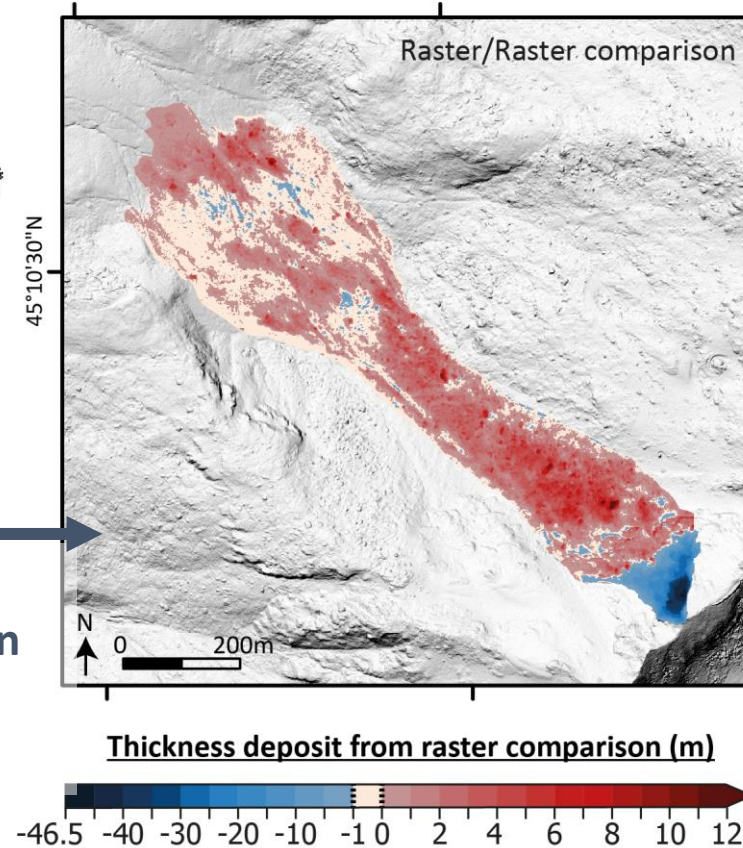
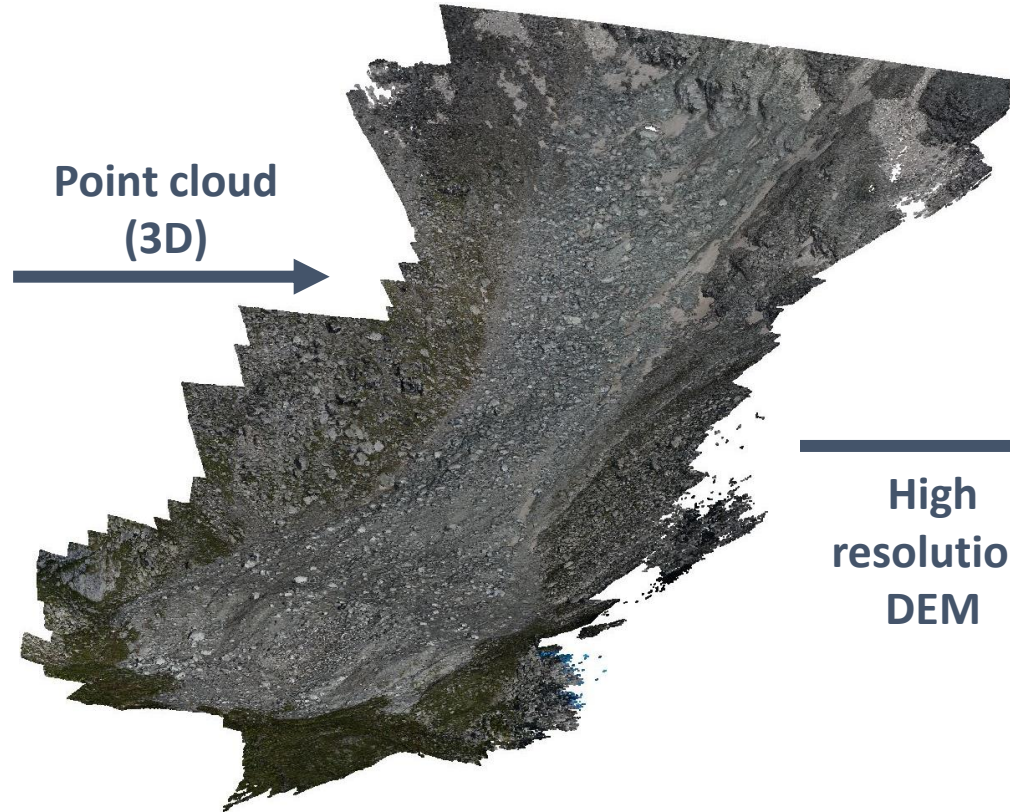


UNDERSTANDING PROPAGATION MECHANISMS 3D modelling (photogrammetry)



Rasters comparison before/after: volume calculation

→ Drone survey (2021 and 2022)



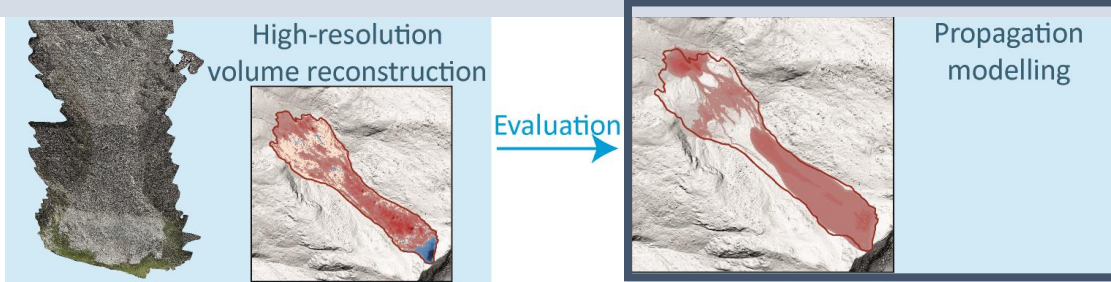
RESULTS & DISCUSSIONS

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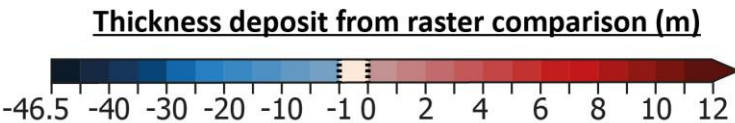
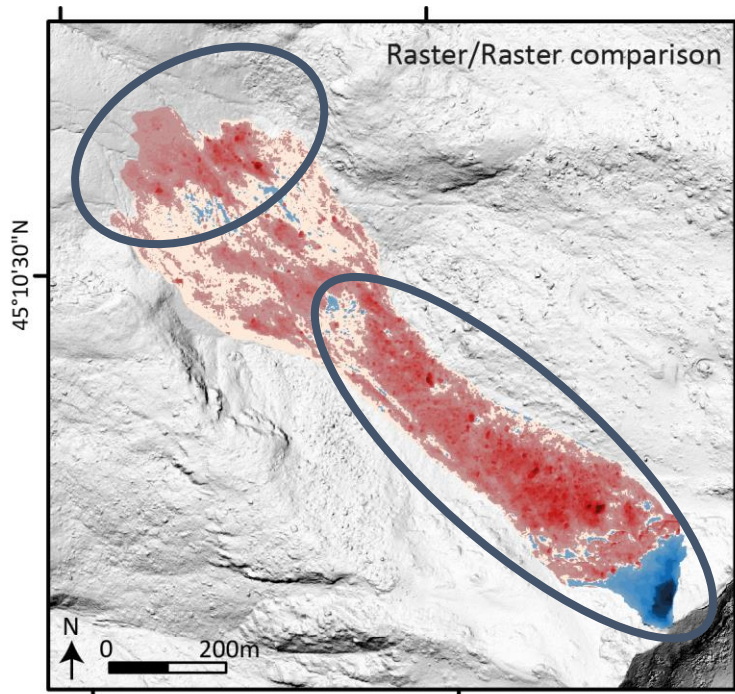
4) Propagation mechanisms



UNDERSTANDING PROPAGATION MECHANISMS

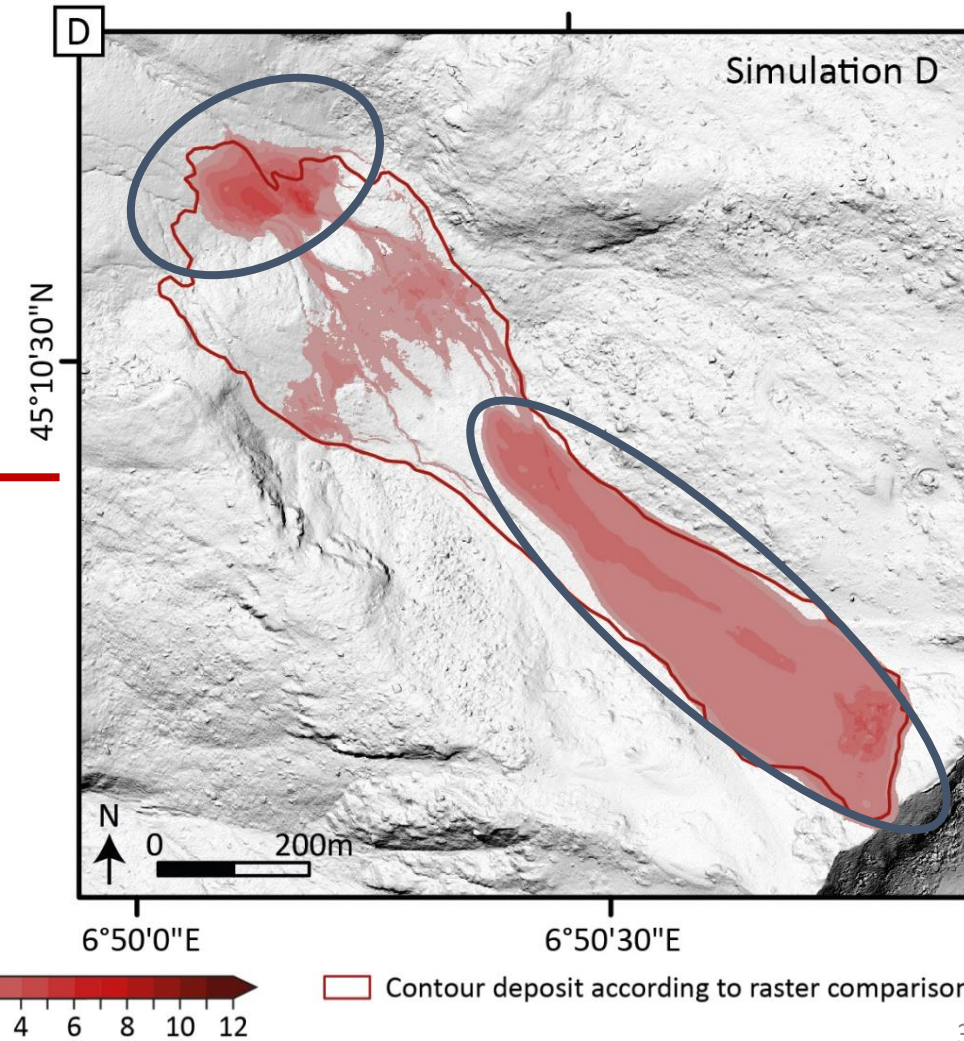


• Simulation D :



→ depth-averaged model with a Voellmy friction law

- Complex flow process
- Evolution of the effective rheological properties along the flow: **transport of snow by the rock avalanche**



CONCLUSIONS

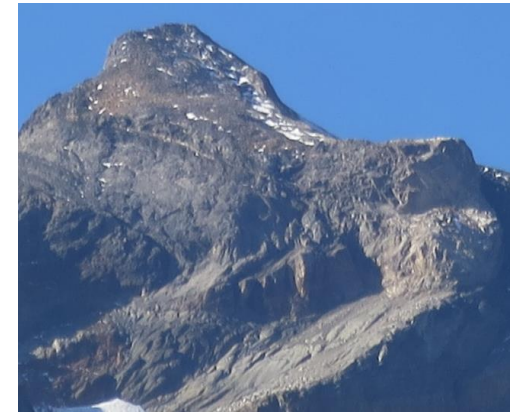
ÉTACHE VALLEY

Cold permafrost

→ Predisposing factors:
Permafrost warming
(transition from cold to
warm permafrost)

→ Triggering factors: **Water infiltration** (hydrostatic pressures
and/or erosion of ice-filled fractures)

→ Propagation modelling = Several phases due to snow
incorporation



GRANGETTES CREST

Warm permafrost

→ Predisposing factors:
Permafrost warming
(approaching to 0°C)
= **Mechanical weakening of ice-
filled joints**

→ **Rockfall deposit barely visible** = Limitation for propagation
modelling

Perspectives :

- **Better integrate water infiltration processes in permafrost modelling**
- **Better understand snow and water effects in the triggering and propagation mechanisms of rock slope failures**



CASE STUDY | [Open Access](#) |

**Predisposing, triggering and runout processes at a permafrost-
affected rock avalanche site in the French Alps (Étache, June
2020)**

