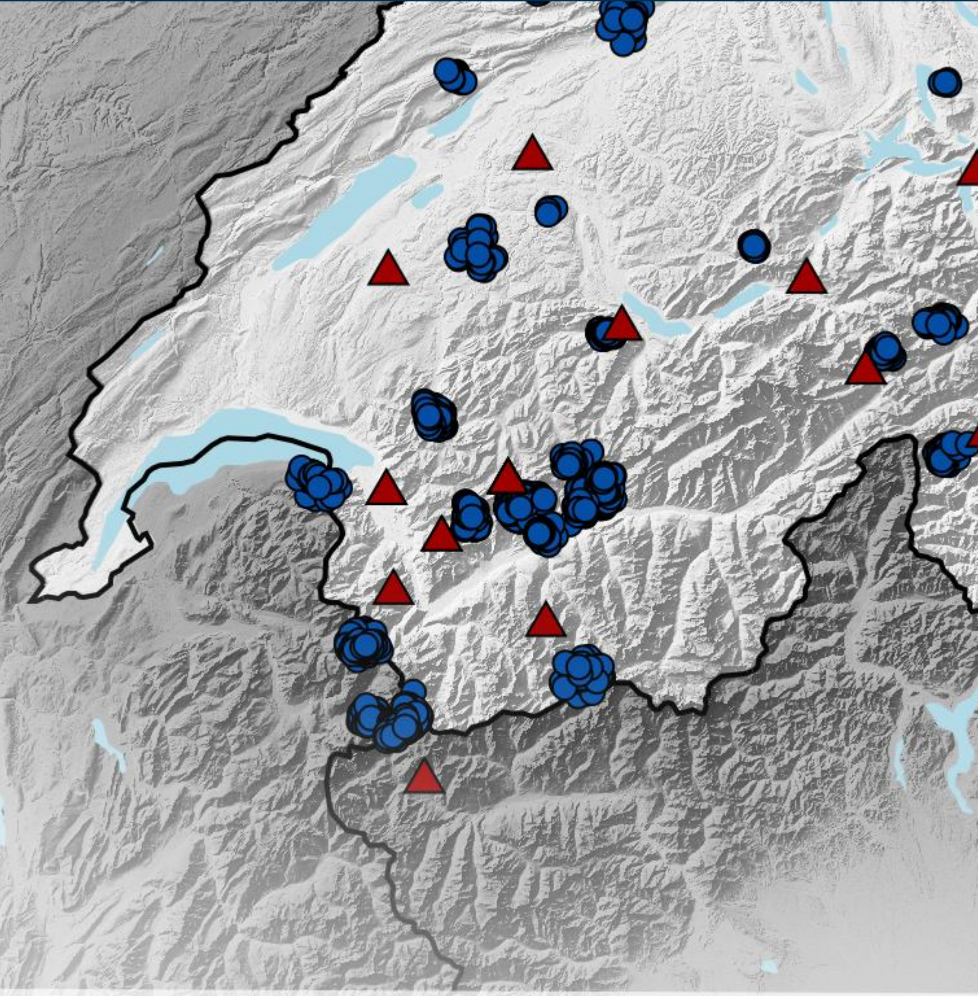
Climate-change induced seismicity:

The recent onset of seasonal micro-seismicity at the Grandes Jorasses, Mont-Blanc Massif



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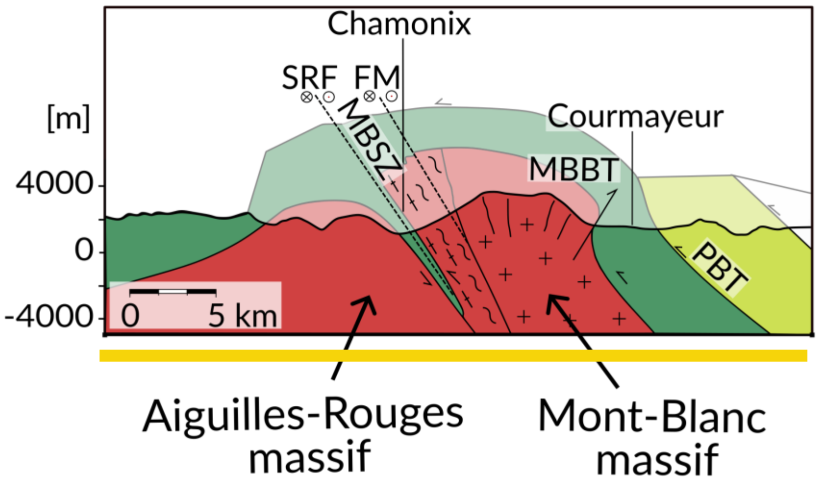
FNSNF
Swiss National Science Foundation

Schweizerischer Erdbebendienst
Service Sismologique Suisse
Servizio Sismico Svizzero
Swiss Seismological Service

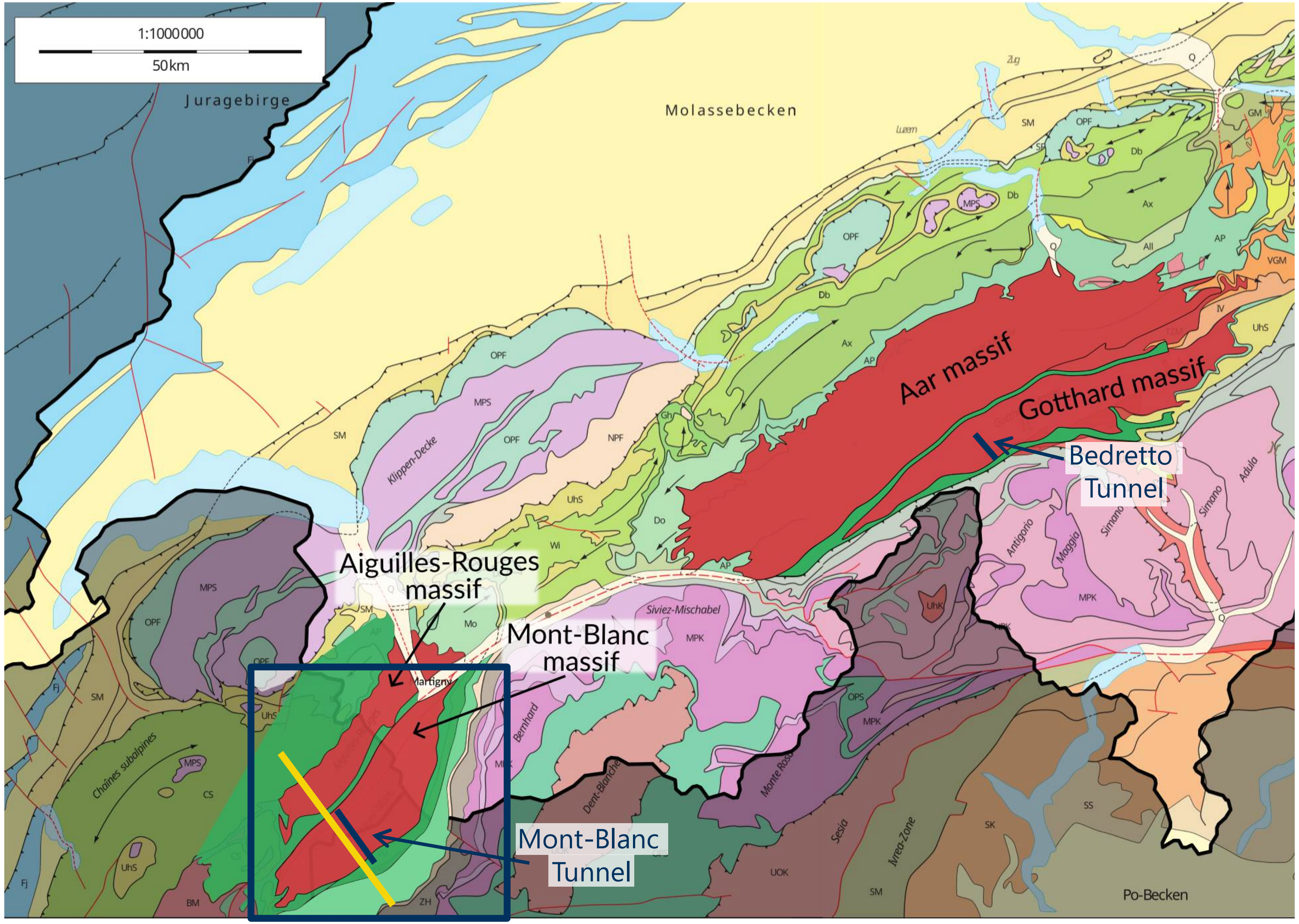
ETH zürich

MUMA

Geological Background Mont-Blanc Massif (**MBM**)



Adapted from Egli & Mancktelow (2013)

