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► To cite this version:

Maëva Cathala, Florence Magnin, Ludovic Ravel, Luuk Dorren, Frederic Berger, et al.. Mapping release and propagation areas of permafrost-related rock slope failures in the French Alps: A new methodological approach at regional scale. EGU 2024 - EGU General Assembly, Apr 2024, Vienna, Austria. 2024, 10.5194/egusphere-egu24-8202 . hal-04755861

HAL Id: hal-04755861

<https://hal.science/hal-04755861v1>

Submitted on 29 Oct 2024

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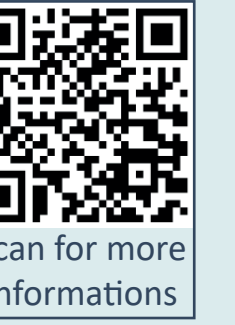
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Mapping release and propagation areas of permafrost-related rock slope failures in the French Alps: A new methodological approach at regional scale

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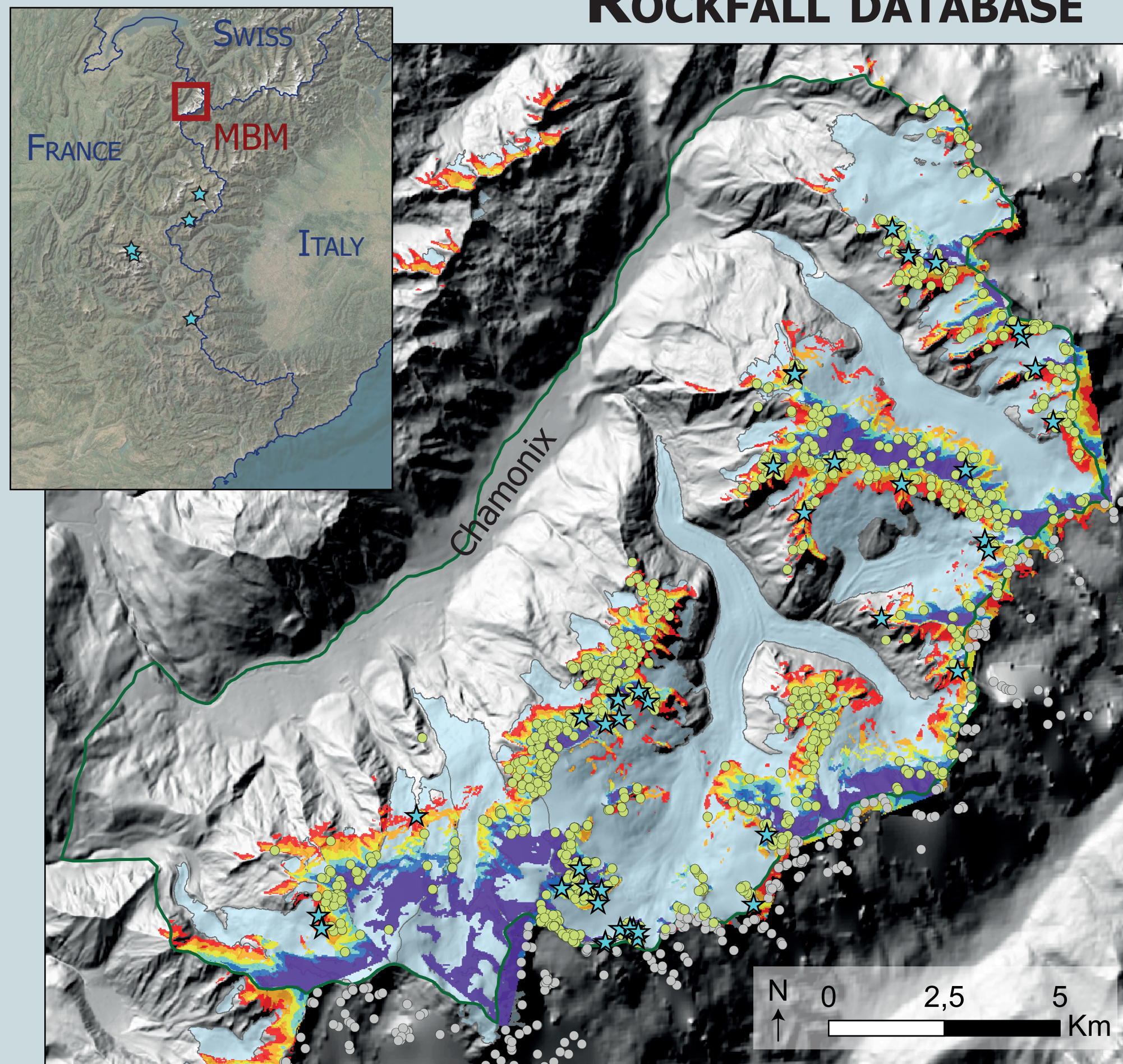


OBJECTIVES

High mountains environments are highly affected by climate change through glacier retreat and permafrost degradation. These phenomena may cause **rock slope failures**, sometimes provoking far-reaching cascading processes threatening human lives and infrastructure. Increasing knowledge on the **triggering mechanism** and **propagation** is therefore required to propose adaptation strategies. In the French Alps, permafrost mapping and extensive rockfall inventories provide relevant data for statistical analysis of their triggering conditions and mobility. In accordance with the GAPHAZ guidelines for hazard assessment (GAPHAZ, 2017), the aims of this study are: (i) to propose a **mapping approach** of susceptible **release areas** of rock slope failures and resulting **runout distances** at a **regional scale** (French Alps), and (ii) to **identify hotspots** for further **hazard assessment**.