Maëva Cathala , Josué Bock, Florence Magnin, Ludovic Ravanel, Matan Ben Asher, Laurent Astrade,
Xavier Bodin, Guillaume Chambon, Philip Deline, Thierry Faug, Kim Genuite ... [See all authors](#) ▾



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Articles sous presse

**Assessing the role of permafrost in the preconditioning
and triggering factors of the September 2020 Crête des
Grangettes rockfall (southern French Alps)**



THANK YOU

maeva.cathala.pro@gmail.com

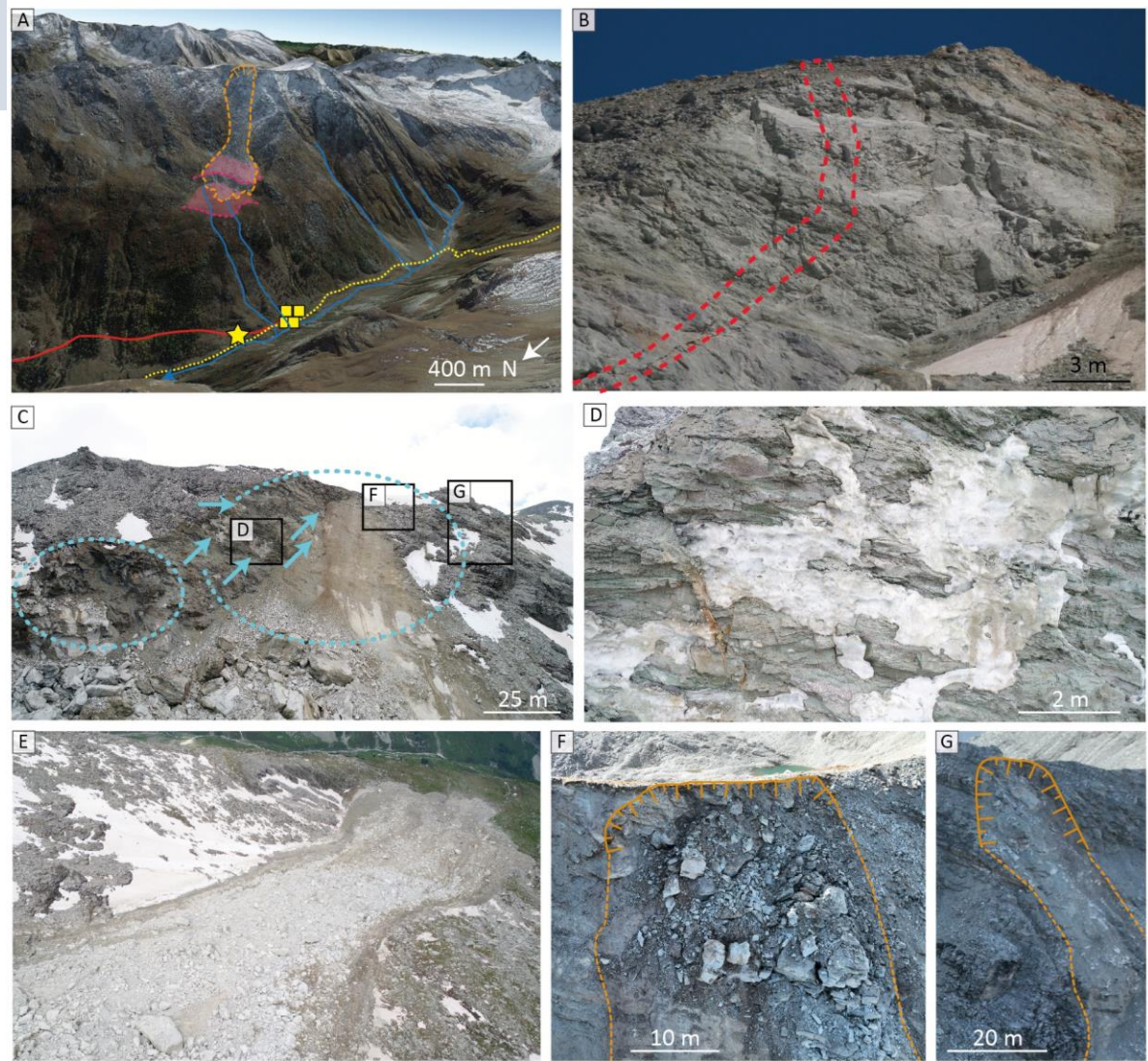
Looking for a Post-Doc ;-)



SUPPLEMENTS

Characteristics of the event

- The rock avalanche occurred on June 18 2020 from the crest line (3126 m).
- H/L: 0,56 (ELA 29°)
- Total drop height: 728 m
- Total runout length: 1296 m
- The deposit extends 600 m above the farm, the parking area, and the hiking trails.
- Ice in the rockfall scars suggests the presence of permafrost, but its local distribution remains to be confirmed.



Rock avalanche observations

- Runout and deposition zone
- ▤ Scar
- ▭ Visible fracture
- Visible ice coating
- Liquid water

Human stakes

- Building
- ★ Parking
- Hiking trail
- Road

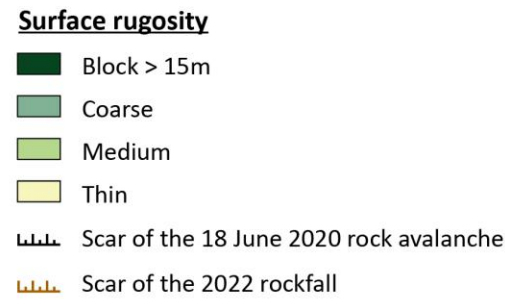
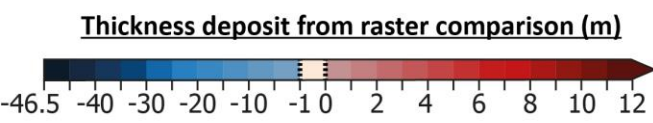
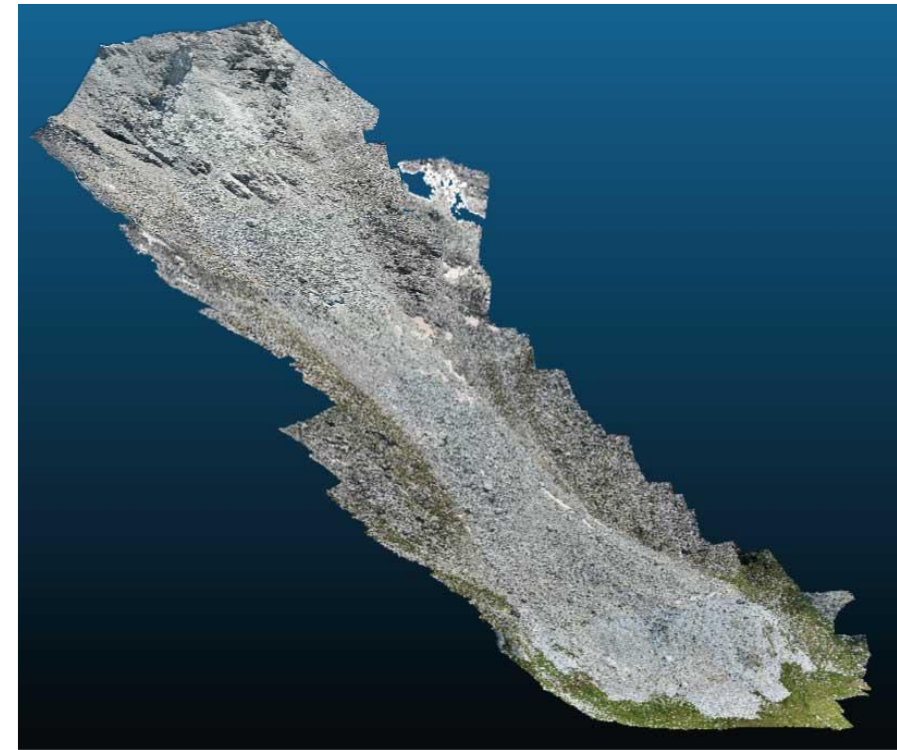
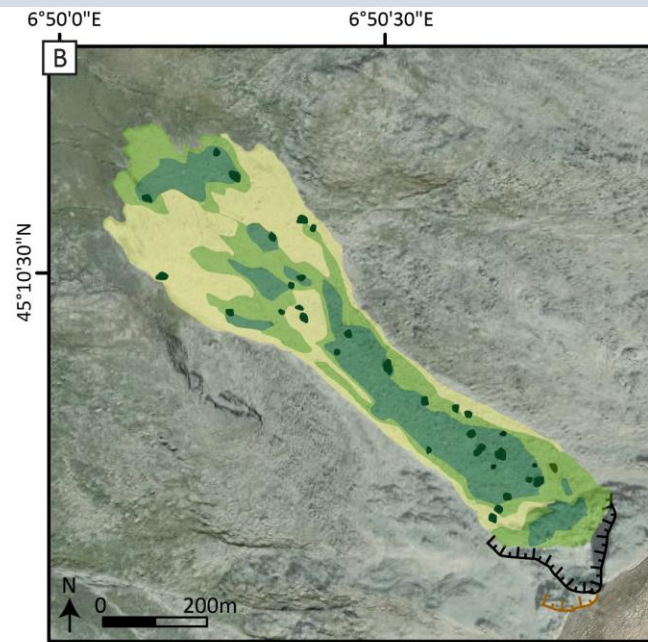
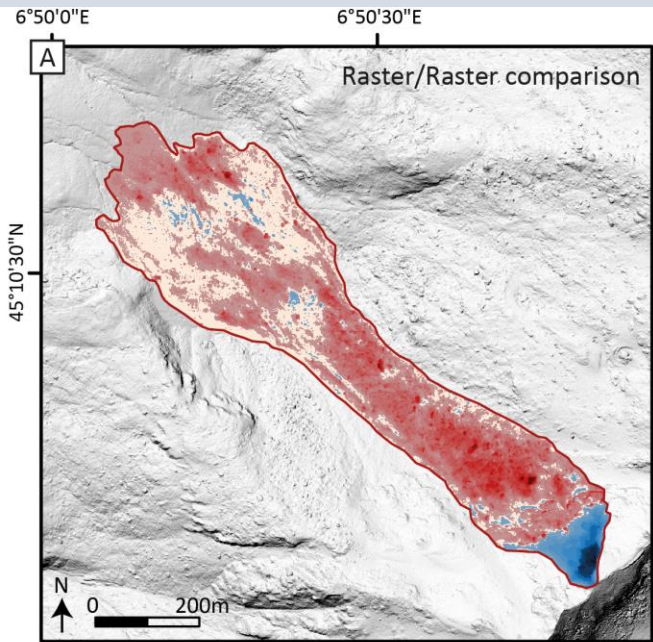
Topography

- ▭ Topographic flat (mean slope < 15°)
- Slope break

Hydrography

- Stream

3D reconstruction



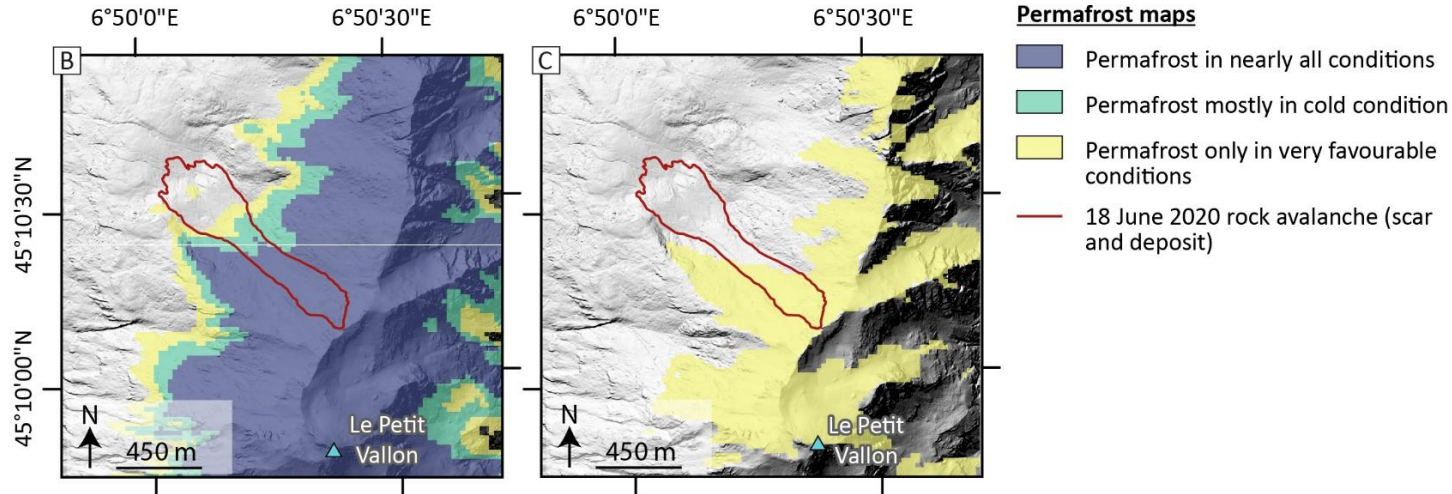
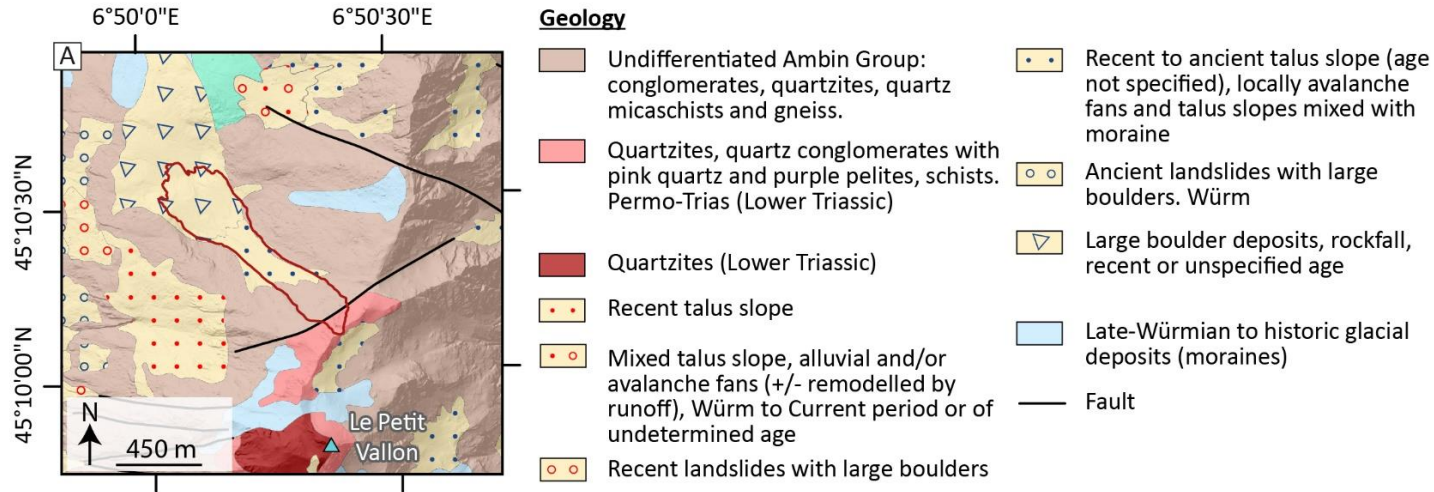
The scar:

- Width: 180 m
- Max depth: 46.5 m
- Average depth: 14.7 m.
- Estimated volume: c. 225 000 m³

The deposit:

- Estimated volume: c. 330 000 m³
- Expansion coefficient: 1.37
- Surface: 175 535 m²
- Average thickness: 1.8 m
- Maximum thickness: 12.6 m
- Maximum observed in the upper/central part which concentrates most of the volume (230 000 m³)

Geomorphological and geological setting



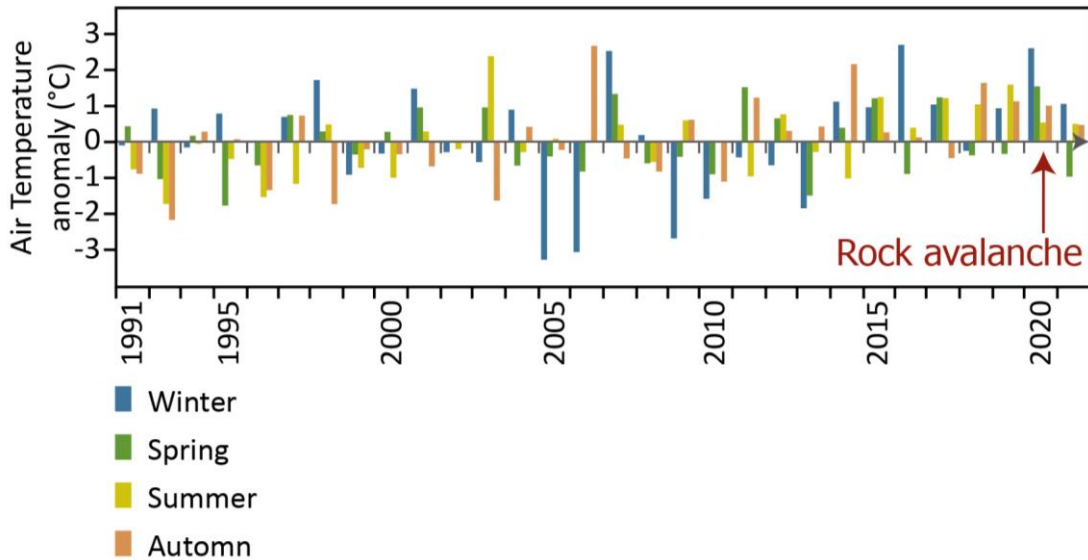
Permafrost Favorability Index (Marcer et al., 2017)

Rock wall permafrost model (Boeckli et al., 2012)

- Glacial and periglacial processes strongly shaped the landscape of the Vallon d'Etache (e.g. moraines, gelifluction lobes)
- A fault near the scar
- Permafrost Favourability Index (PFI) suggests that the rock slope failure occurred in a an area favourable to permafrost in all conditions
(PFI tends to overestimate permafrost favourability in current climatic conditions because the active rock glaciers used for the model calibration are inherited of the LIA climate conditions)
- The permafrost model by Boeckli et al. (2012a; 2012b) suggests that it occurred in an area of permafrost occurrence only in favourable conditions

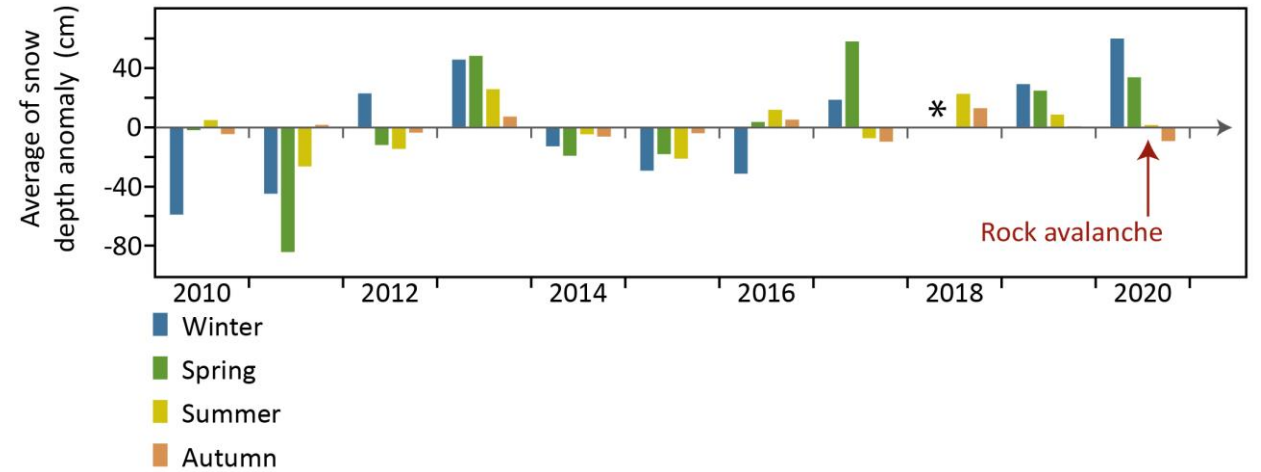
→ None of the two maps are fully representative of permafrost conditions

Meteorological context



Air temperature anomalies:

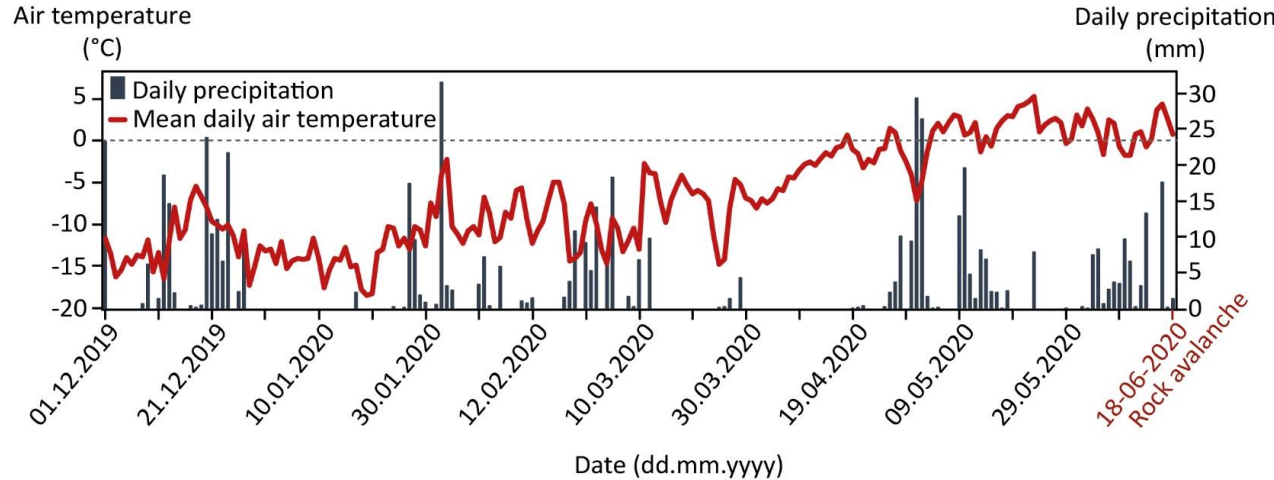
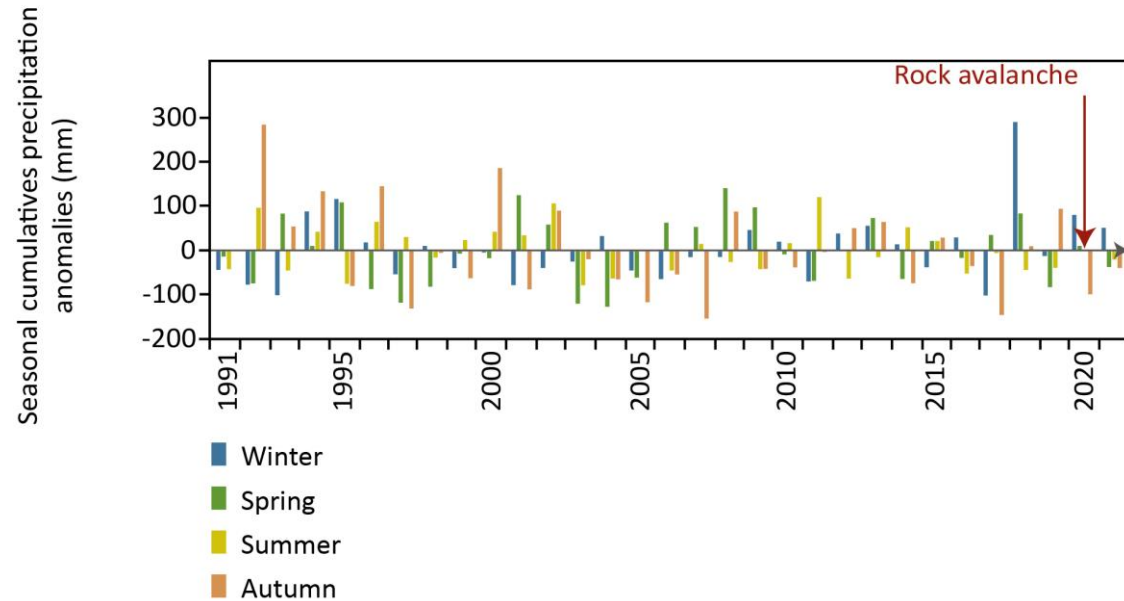
- 2020 annual average air temperature: the warmest in the 1985-2014 period
- The 6 month period prior to the event: the second warmest winter and the warmest spring since 1985 at Bessans



Snow anomalies:

- Average snow depth over the winter period: 186 cm = 48% (60 cm) more snow than the 2010-2019 winter periods at Bonneval-sur-Arc