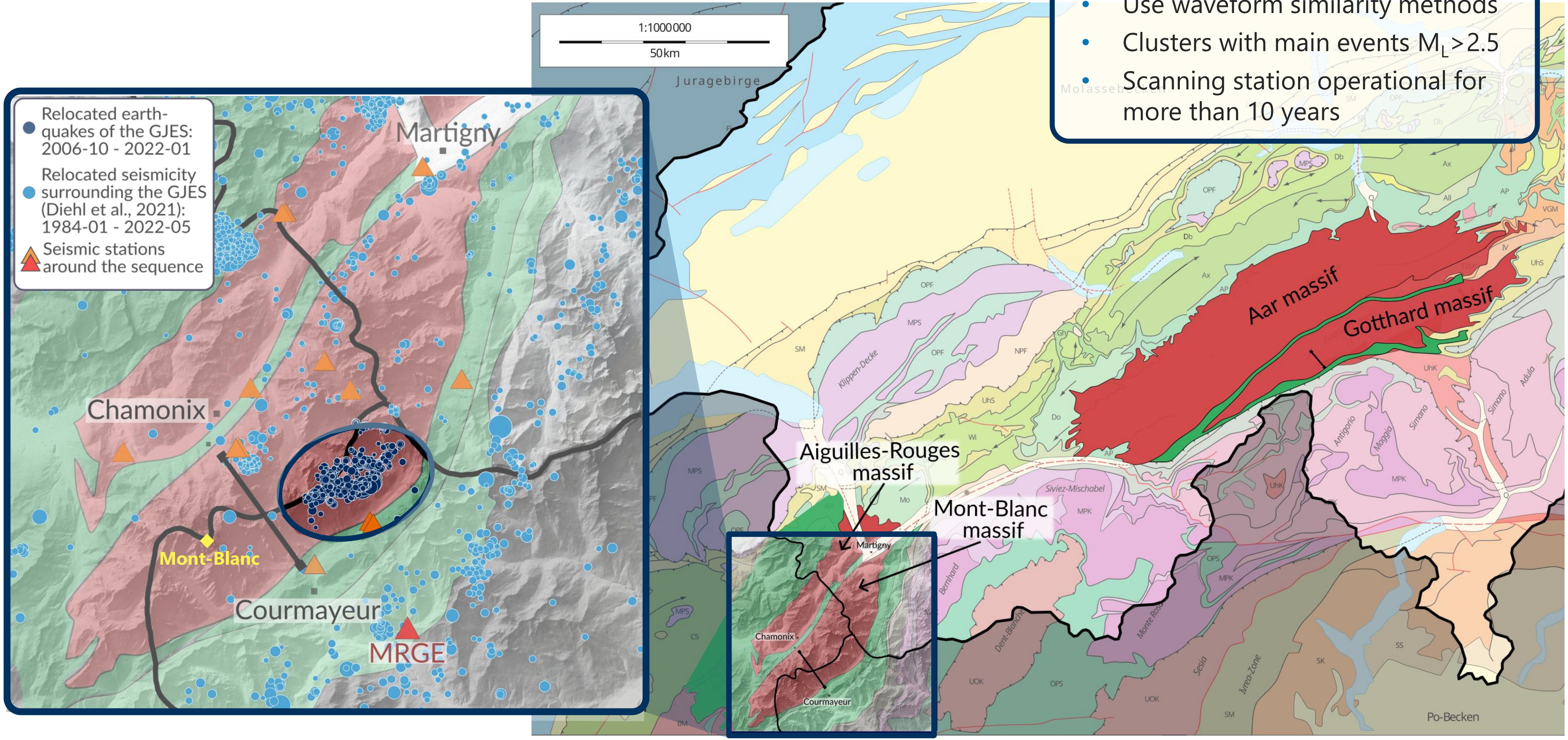


Adapted from Pfiffner (2009)

Geological Background Mont-Blanc Massif (**MBM**)

Approach:

- Use waveform similarity methods
- Clusters with main events $M_L > 2.5$
- Scanning station operational for more than 10 years



Adapted from Pfiffner (2009)

Analysis Workflow

1. Spatial Clusters
2. Template Matching
3. Magnitude Estimation
4. Statistical Analysis
5. Relocation

QuakeMatch

T. Toledo, PICO Session F today

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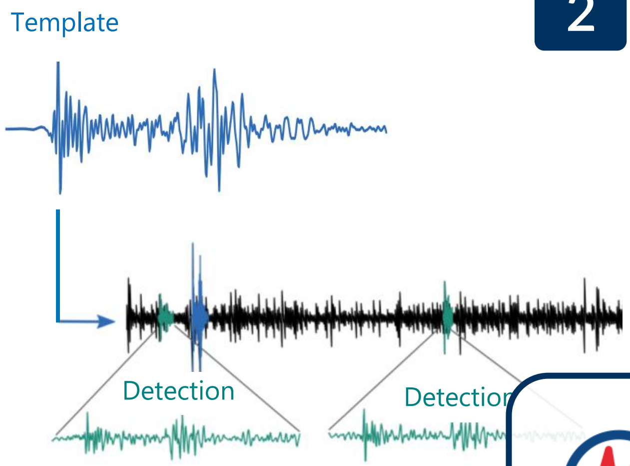

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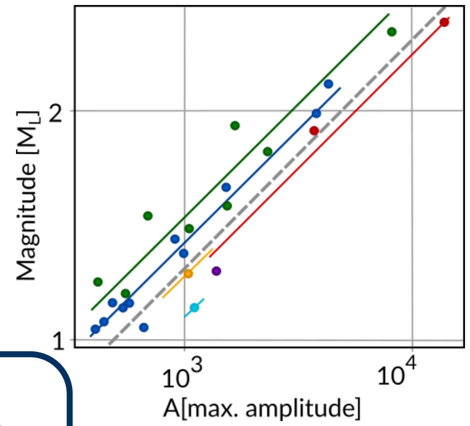

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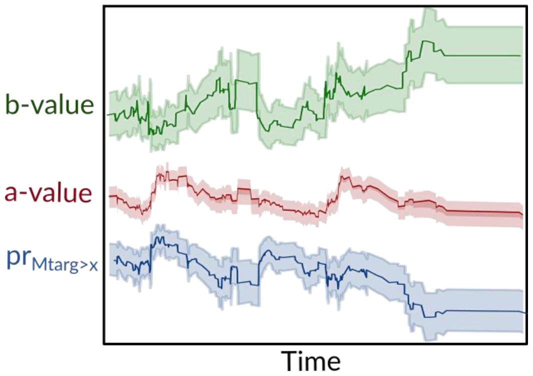

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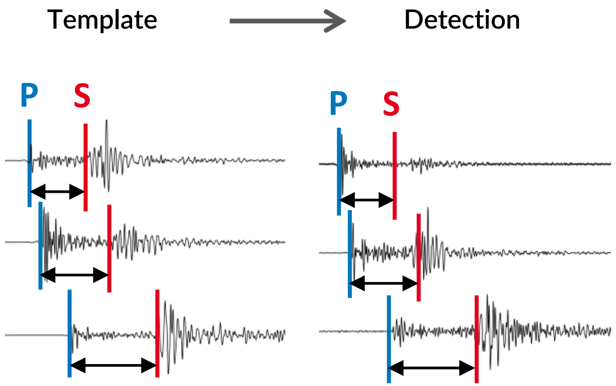
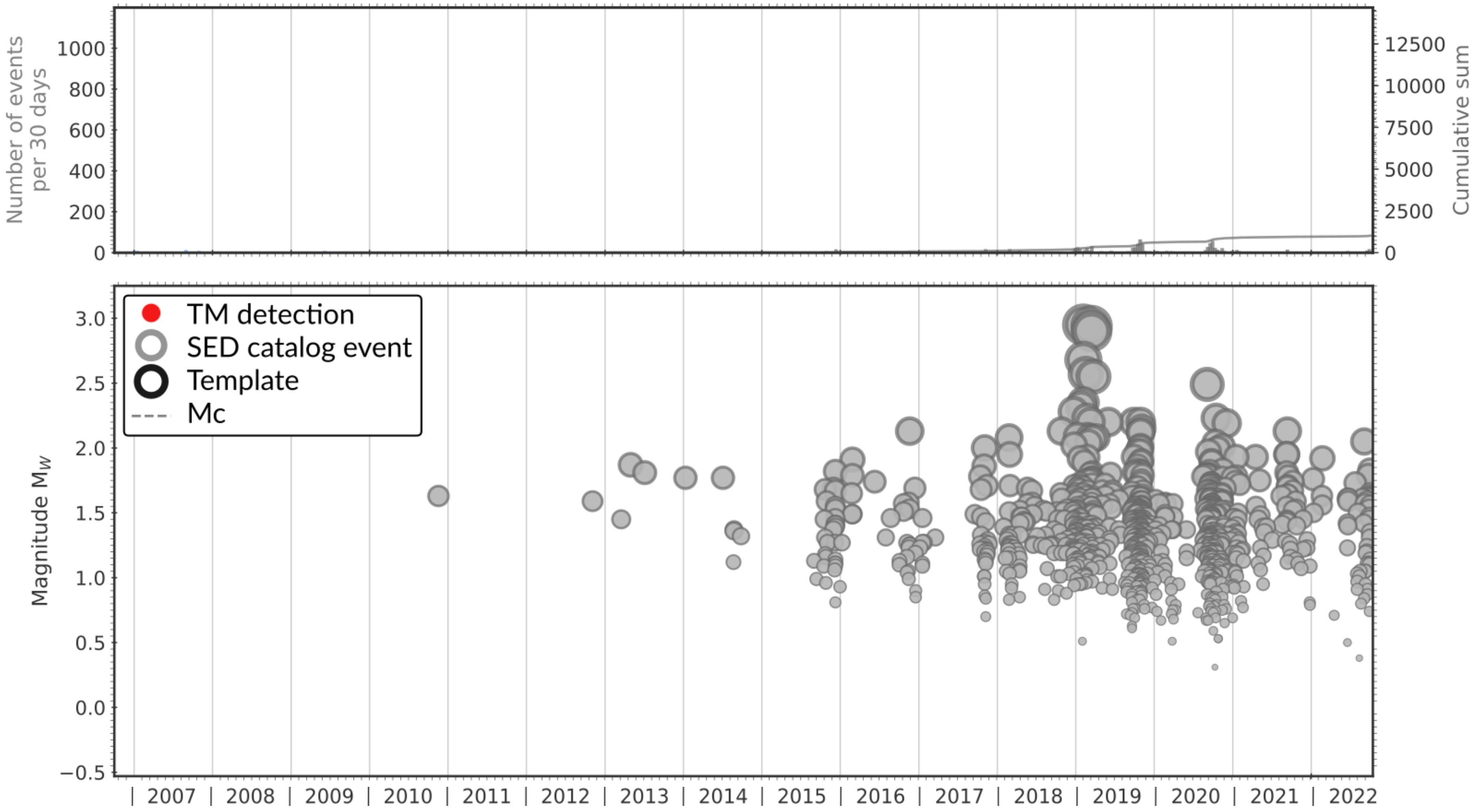