Meteorological context



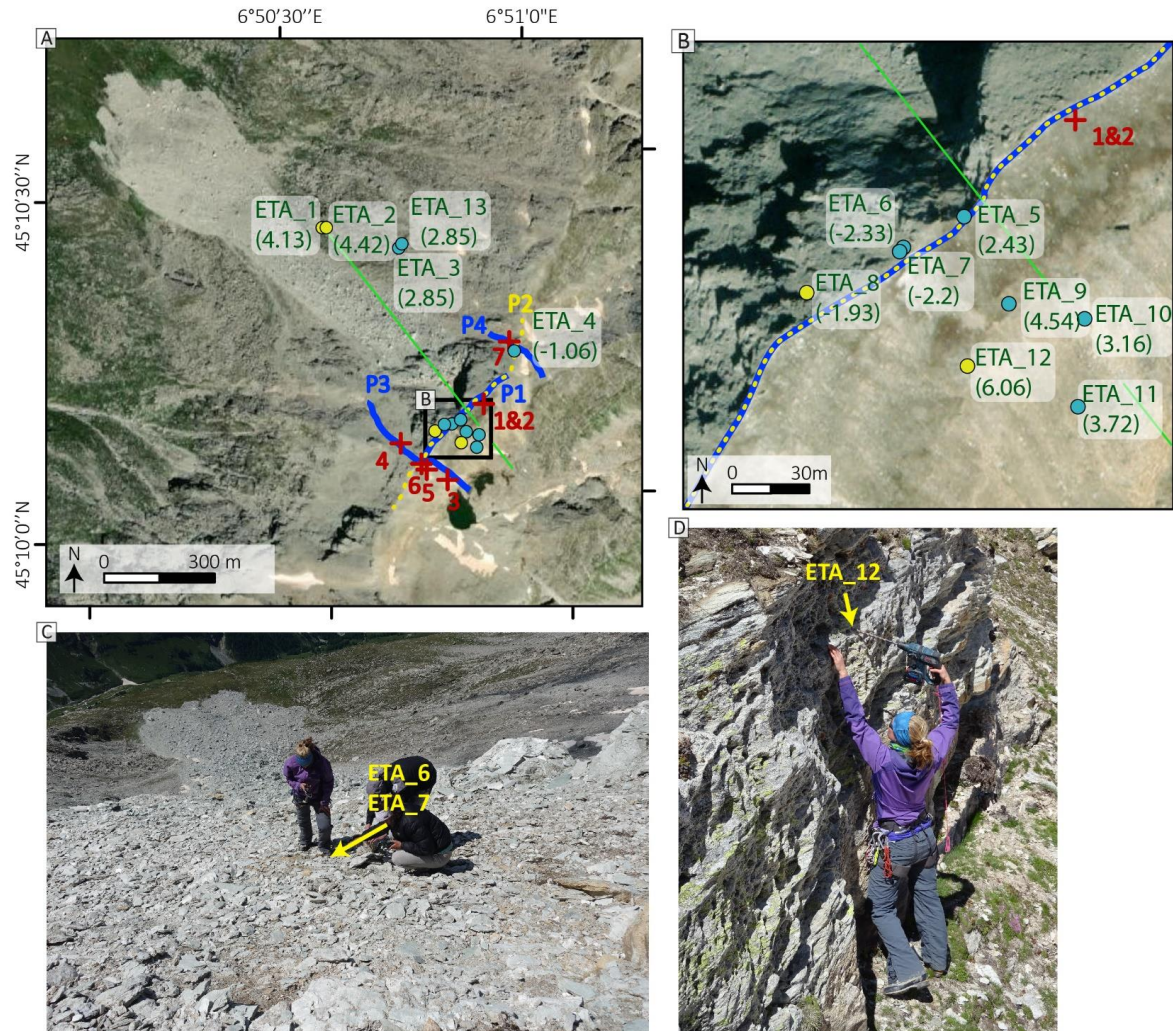
Precipitation anomalies:

- The cumulative precipitation records during the 2020 winter (271.2 mm) is +41.6 % (80 mm) higher than the average of 1991-2020
- The spring records (224 mm) show that the cumulative precipitation was only +4.4 % (10 mm) higher than the average of 1991-2020

Precipitation prior to the rock avalanche:

- Significant rainfall the week prior to the event (15 % of the spring 2020 rainfall in Bessans)
- Significant input of water (snow melt and rainfall, or rain on snow) suggested by positive air temperatures at the scar location

Ground temperature measurements

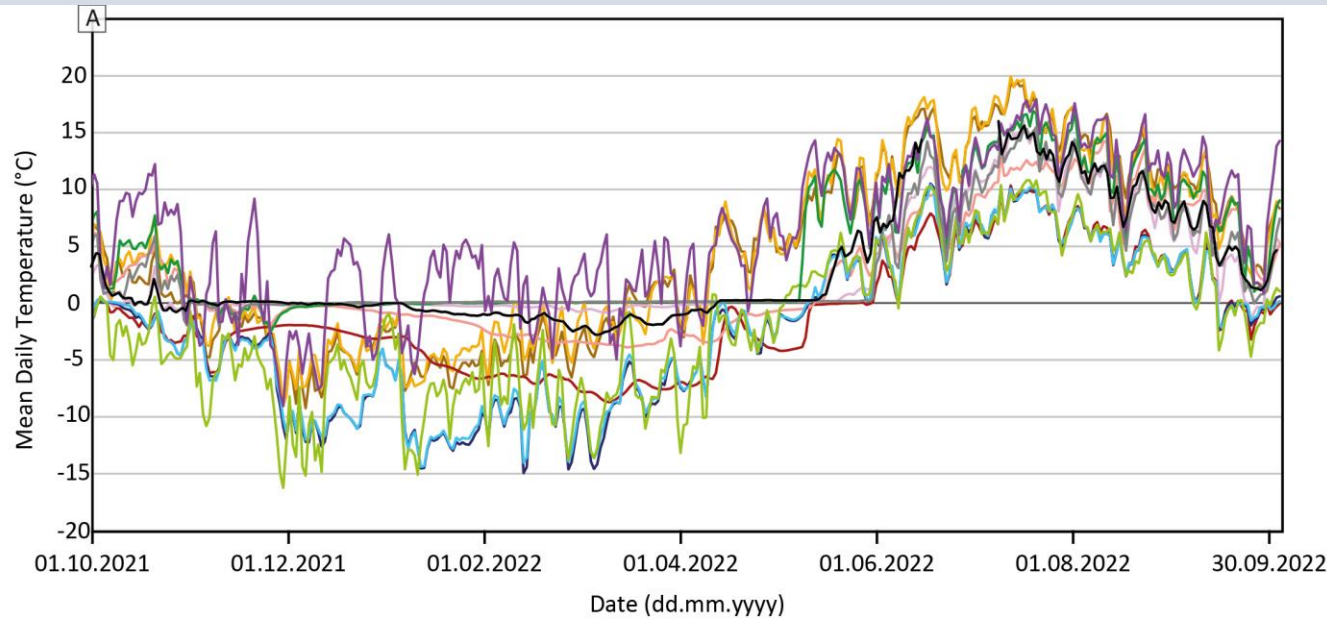


- 12 loggers installed (c. 10 cm below the surface)
 - elevation range from 2675 m to 3116 m asl.
 - different ground conditions and sun-exposure.
 - data recorded from 2021/10/01 to 2022/09/30.

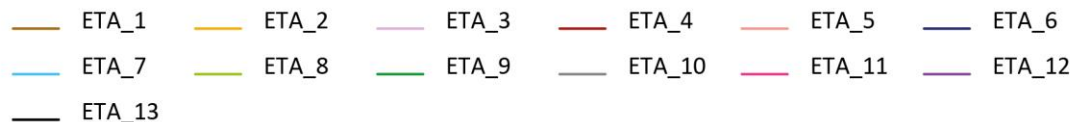
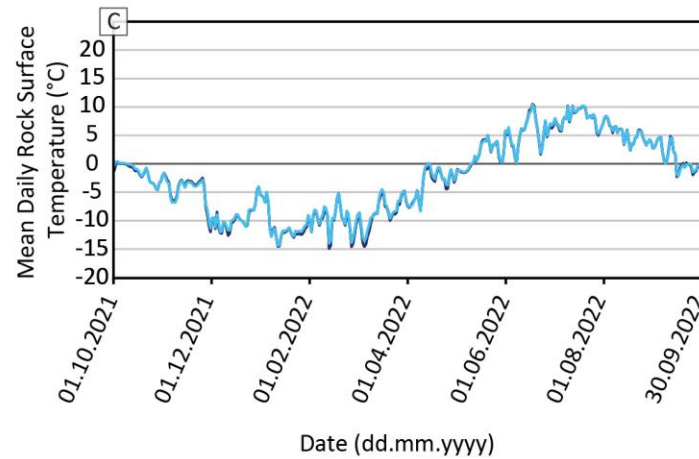
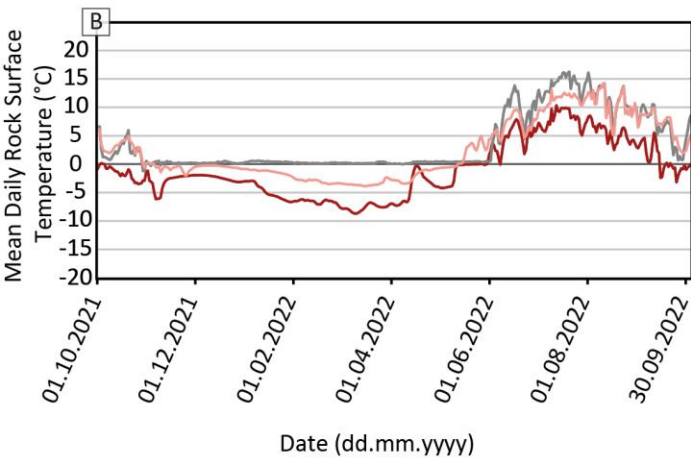
Field investigation

- Sensors on gentle slope (MAGST (°C))
- Sensors on rock outcrop (MAGST (°C))
- ERT profile and profile number (electrod spacing 5 m)
- ERT profile and profile number (electrod spacing 20 m)
- Linear section for heat transfer modeling
- Rock sample for petrophysical analysis

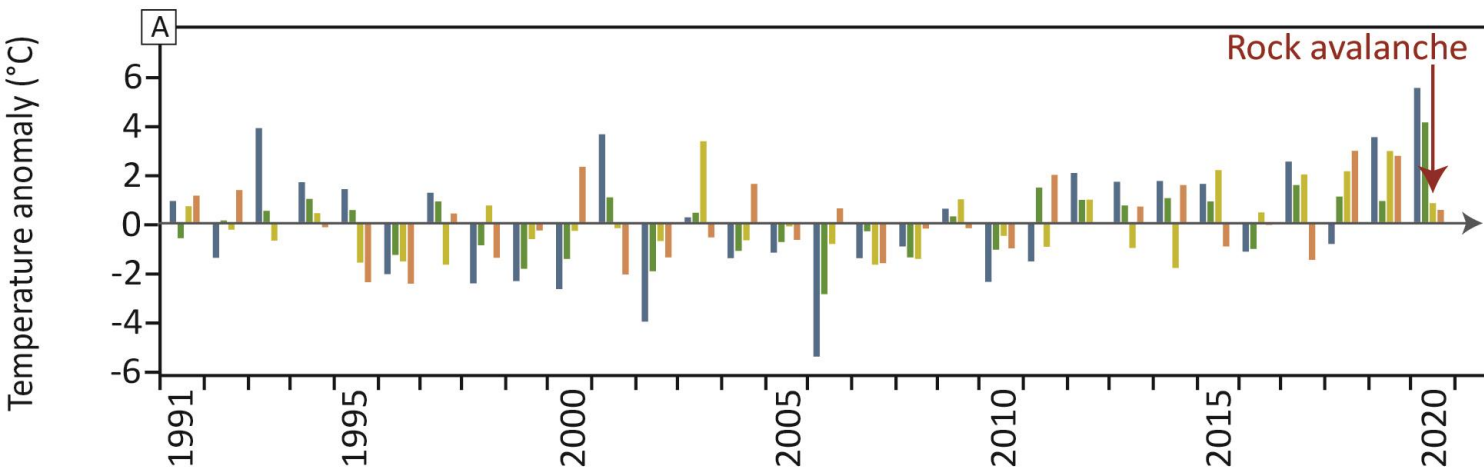
Ground temperature measurements



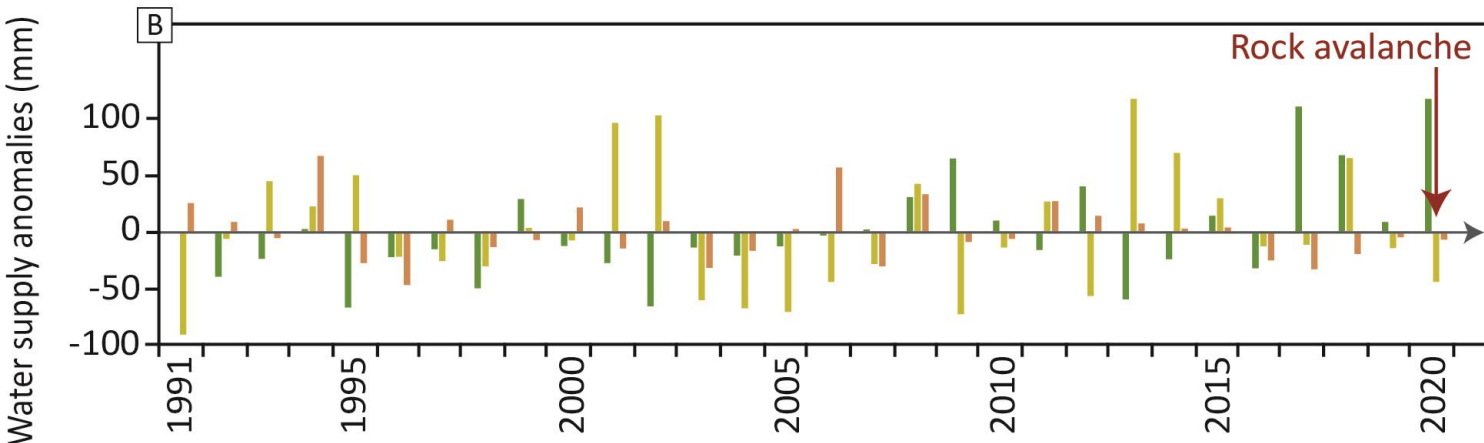
- MAGST: ranges from -2.3 to 6.1°C
- Sensors affected by snow (dampened daily oscillation and persistent sub-zero temperature in winter and spring).
- Effect of permafrost at depth (suggested by low temperature in winter for ETA_4 & ETA_5)



Energy balance modelling



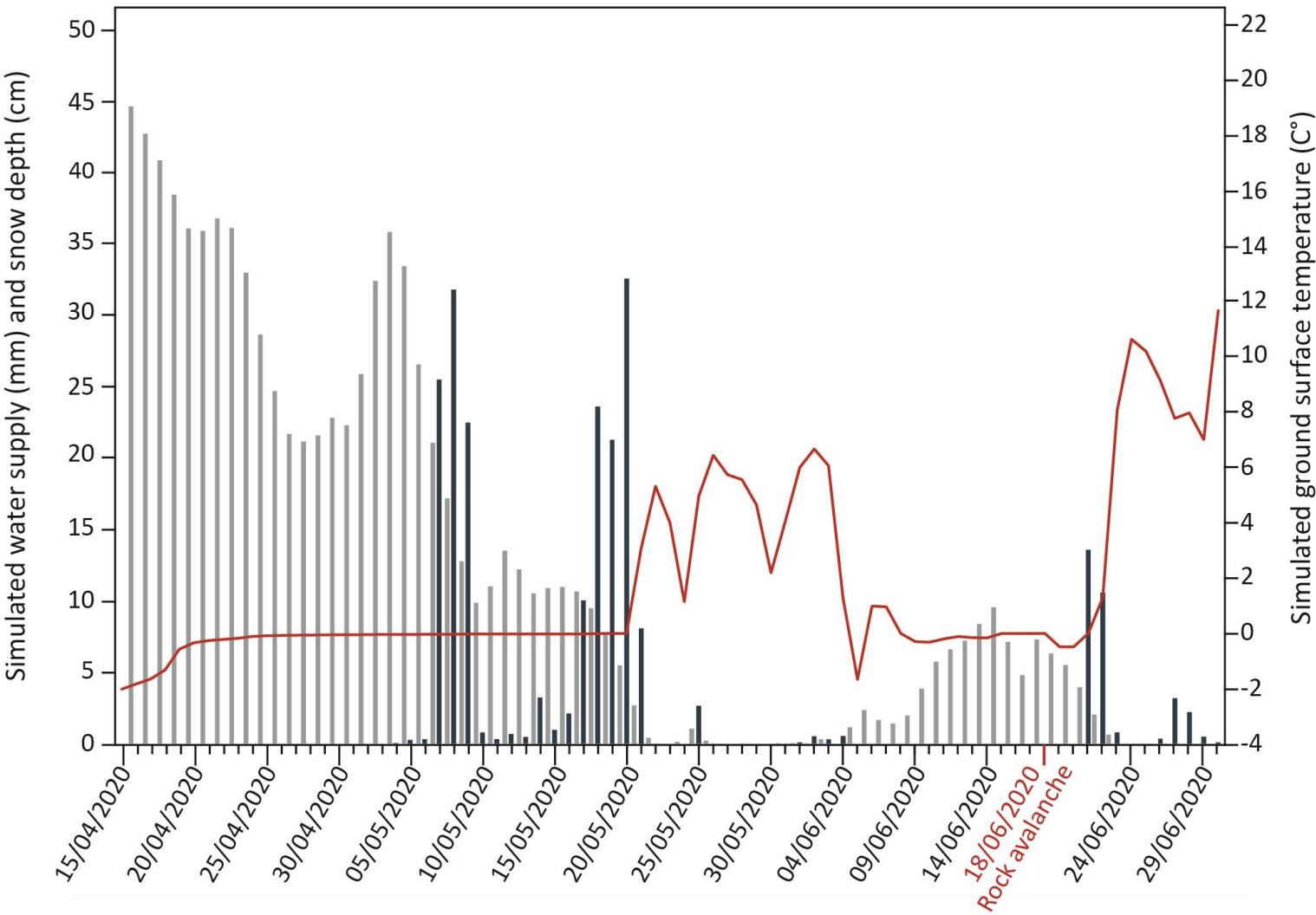
- Winter 2020: +5.5 °C warmer compares to 1991-2020 (2.9°C higher than the air temperature anomaly)
- Spring 2020: +4.1 °C warmer 2.9°C (2.6°C higher than the air temperature anomaly)
- Spring 2020: the largest available water supply (rainfall and snowmelt) since 1958 (+120 mm compared to 1991-2020).



- **Outstandingly high GST** (well higher than the air temperature)
- The **GST records are unprecedented** since the start of the modelled time series (1958)

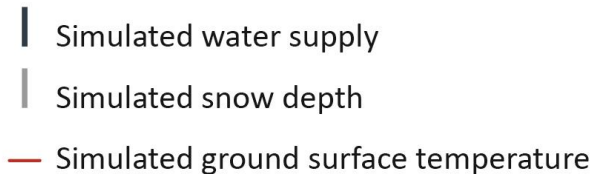
- Winter
- Spring
- Summer
- Autumn

Energy balance modelling

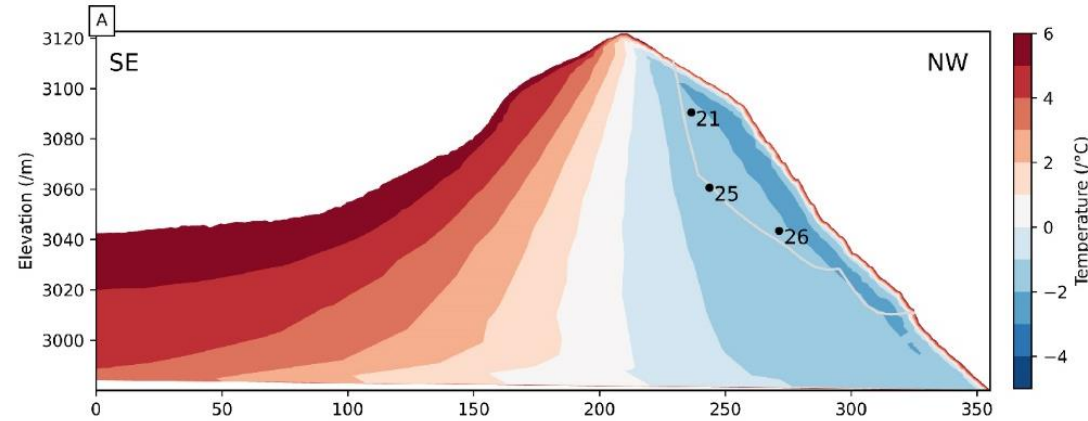


- Significant water supply available for infiltration during May 2020, extending up to 14 days prior to the event
- Substantial precipitation and snowmelt.

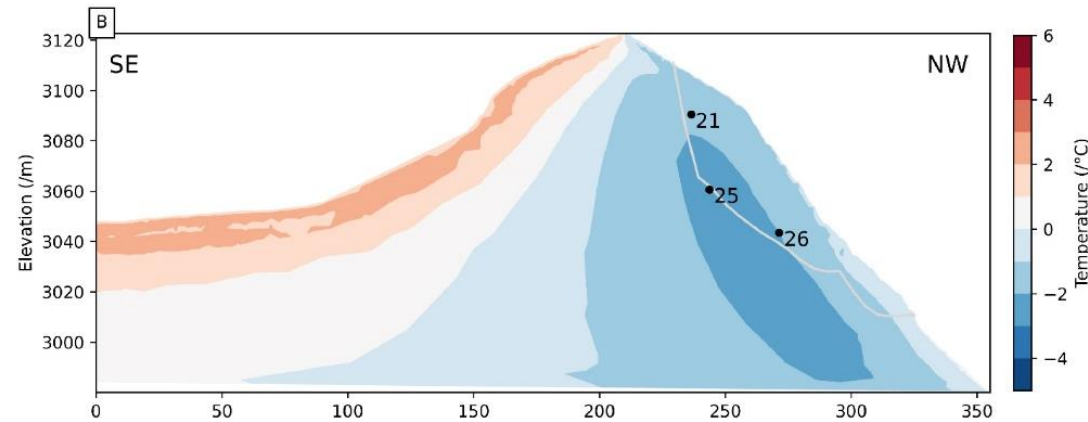
→ The rock avalanche also occurred during the **spring with the greatest water supply ever simulated since 1958.**



Heat transfert simulation

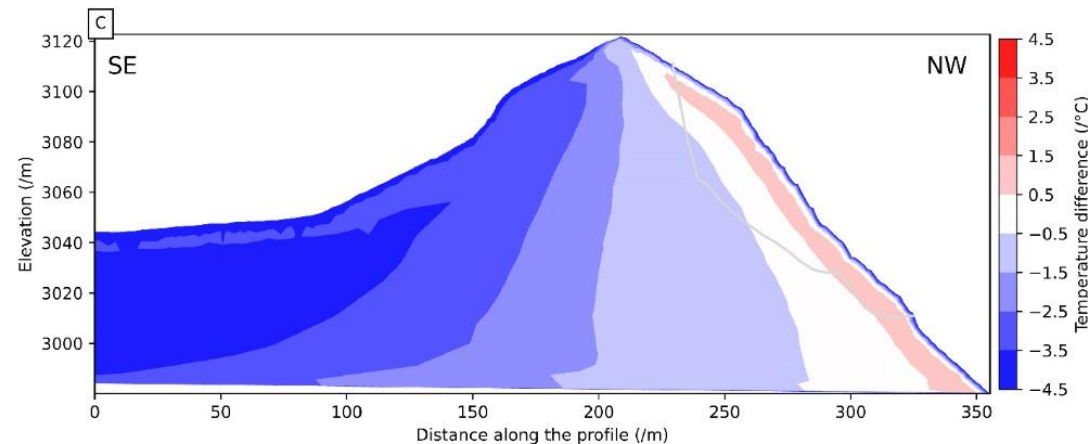


Simulation 1: **Forced** with rock surface temperature deduced from **air temperature** (does not account for the presence of snow)
= Strong horizontal gradient of temperature (4.5 °C difference between the SE and NW aspects)



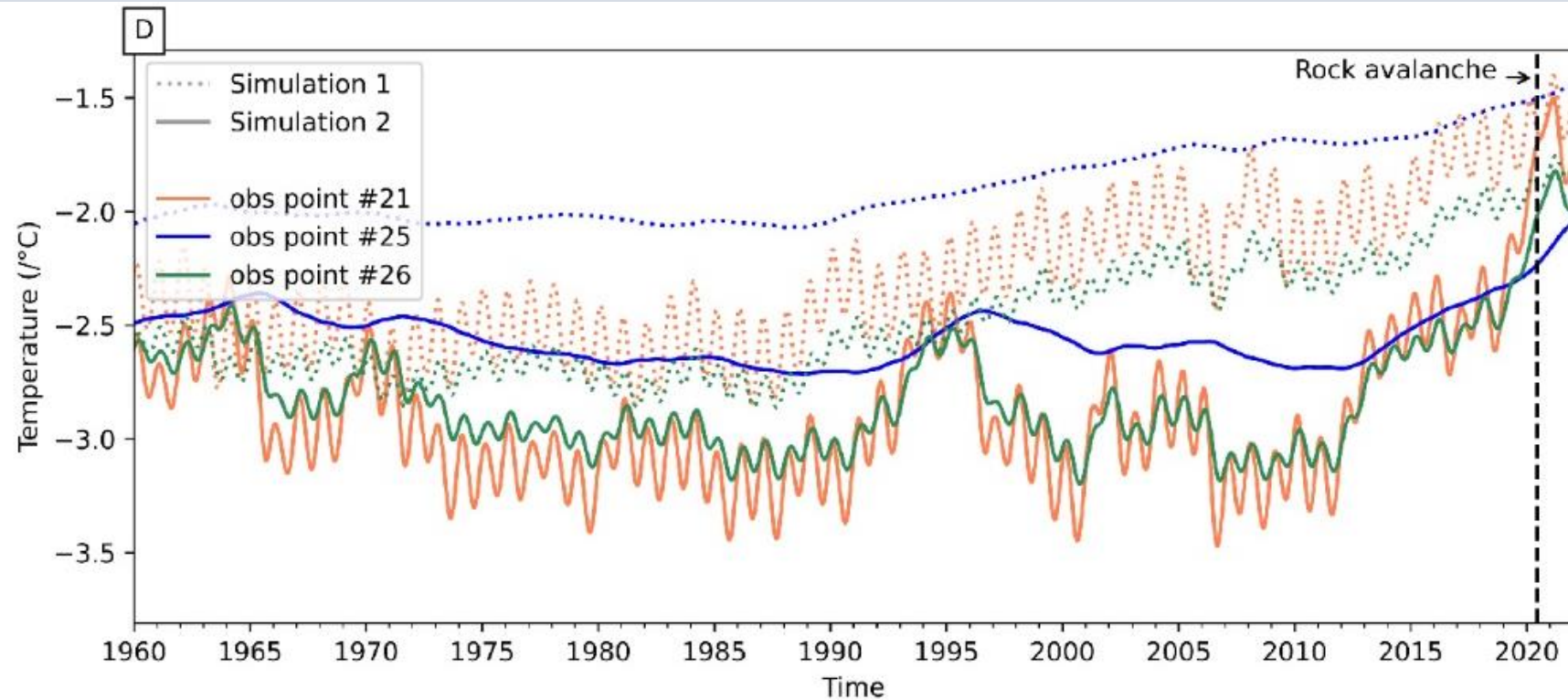
Simulation 2: **Forced with Cryogrid output data**
= Smoother pattern:

- South: cooling effect (due to albedo increase & delay of seasonal thaw because of snow cover).
- North: warming effect (the insulating effect of snow cover reduces winter cooling).