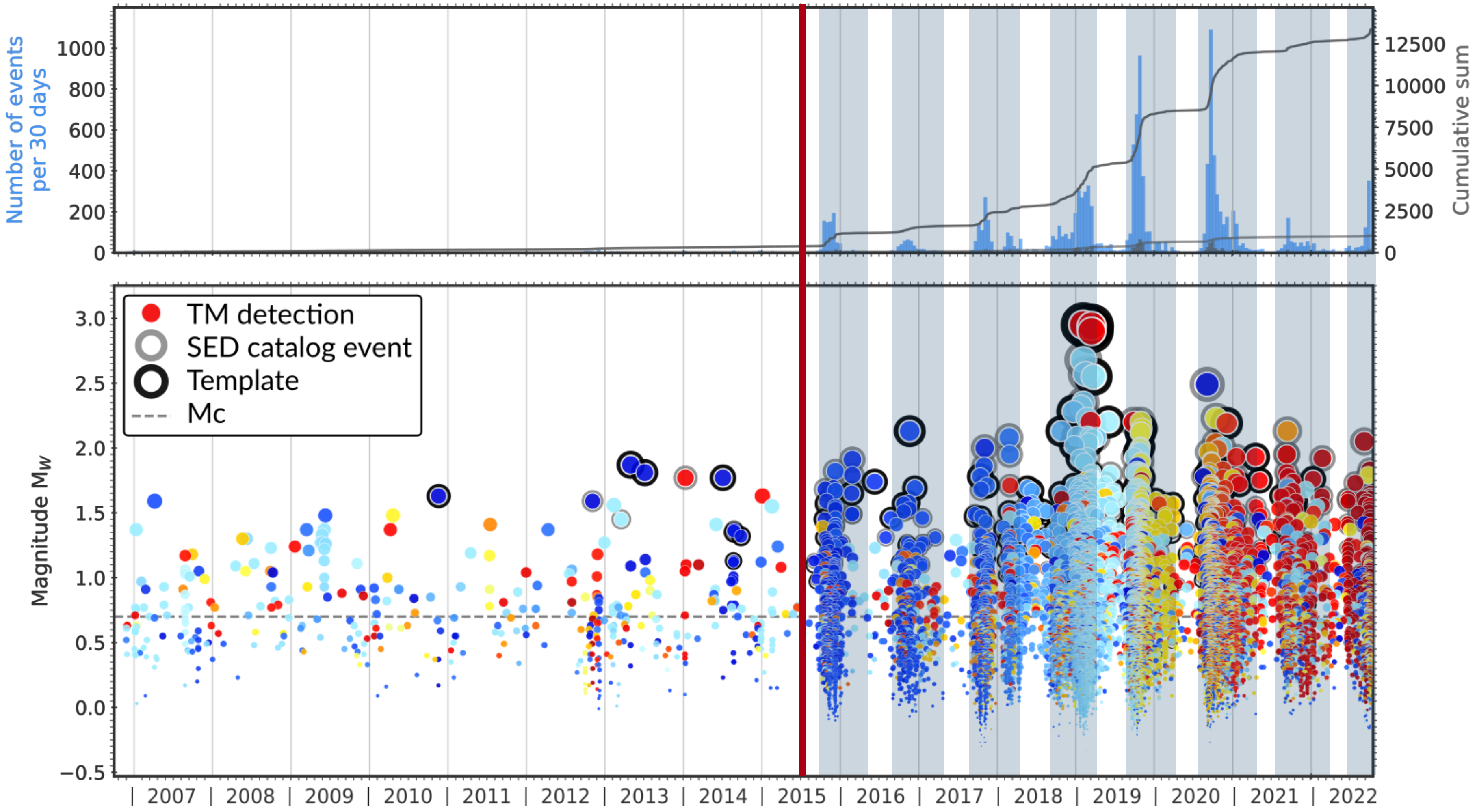
Herrmann et al. (2019), Toledo et al. (2025)

Earthquake activity



- 1142 routinely monitored earthquakes
- 372 templates

Earthquake activity



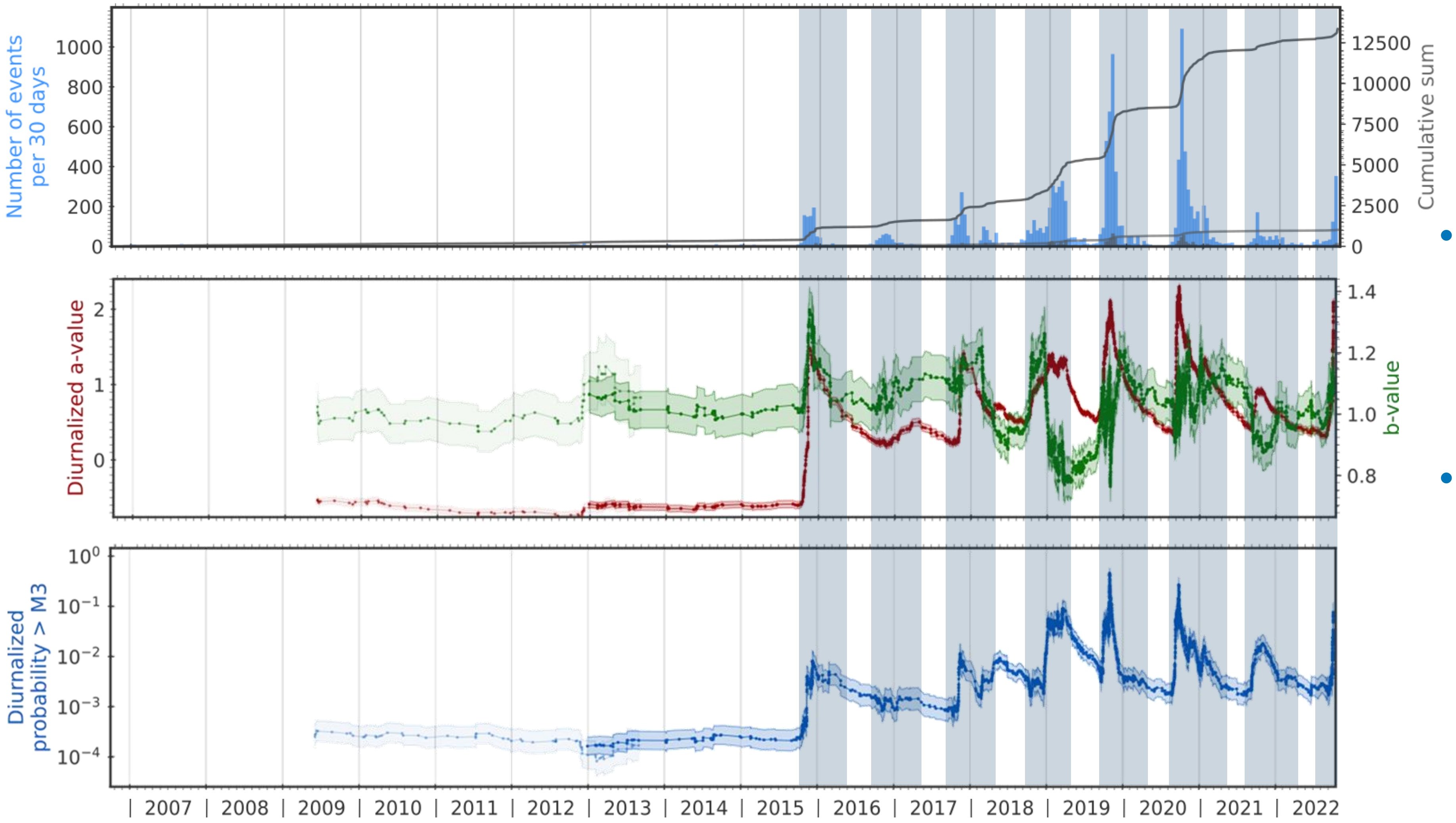
- 1142 routinely monitored earthquakes
- 372 templates
- >12000 detections

Two main observations:

1. Strong **seasonal character** in the seismicity with a step-wise increase of the seismicity in fall and decrease in early spring

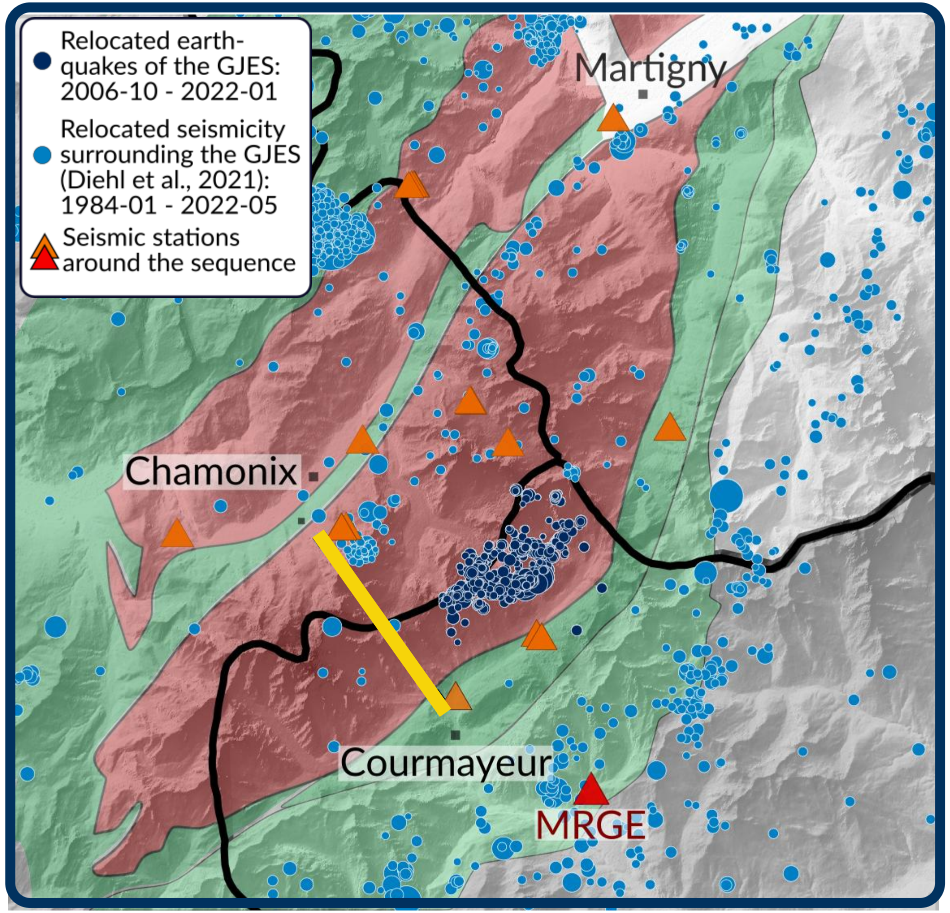
2. Increase in seismic activity compared to pre-2015

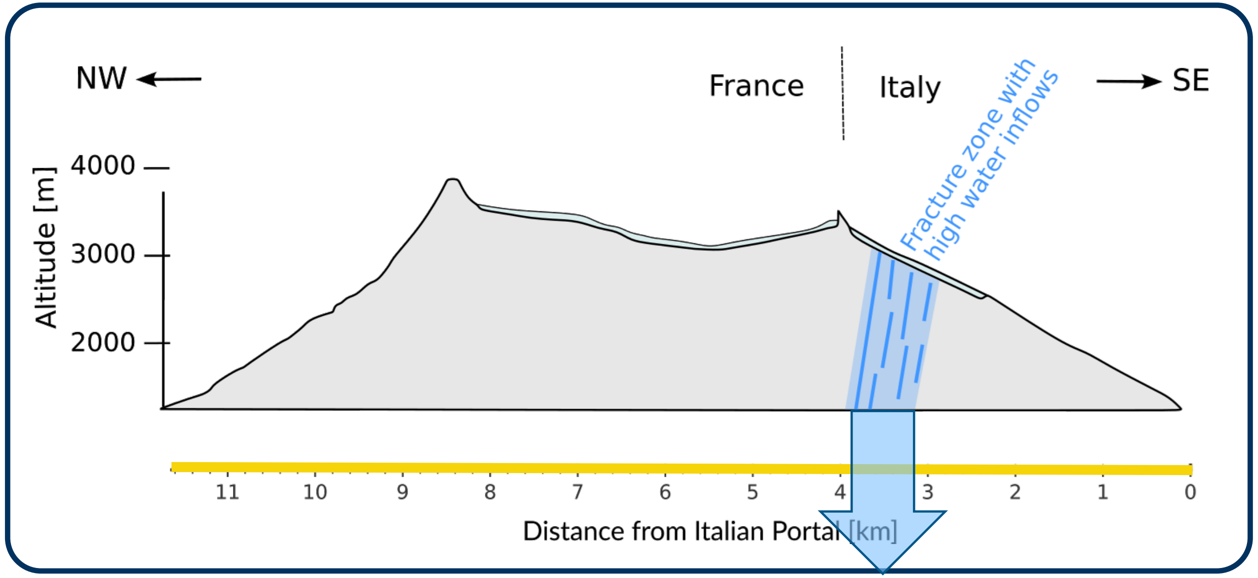
1st observation: Seasonal character in seismicity



- Strong increase in seismic activity in 2015 accompanied by a stronger fluctuation of the three statistical parameters, e.g., higher b-values in fall
- **Which seasonal forcing process explains the observations?**

Mont Blanc Tunnel



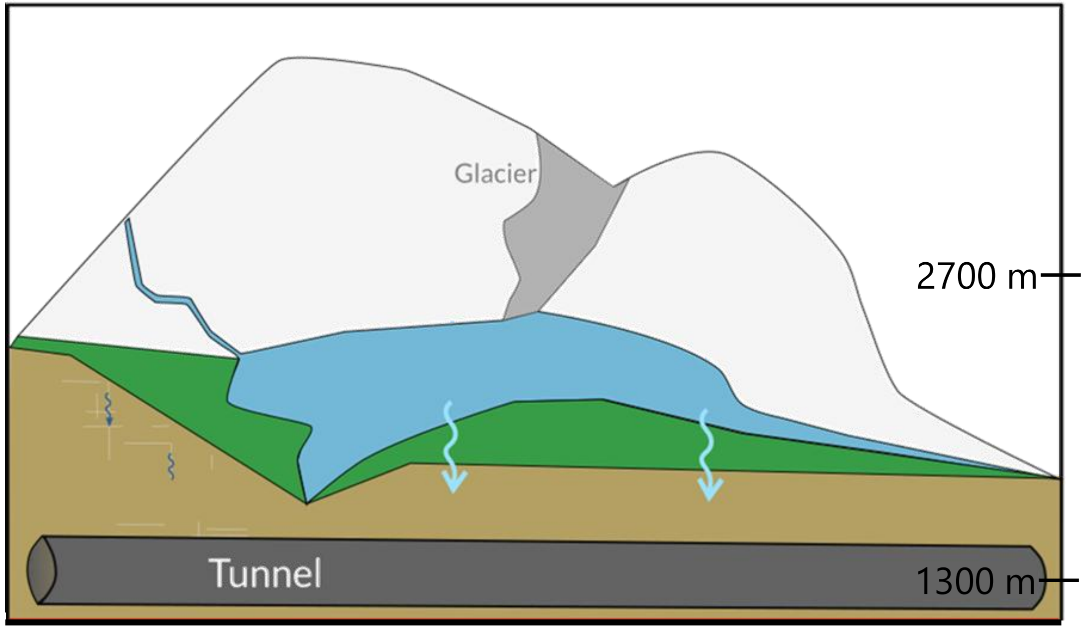


Mont Blanc Tunnel road tunnel

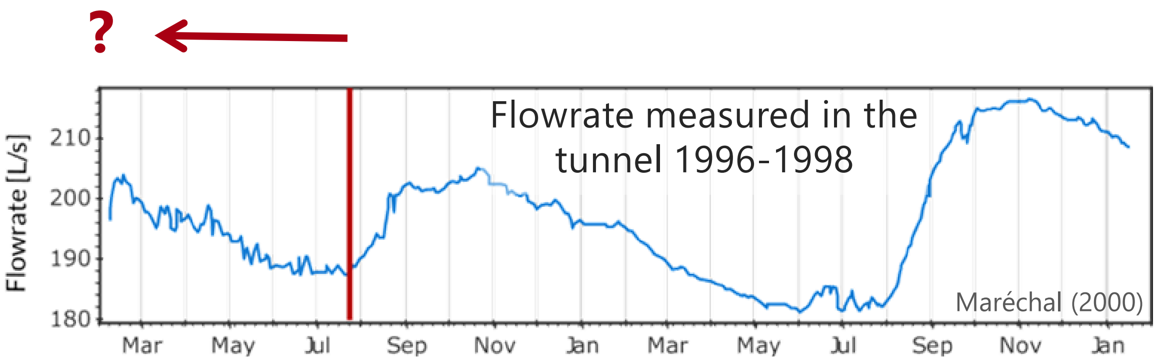
- Drilled end of 1950s through Mont Blanc external crystalline massif
- Large water inflows (1084 L/s on the first day) when the tunnel intersected a strongly fractured 600m wide fault zone
  → stopped drilling for 4 months

https://www.youtube.com/watch?v=3et-uxkw2BQ&t

1st observation: Seasonal character in seismicity



How long does runoff at the surface need to reach the tunnel?

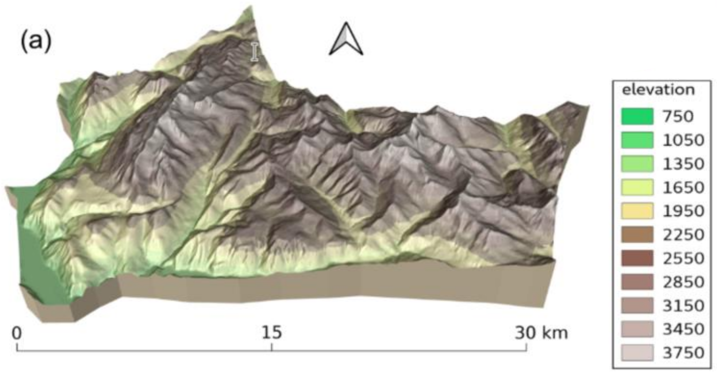


S2M meteorological and snow cover model

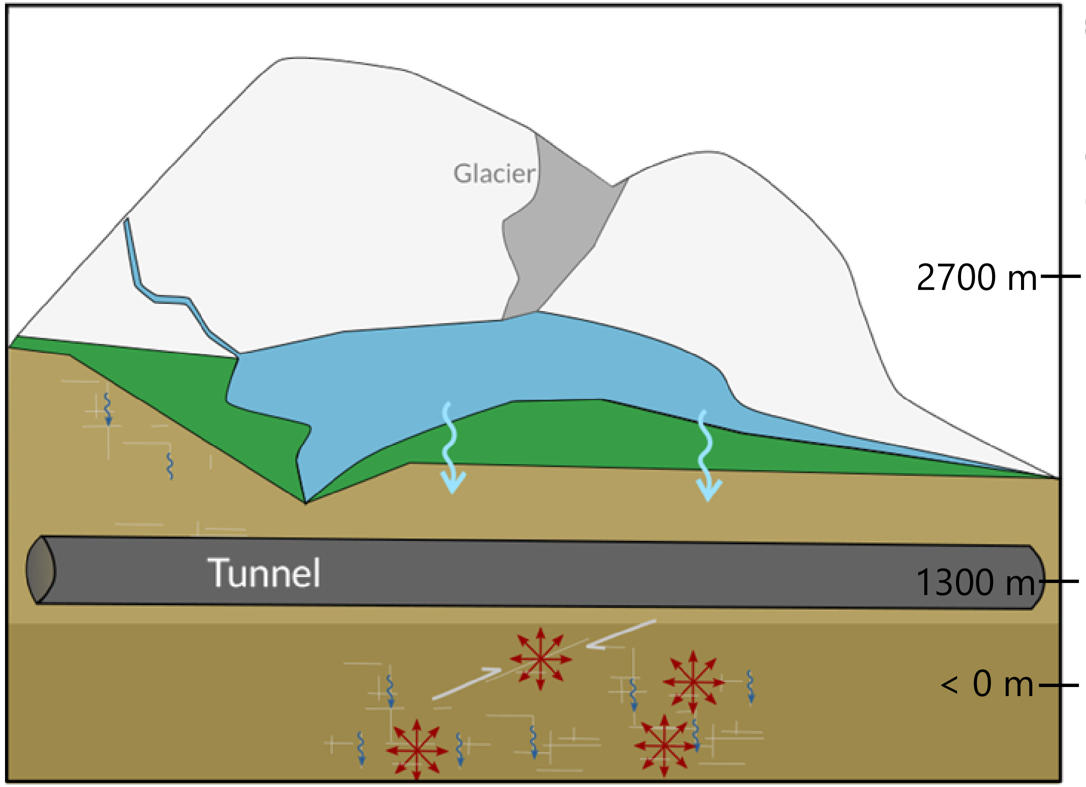
- High-resolution model that simulates meteorological, hydrological, and snow-pack parameters
- Calibrated by 453 meteorological stations from the area
- Area: French Alps (including MBM), Pyrenees and Corsica
- Period: 1958 – 2021