→ Heat transfer simulations confirm the presence of permafrost below the NW face

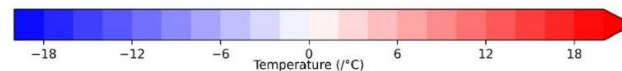
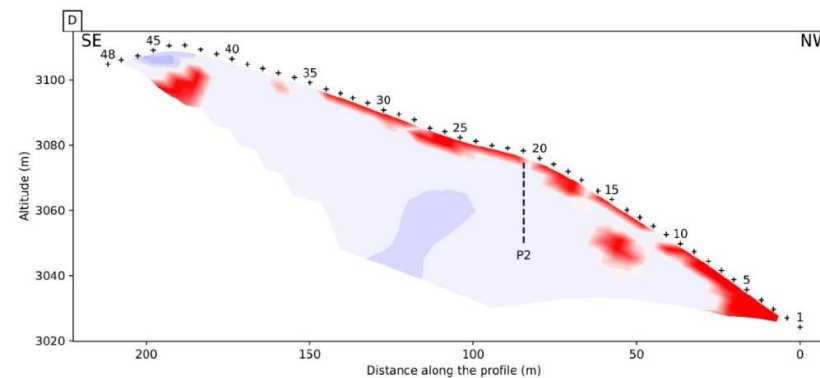
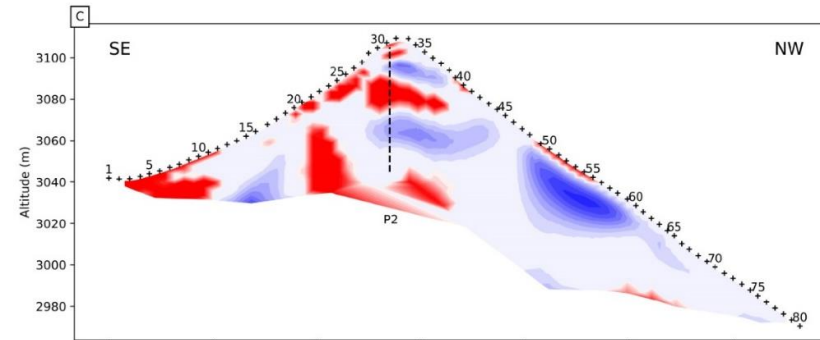
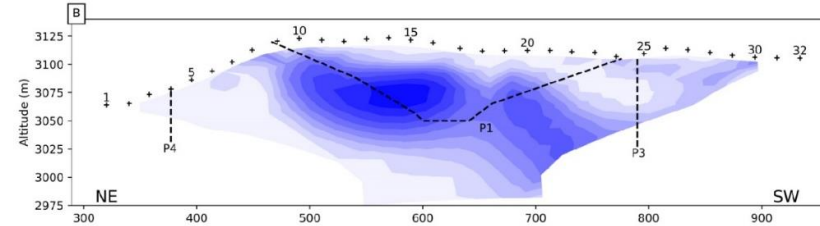
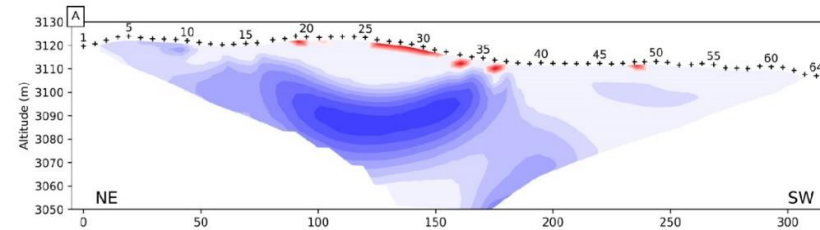
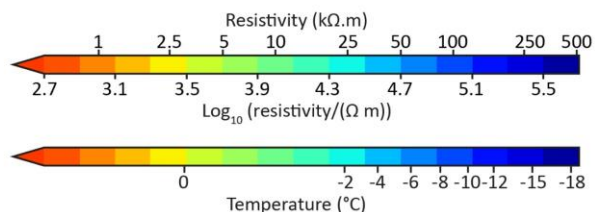
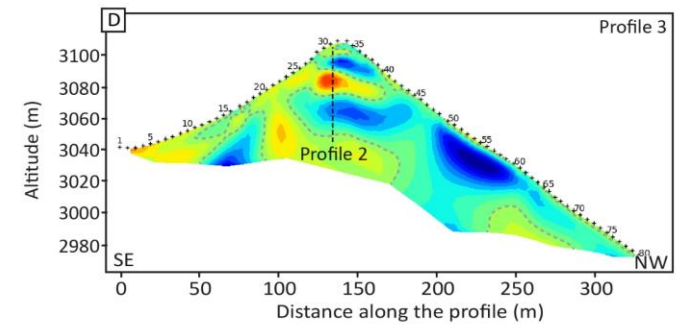
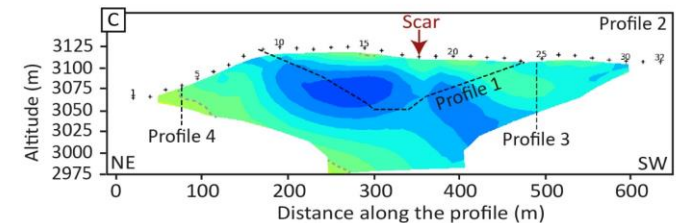
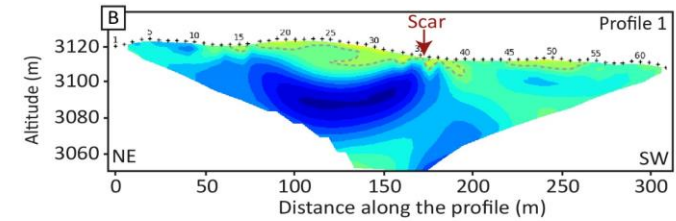
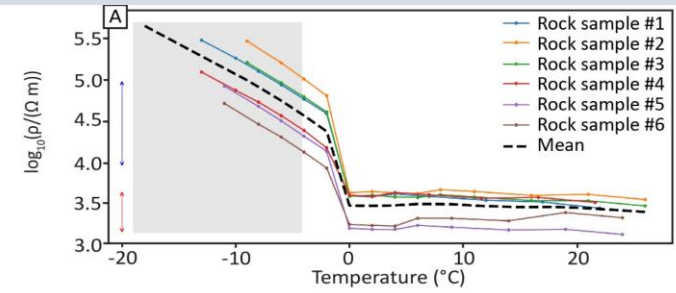
Heat transfert simulation



- Significant **warming trend** over the **past decade**
- Potential **transition from cold to warm permafrost** occurring from a few years to a few months prior to the event
- Simulation 2: **Increasing permafrost temperature since the 1990s**, with a particularly **sharp increase observed since 2012** at the depth of failure (reaching up to $+0.06 \text{ } ^\circ\text{C y}^{-1}$ at 30 m depth)

→ **Both the presence of an ice-rich layer and the steady warming of permafrost has certainly set preconditions for the rock avalanche.**

Geoelectrical survey

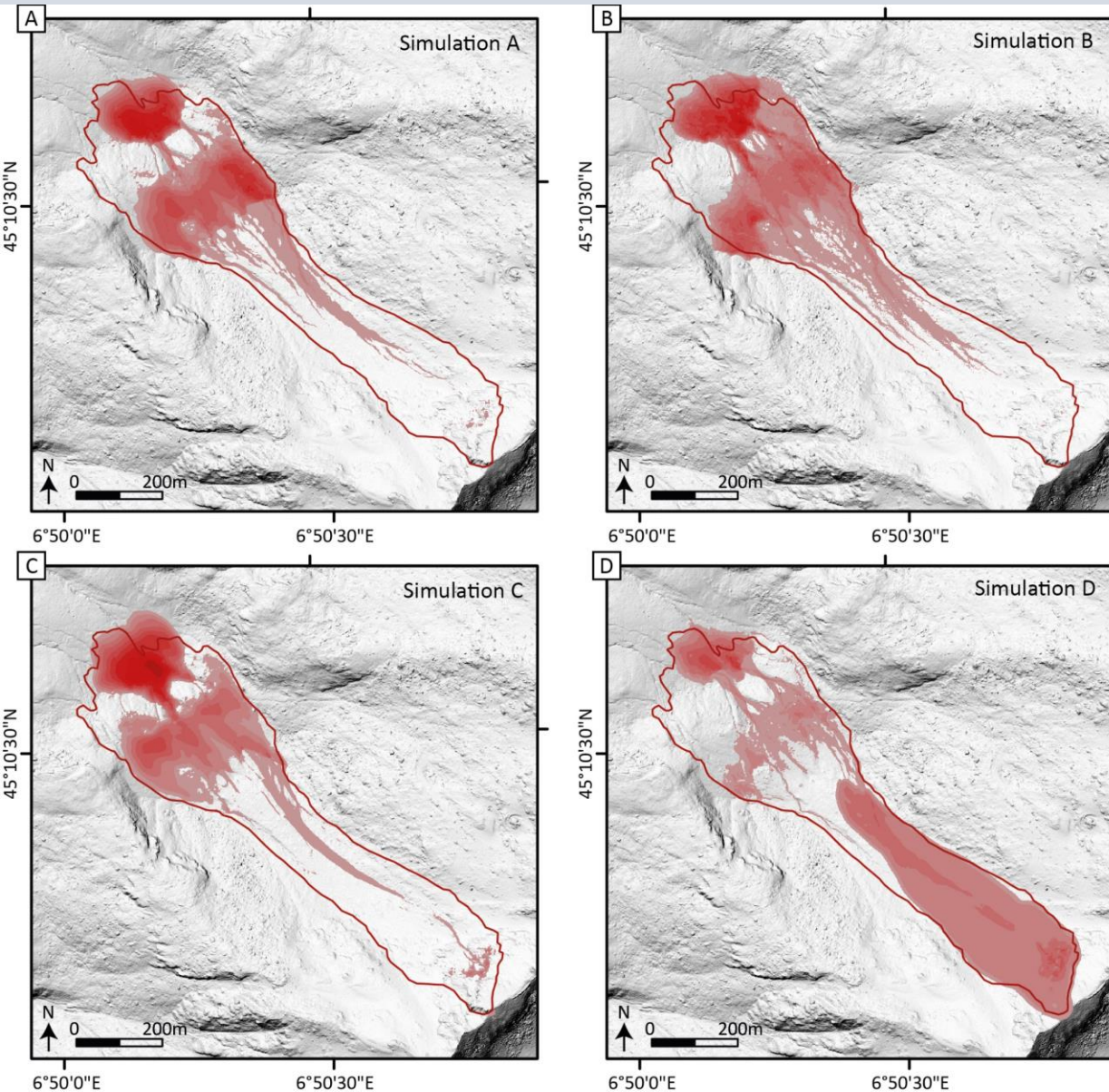


- High resistivity values ($> 10 \text{ k}\Omega \text{ m}$) confirms the presence of permafrost in the rock avalanche scar location
- Values exceeding those measured in the laboratory ($> 250 \text{ k}\Omega \text{ m}$) likely reveal a relatively **high ice content** around the rock avalanche scar.