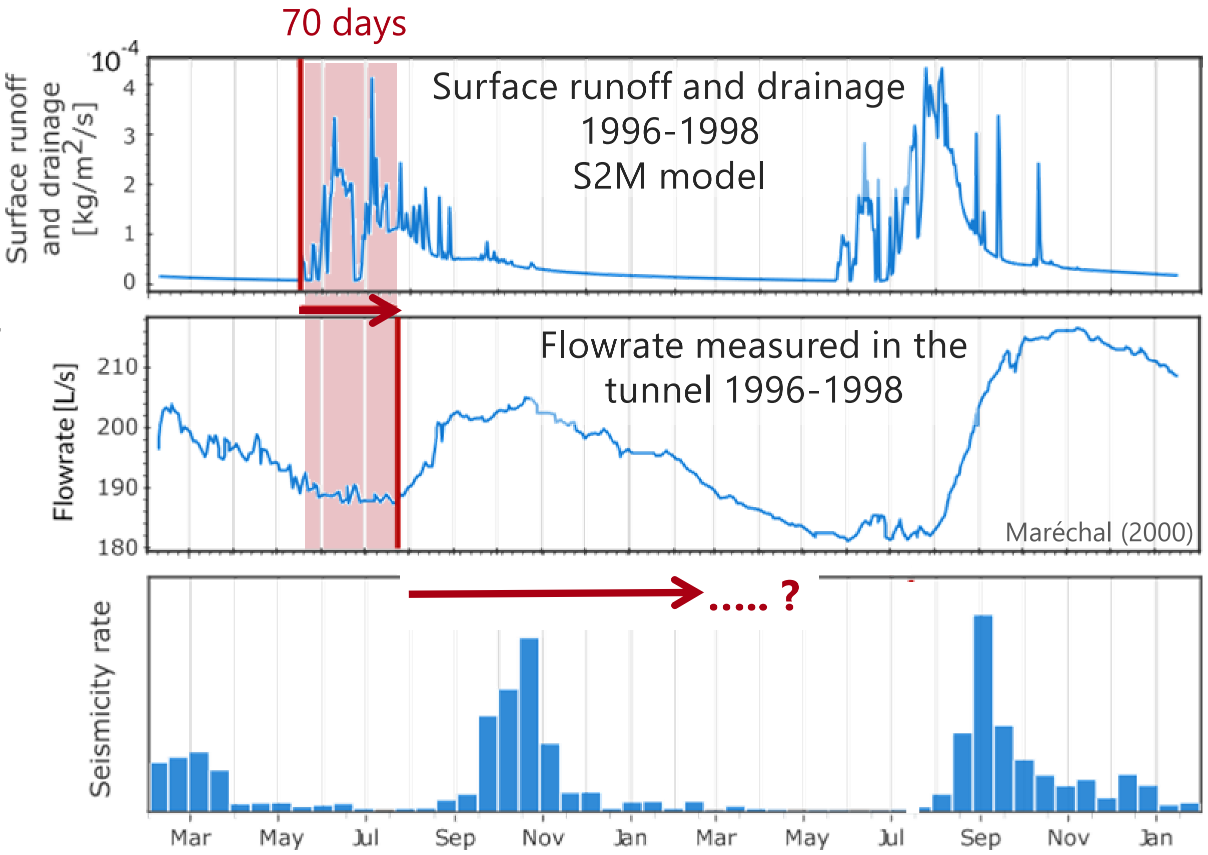
→ Provides long-term, open-access meteorological and snow data

Vernay, et al., (2022)
Dataset: https://www.aeris-data.fr/en/landing-page/?uuid=865730e8-edeb-4c6b-ae58-80f95166509b#v2020.2.%20The



1st observation: Seasonal character in seismicity





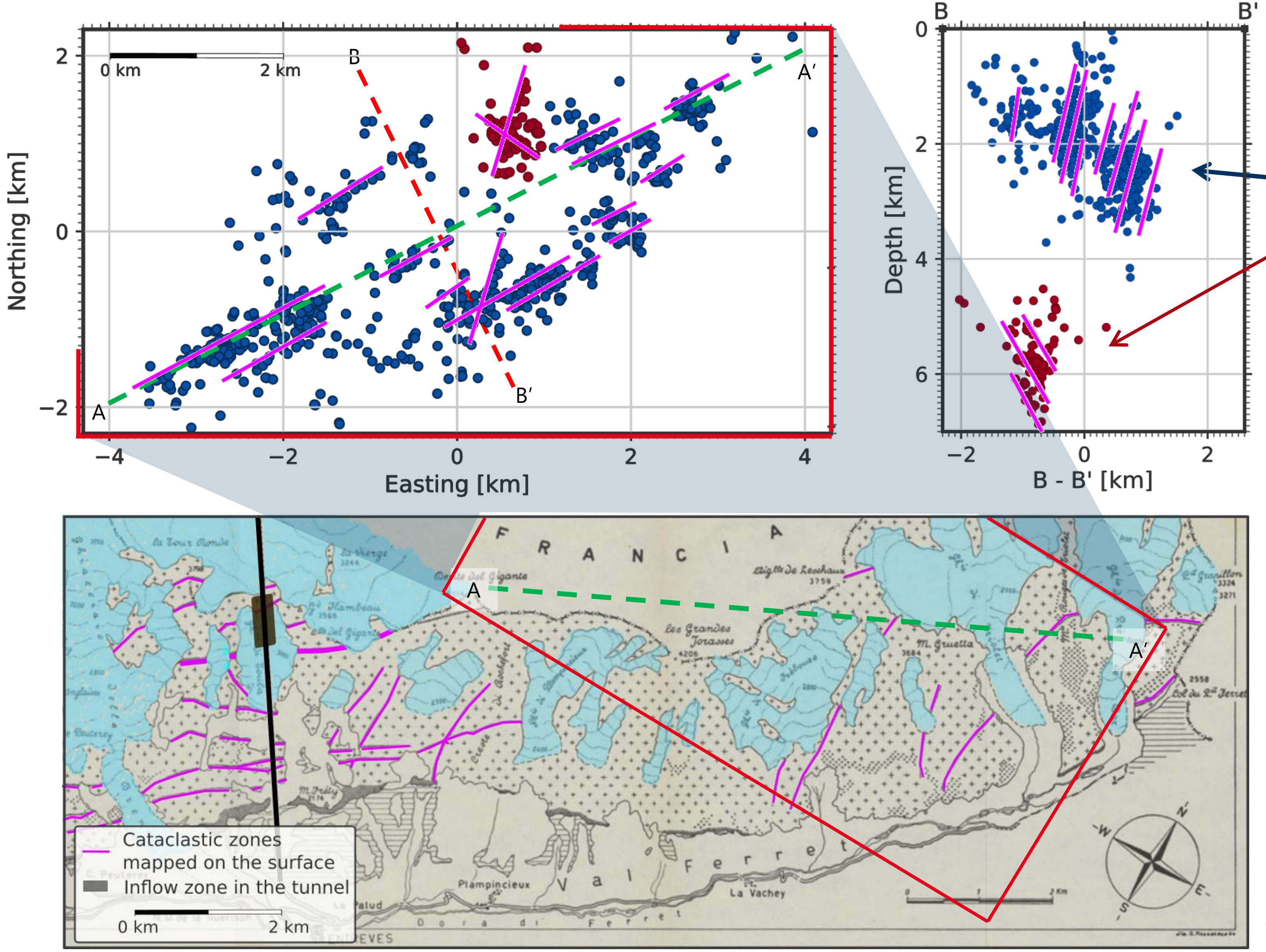
Tracer Tests on Glacier de Toule *(Dubois, 1992 and Marechal, 1998)*: Confirmed the water circulation between the surface and the fracture zone in the tunnel.

→ Is the seasonality in the seismicity driven by the same mechanism?

Earthquakes triggered by higher pore fluid pressure:

Higher pore fluid pressure reduces effective normal stress on a fault, lowering frictional resistance and facilitating earthquake triggering.

1st observation: Seasonal character in seismicity: Earthquake locations



Depth section:

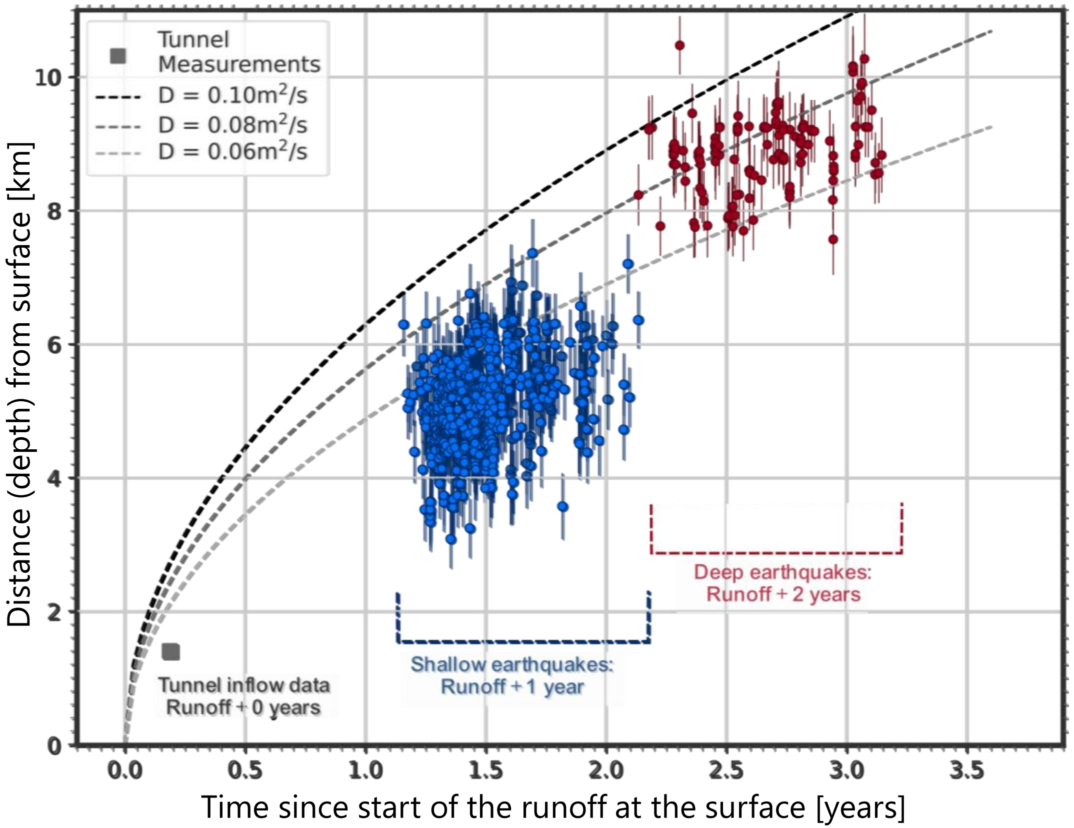
Shallow cluster

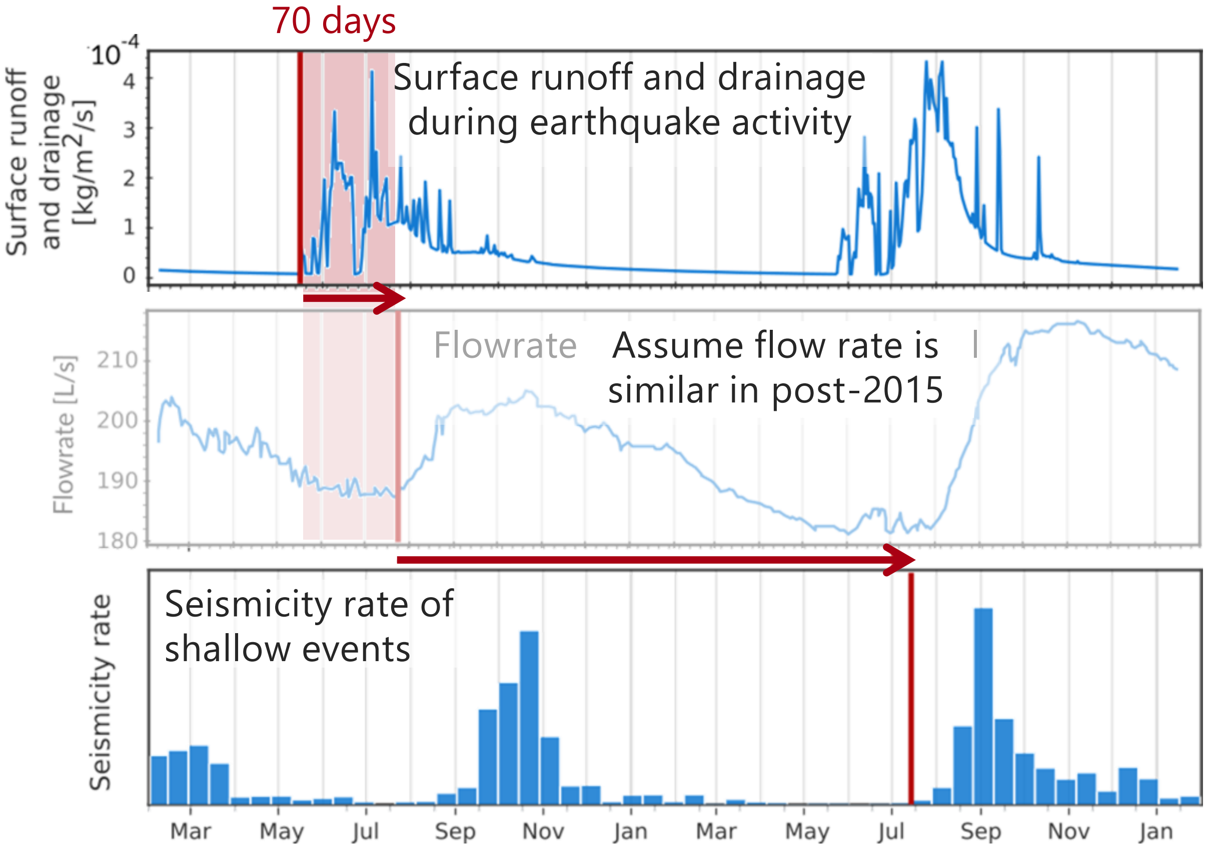
Deeper cluster

- Alignments of seismicity resemble mapped surface faults
- Link of seismicity to fault system: Pathways for deep groundwater circulation?

Baggio (1964)

1st observation: Seasonal character in seismicity - Hydraulic diffusion modelling



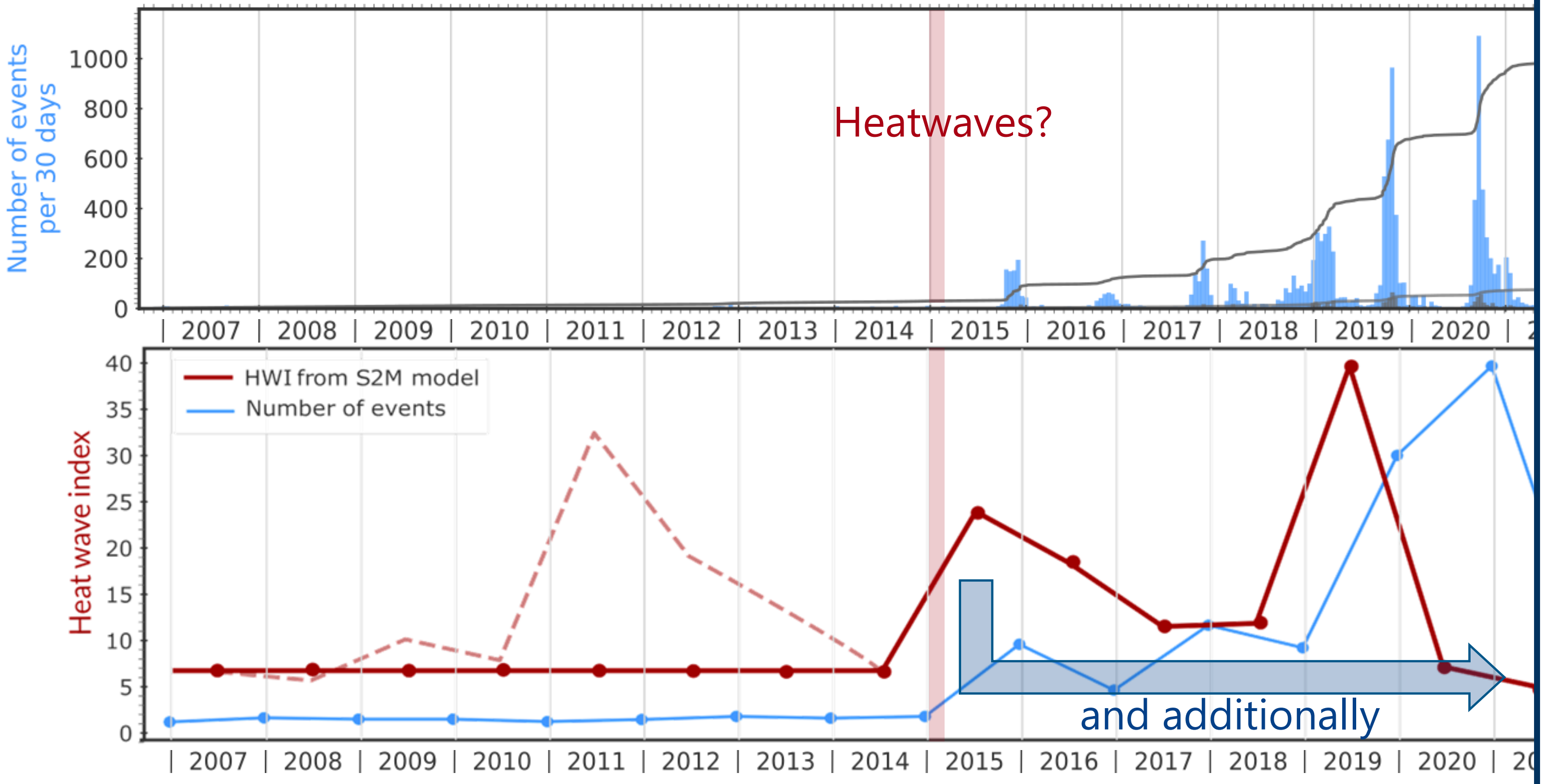


Diffussivities calculated with: $r = \sqrt{4\pi D t}$

Shapiro et al. (1997)

- Shallow earthquakes (<4.4 km) triggered by surface runoff of the previous year.
- Deep earthquakes (>4.4 km) triggered by surface runoff two years prior.

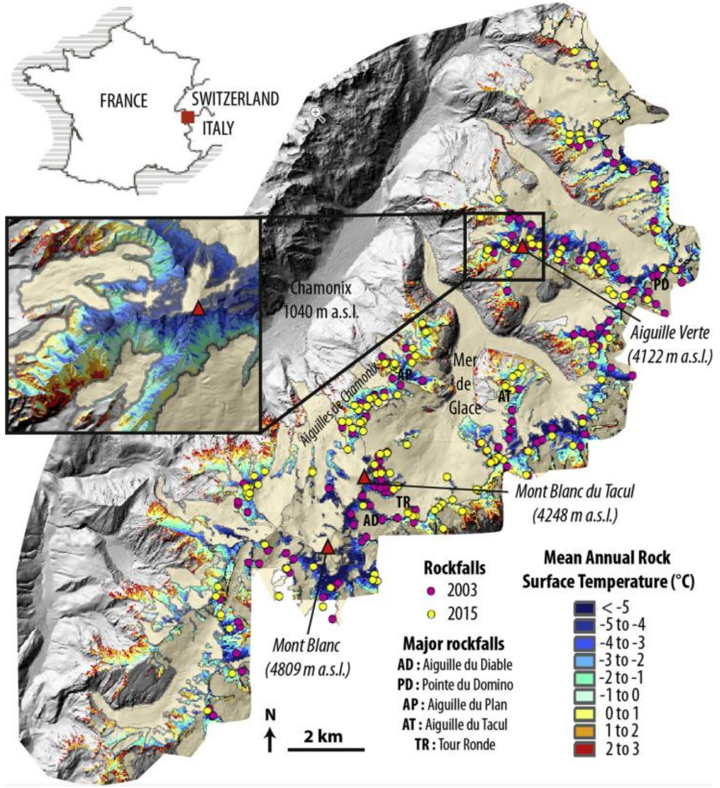
2nd observation: Start of seasonal activity in 2015



Heat Wave Index (HWI)

- A metric to quantify the intensity and duration of heat waves based on daily temperature data
- Daily maximum temperature above the 90th-percentile (compared to 1981-2010)
- Must last at least 3 days consecutive days → **heat wave**
- **Heat wave magnitude**: Sum of all daily maximum temperatures above 0°C during the heat wave
- **Heat wave index**: The largest heat wave magnitude recorded in a given year.