Temperature-converted tomograms limitation :

As laboratory petrophysical measurements are carried out on intact and saturated samples, they are not representative of field conditions (unsaturated rock, fractures, variable ice content)

Propagation modelling : Method

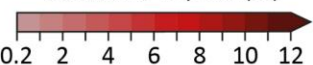


Flow-like propagation: continuous hydraulic was used and the flowing material was assumed to behave as a granular material (e.g., Pirulli and Mangeney, 2008; Sosio et al., 2012, Peruzzetto et al., 2022)

→ depth-averaged model with a Voellmy friction law

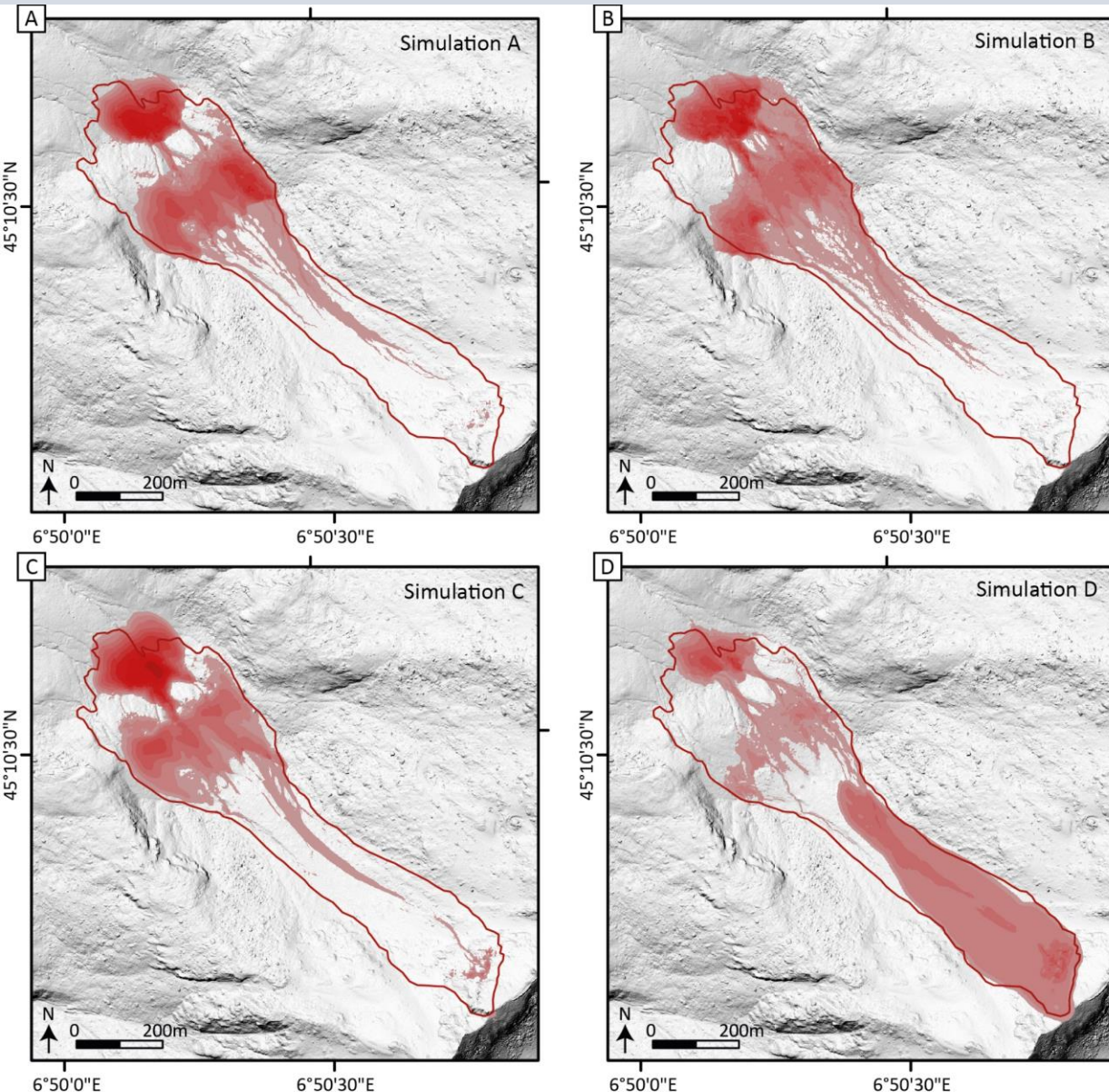
→ The material is characterized by the two rheological parameters μ (dry friction coefficient) and ξ (turbulent friction coefficient, in m s^{-2})

Simulated deposit (m)



□ Contour deposit according to raster comparison

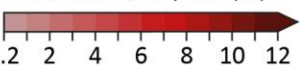
Propagation modelling : Method



- Simulation A ($\mu = 0.35$ and $\xi = 1,000 \text{ m s}^{-2}$)
- Simulation B (0.25 and $\xi = 100 \text{ m s}^{-2}$) correspond to a different balance between the dry and turbulent friction terms
- Simulation C ($\mu = 0.5$ and $\xi = 10,000 \text{ m s}^{-2}$) corresponds to an almost purely frictional rheology
- Simulation D:
 - Upper part: a volume of 230,000 m³ was considered. (In order to reproduce the relatively homogeneous deposit thickness along the upstream gully, the Voellmy law was enriched by adding a cohesive stress τ_c to the frictional contributions). $\tau_c/\rho = 16.5 \text{ m}^2 \text{ s}^{-2}$, $\mu = 0.1$ and $\xi = 1,000 \text{ m s}^{-2}$
 - Lower part: a volume of 90,000 m³ was considered (with a simple Voellmy law). $\mu = 0.25$ and $\xi = 1,000 \text{ m s}^{-2}$ for the lower part

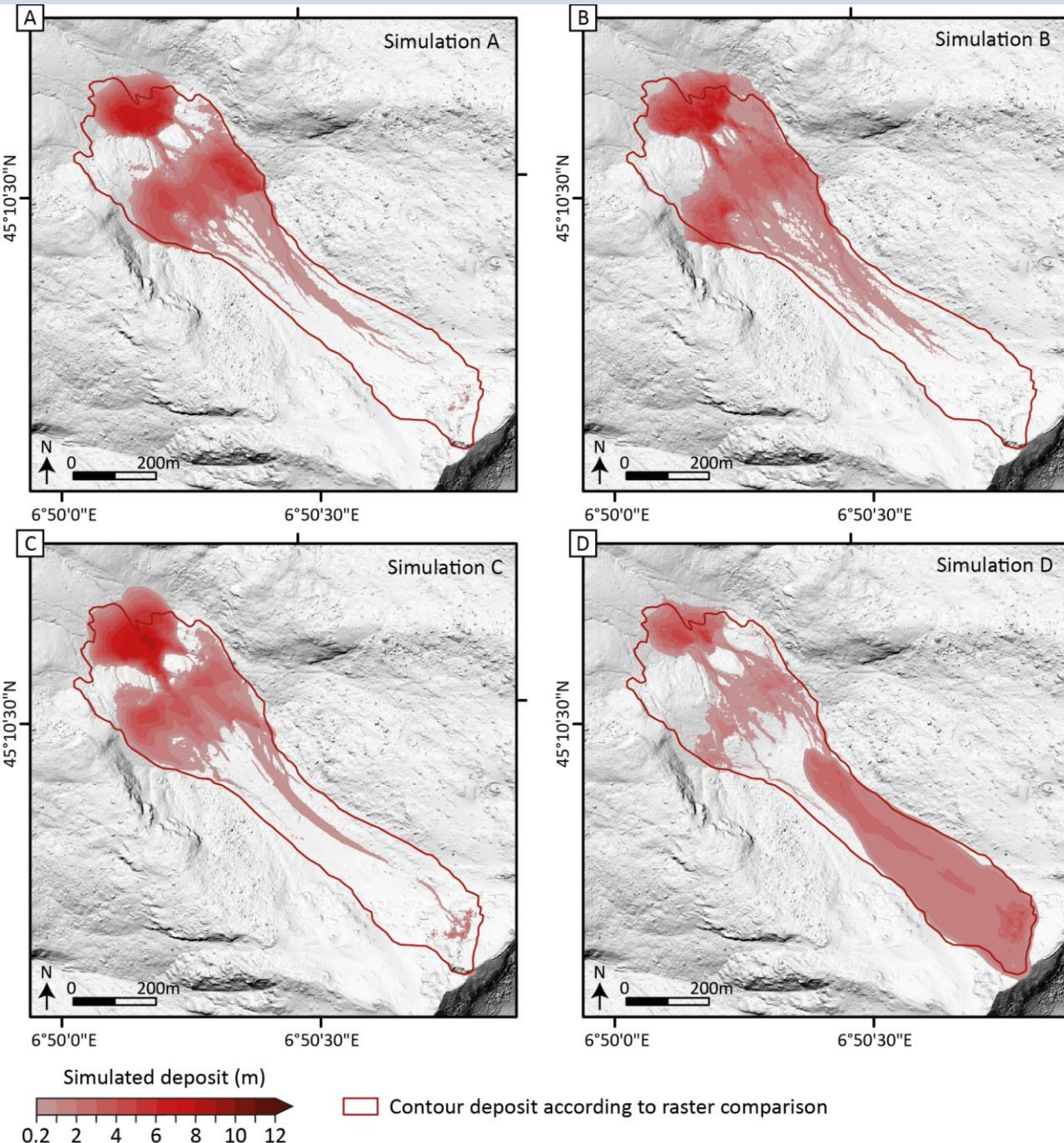
= Simulation D corresponds to the merged deposits

Simulated deposit (m)



Contour deposit according to raster comparison

Propagation modelling : Results



Simulations A, B, C: the thickest parts of the deposits are always located in the two flat zones, especially in the distal lobe whose simulated thickness can reach 8 m

- This inability of the simulations to reproduce the actual distribution of the deposit can be interpreted as an indication that the **flow model is oversimplified**, and fails to account for important **physical processes** that were at play during the avalanche propagation
- Such complex mechanisms would require more sophisticated modelling tools based, typically, on multiphase approaches

Simulation D: thickness distribution appears to be better reproduced. The simulated deposit is thicker in the upper-central area as well as at the lower front.

- Even if the physical basis of this composite simulation remains debatable, the result seems to confirm that the propagation of the Étache rock avalanche involved distinct materials characterised by markedly different rheological properties

- Numerical simulations allow to highlight a relatively complex flow process
- Voellmy friction law appears insufficient to fully reproduce the observations = need for multiphase approaches
- The results suggest an evolution of the effective rheological properties along the flow, which could be due to the **entrainment of snow by the rock avalanche**

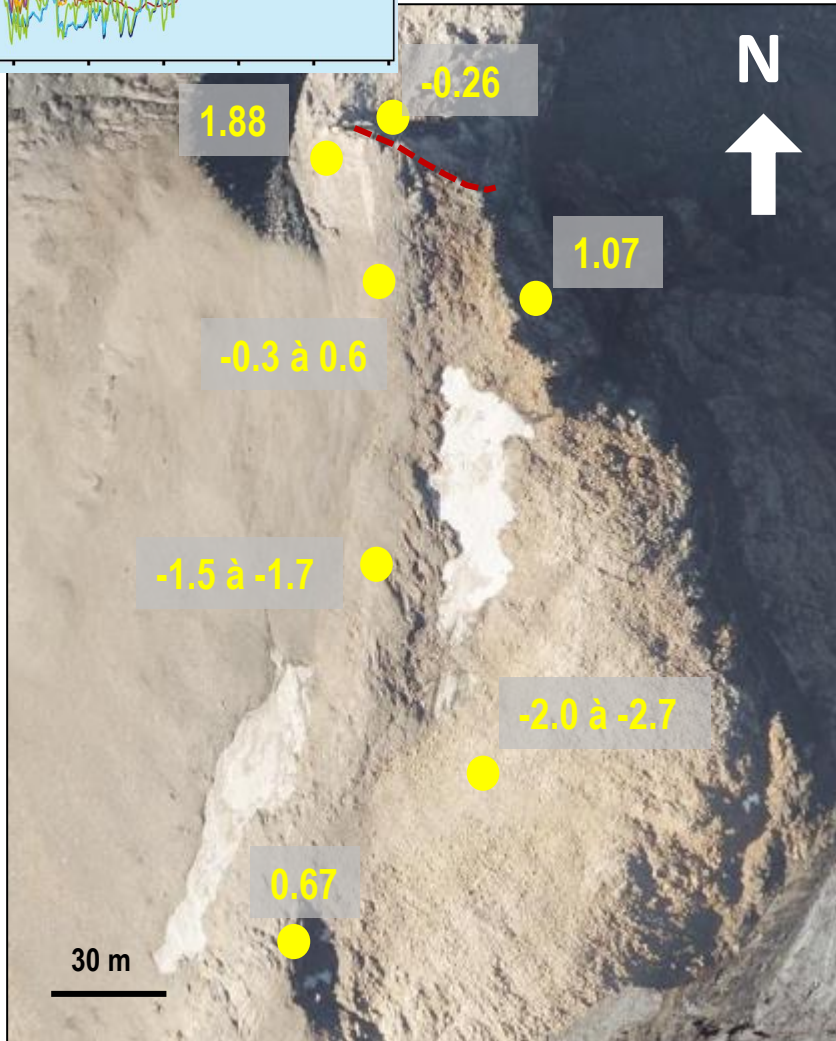
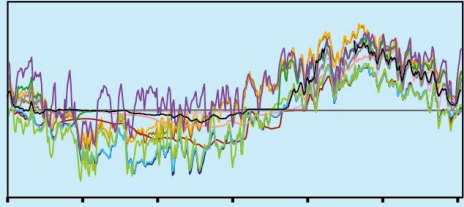
CARACTÉRISER L'ÉTAT THERMIQUE DU SITE