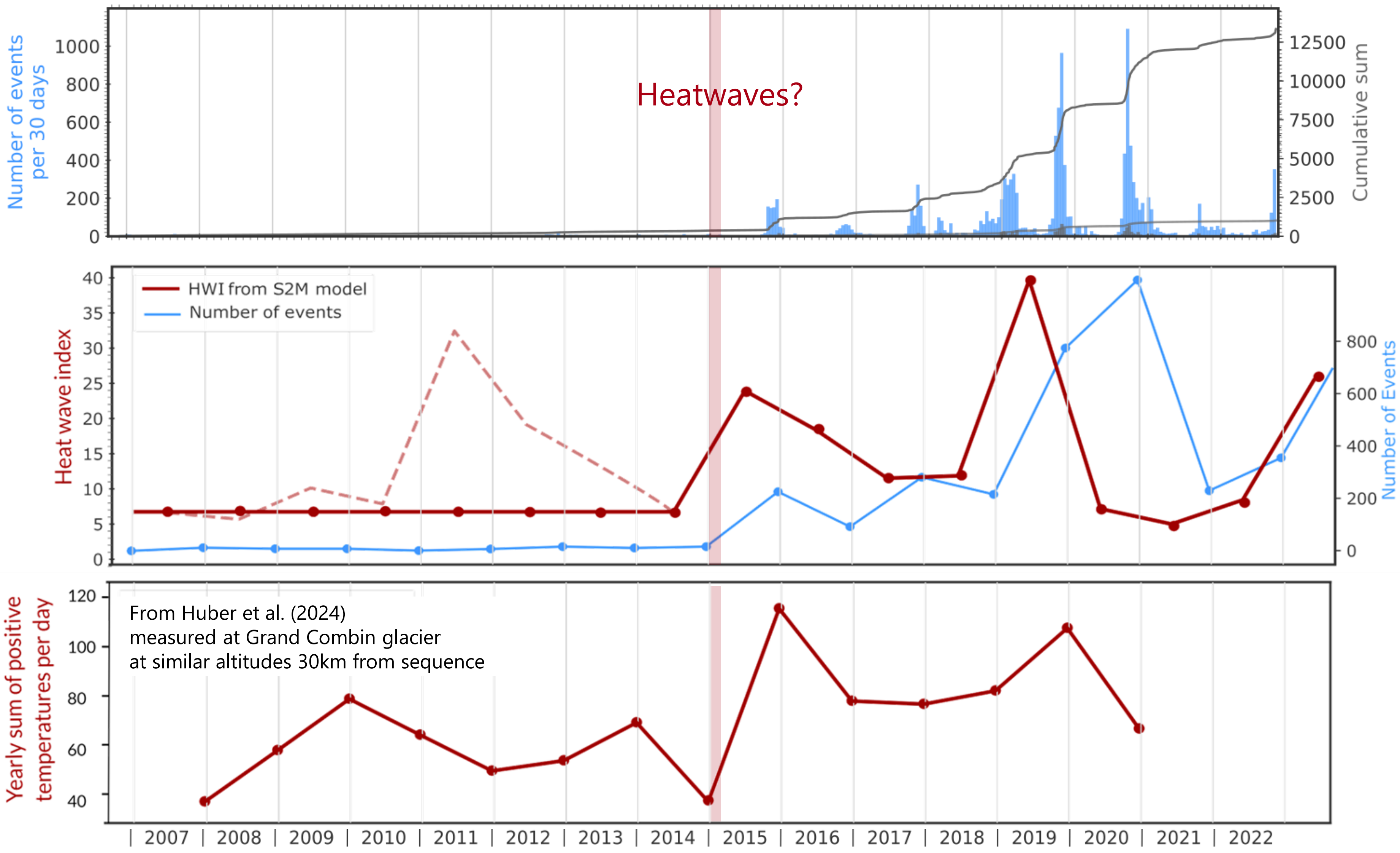
High-altitude temperature impacts



- Increase in temperature:
  Heat waves in 2003 and 2015 triggered numerous low-magnitude rockfalls in permafrost regions.
- Significant climate-driven changes intensified in high-altitude environments over the last decade

Corona-Lozada et al. (2019)

2nd observation: Start of seasonal activity in 2015



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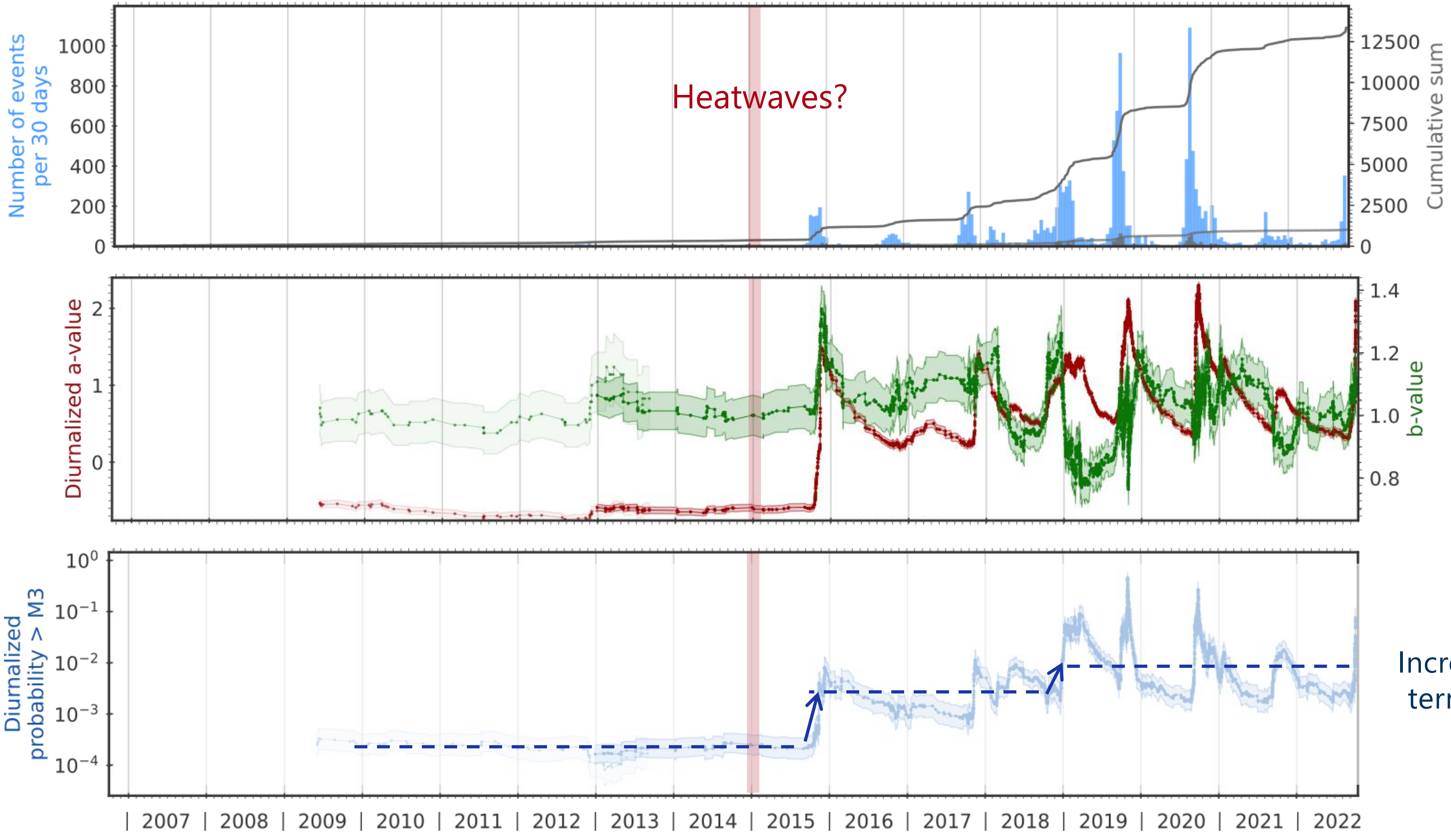
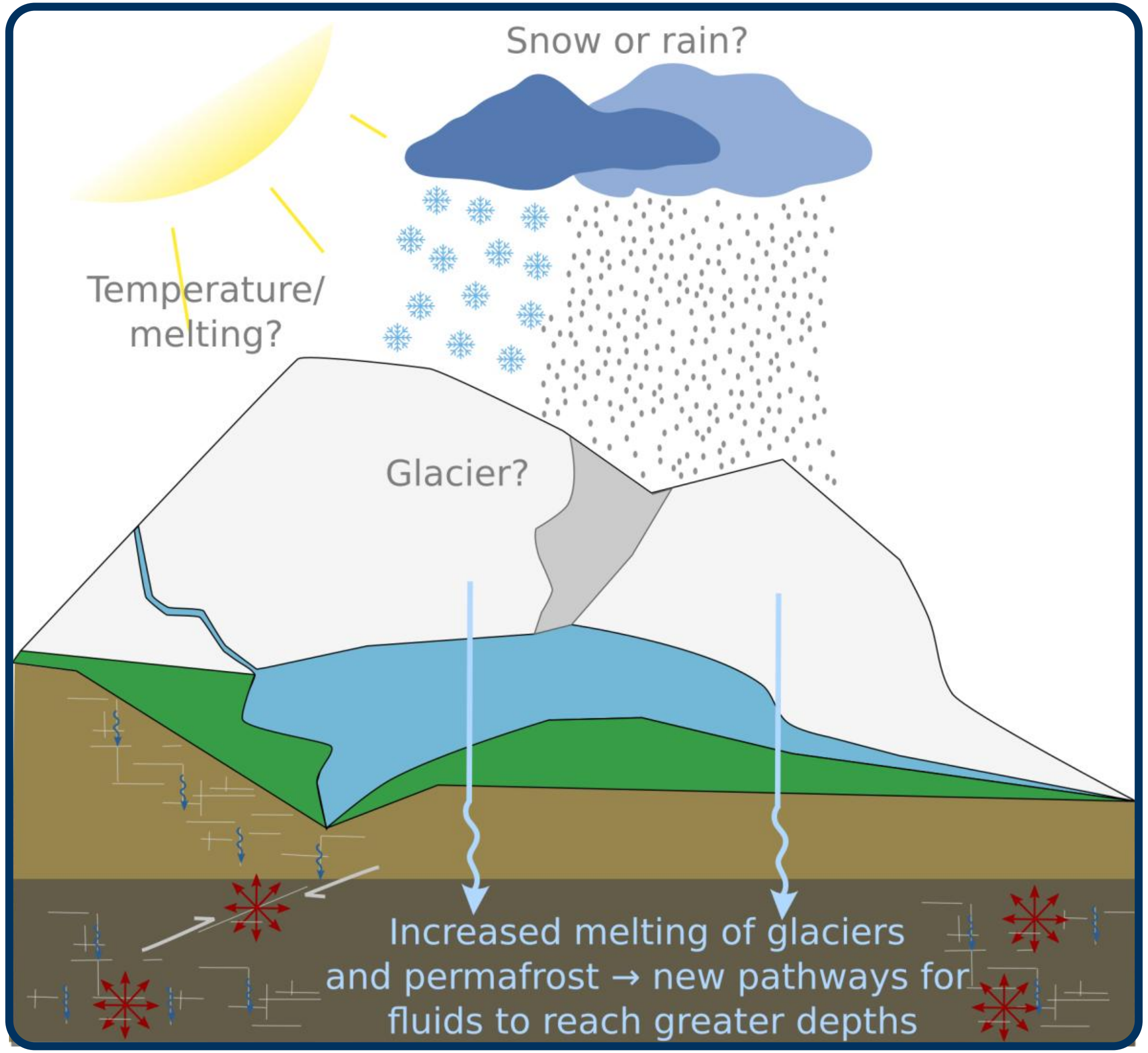


Increase in the short-term seismic hazard

Conclusions & Outlook

- Since 2015 documented impact of climate change temperature increase at high-altitude levels.
- New fluid pathways (i.e., dominant fracture zones) became open in 2015.
- 1D diffusion model of melt water infiltration can explain the tunnel inflow and seismicity.
- Significant increase in short-term seismic hazard.
  → May affect other alpine regions/communities



Conclusions & Outlook

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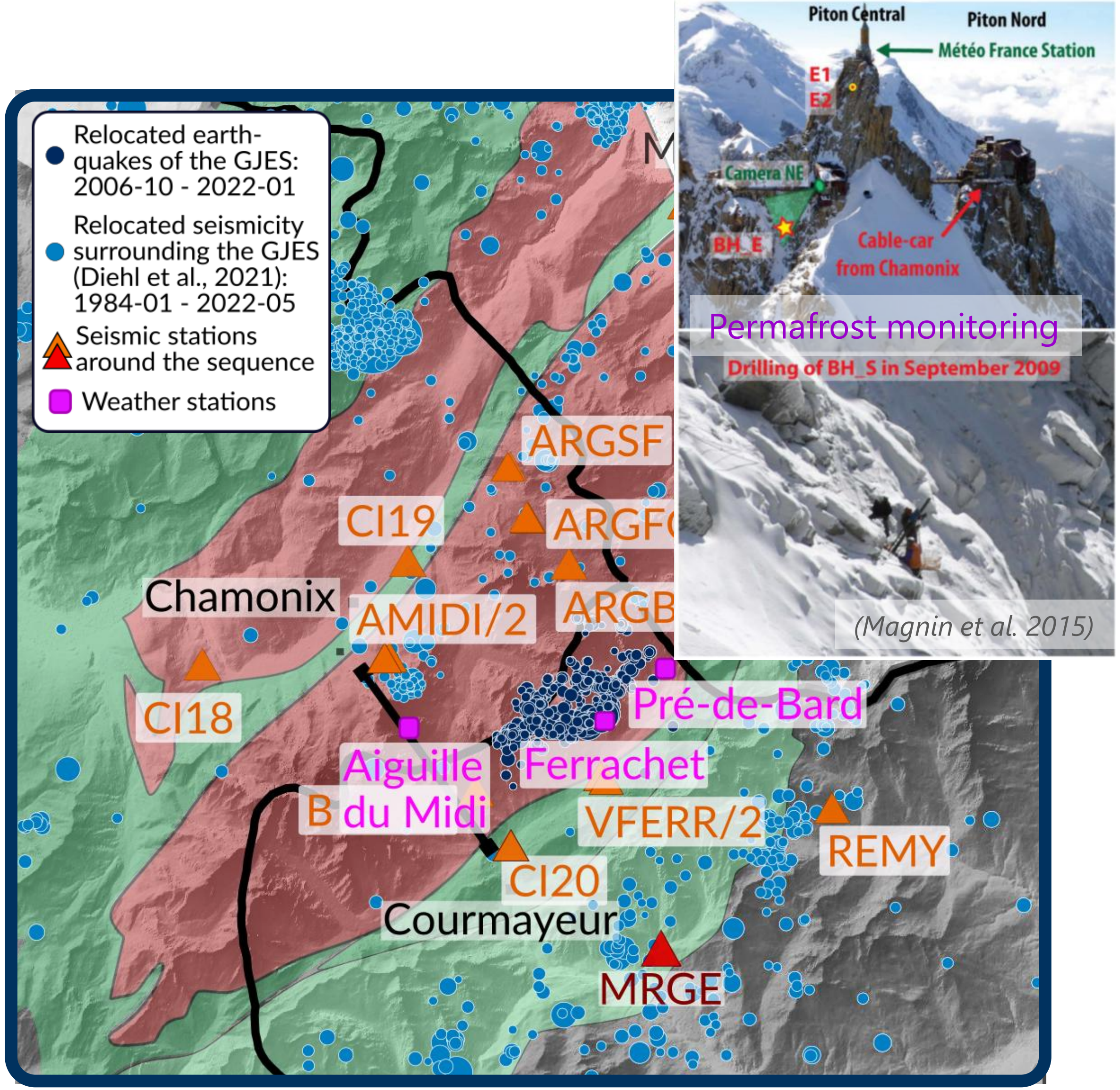
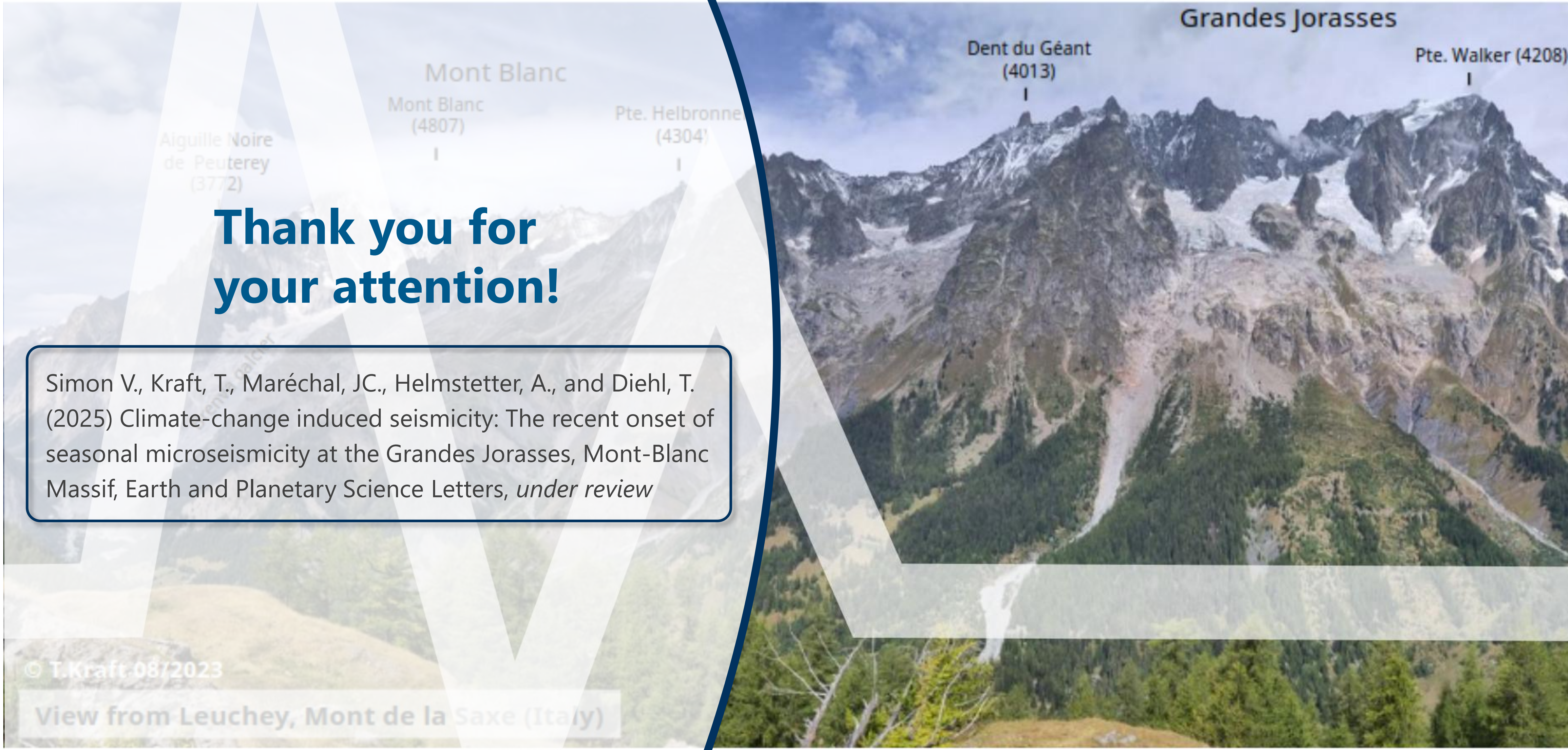
- Earthquake sequence at the Mont Blanc Massif shows a natural laboratory to study climate-triggered seismicity:
  - Locations confined to small area
  - Existing tunnel with runoff data from the affected fault zone
    → Determine timing and driving mechanisms
  - Dense seismic network
  - Dense climatological network





Thank you for your attention!

Simon V., Kraft, T., Maréchal, JC., Helmstetter, A., and Diehl, T. (2025) Climate-change induced seismicity: The recent onset of seasonal microseismicity at the Grandes Jorasses, Mont-Blanc Massif, Earth and Planetary Science Letters, *under review*