Étache valley

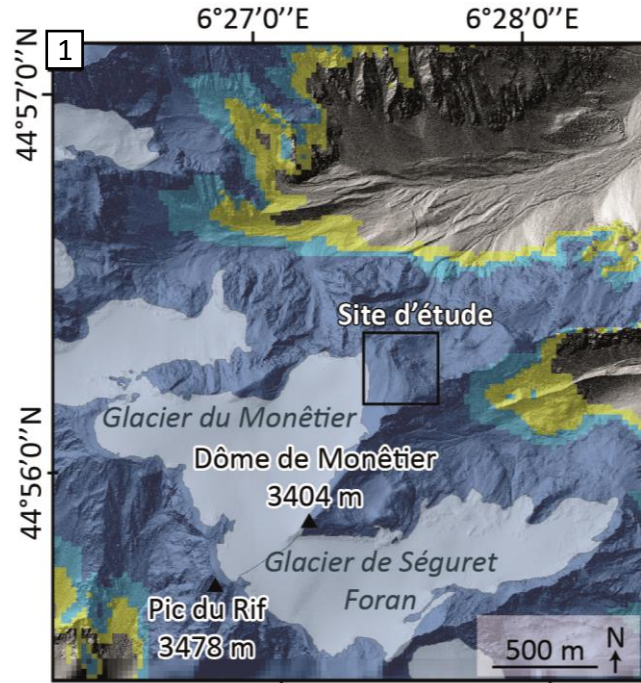


Grangettes

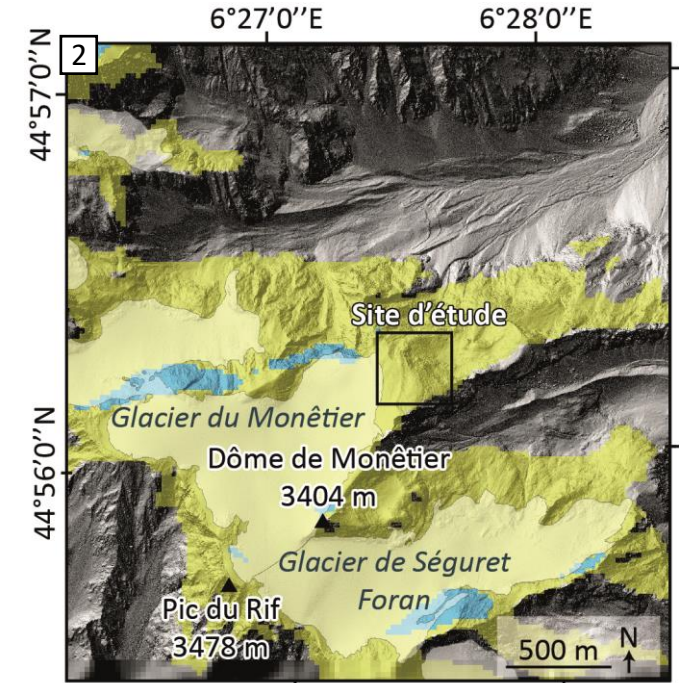
Mesures de température *in-situ*



1- Carte de permafrost dans les formations superficielles



2- Carte du permafrost de paroi



- Permafrost présent dans presque toutes les conditions
- Permafrost présent principalement dans les conditions froides
- Permafrost présent uniquement dans les conditions très favorables

→ Présence de permafrost **sous-estimée en paroi**, **sur-estimée dans les formations superficielles**

RESULTS & DISCUSSIONS

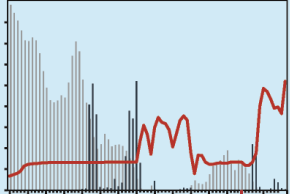
1) Thermal conditions

2) Preconditioning mechanism

3) Spatial and temporal evolution of permafrost

4) Propagation mechanisms

Hydrological and energy balance modelling

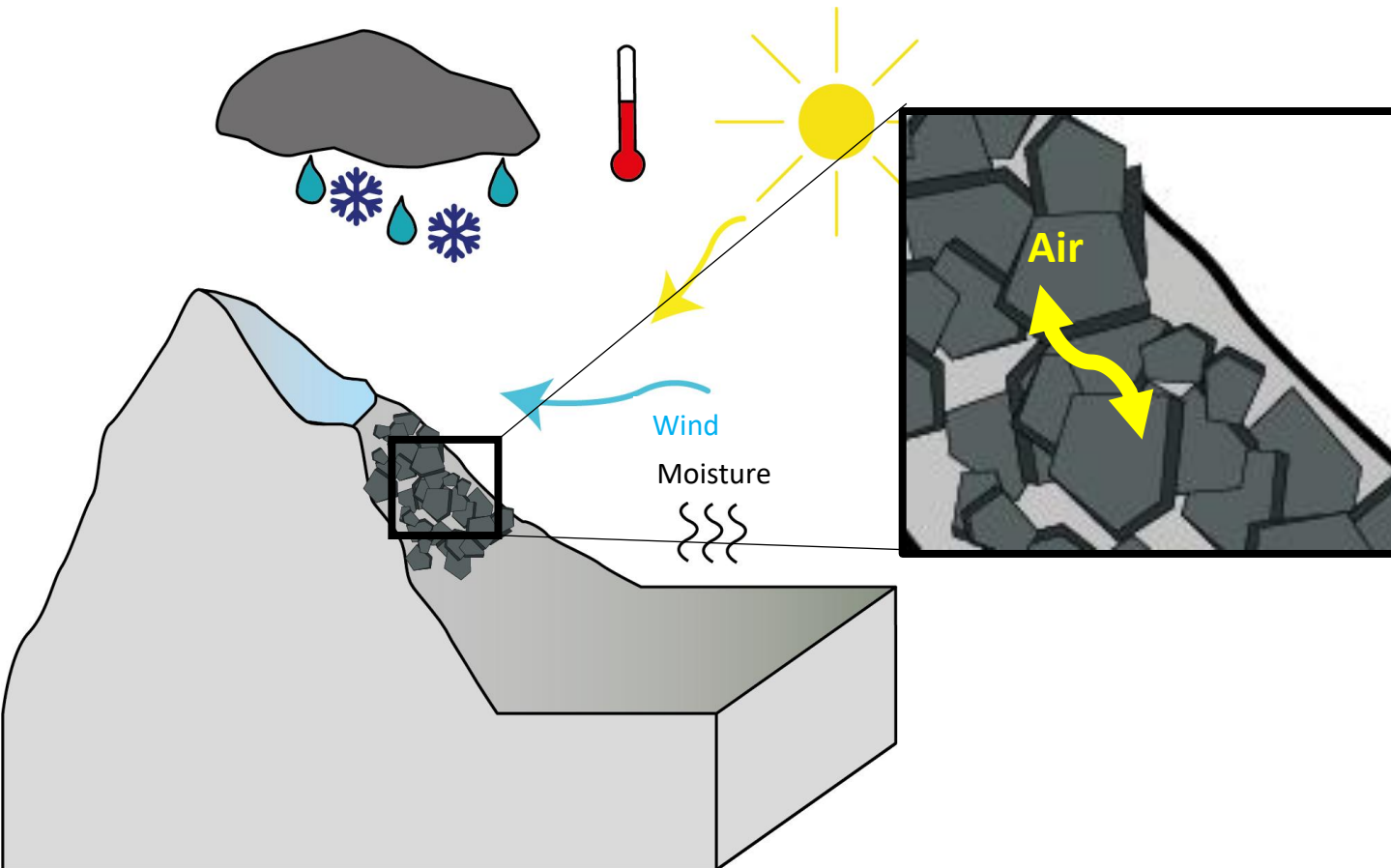


THERMAL AND HYDROLOGICAL CONDITIONS OF THE GROUND BEFORE THE EVENT Grangettes crest



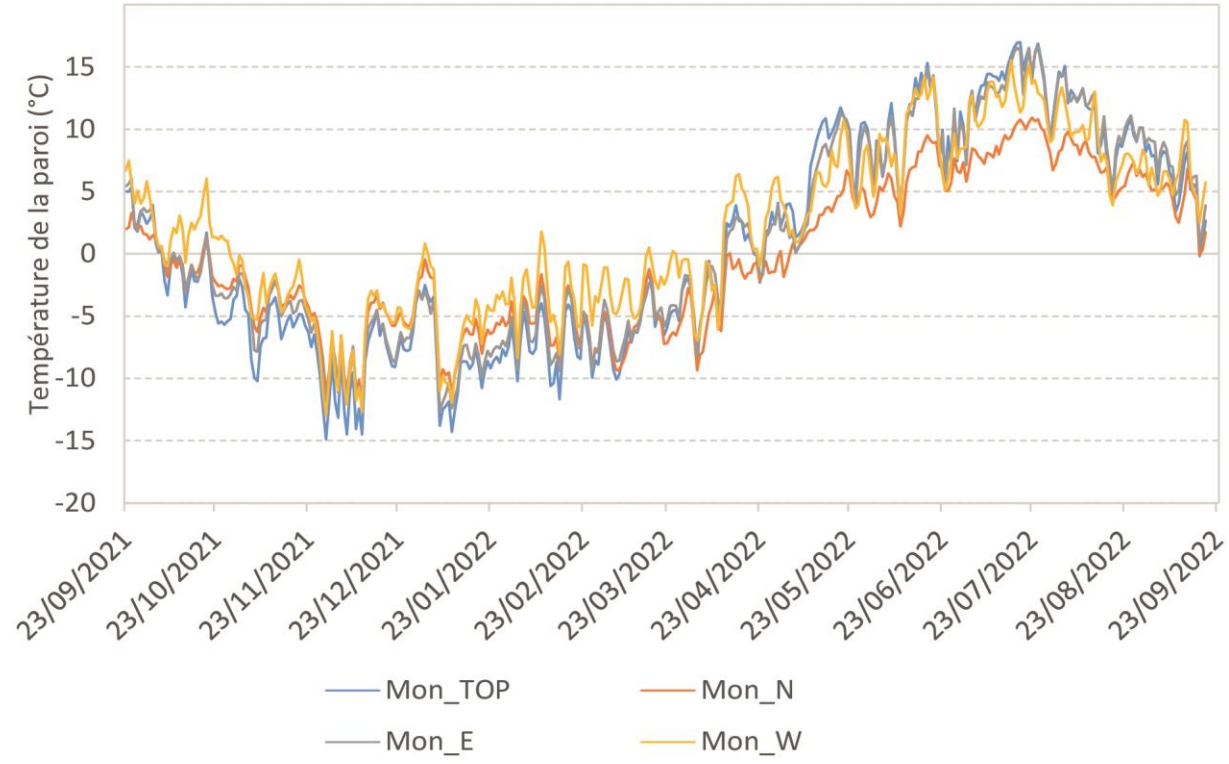
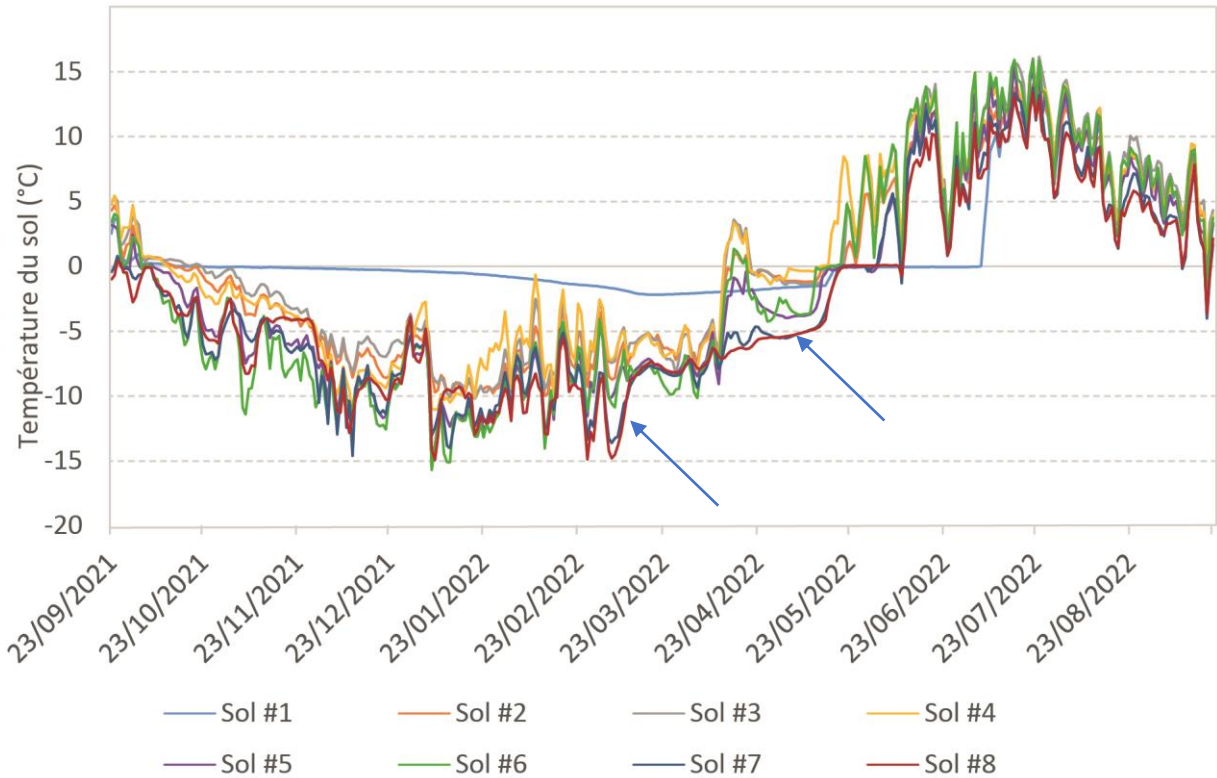
No modelling with *CryoGrid*

→ Air circulation between blocks controlling surface temperature



Crête des Grangettes

Mesures de Températures *in-situ*



Crête des Grangettes