METHODS

ROCKFALL DATABASE



Mont Blanc Massif (MBM) database
 (1389 events >100 m³)

- Rockfalls used for statistical analysis
- Rockfalls outside of the raster extent
- Raster extend for MBM database analysis

High Mountain Database (48 events)

- ★ Rockfall used to analyse the mobility

Permafrost: Mean Annual Rock Surface Temperature (MARST; °C)

- < -2
- -2 to -1
- -1 to 0
- 0 to 1
- 1 to 2
- 2 to 3

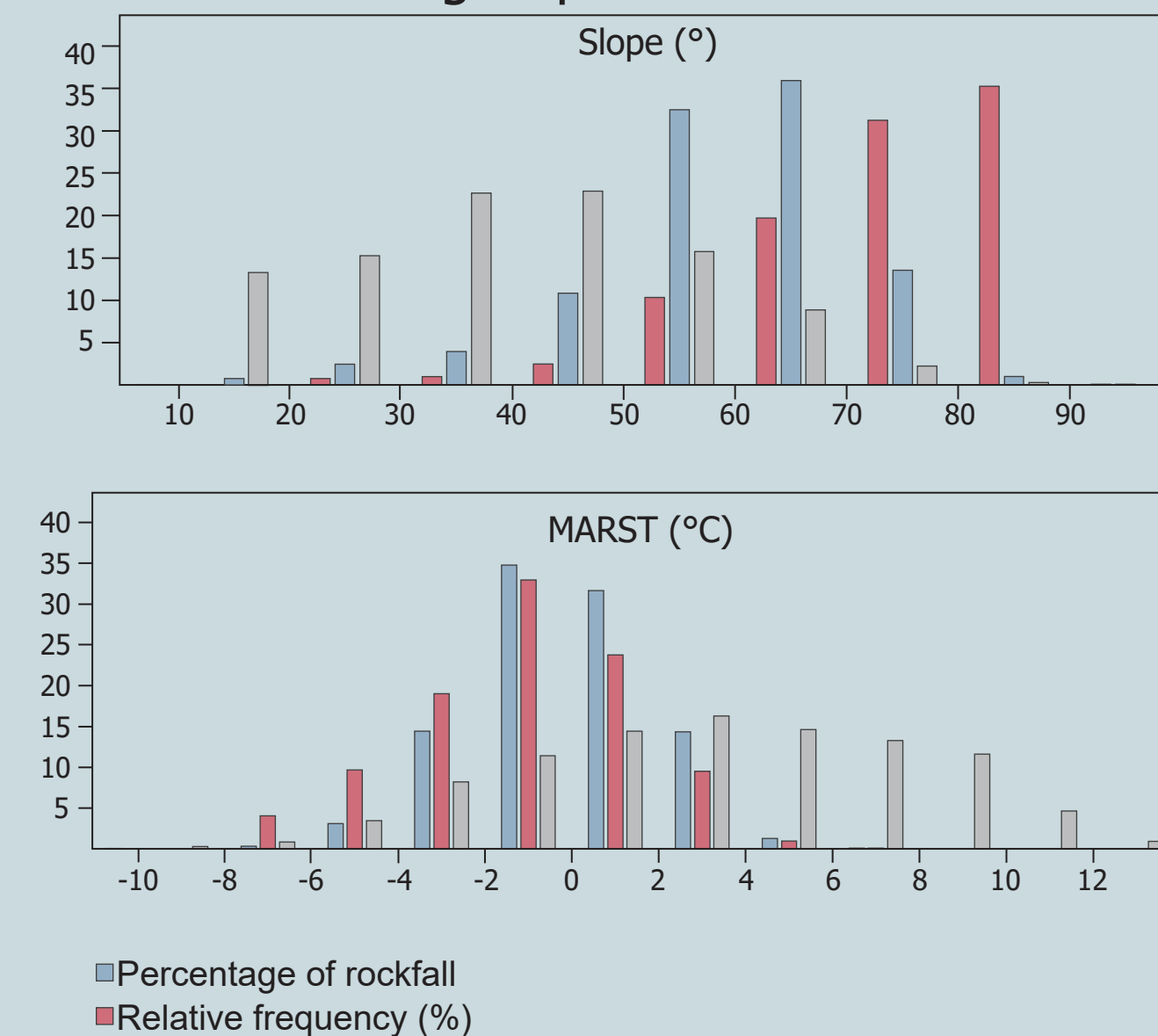
Glacierized areas: ■

The propagation database complete the **3630 events recorded by Rock the Alps** (Interreg Project) in order to calibrate the RockavELA model.

STATISTICAL ANALYSIS

Statistical distribution of rockfall according to triggering conditions

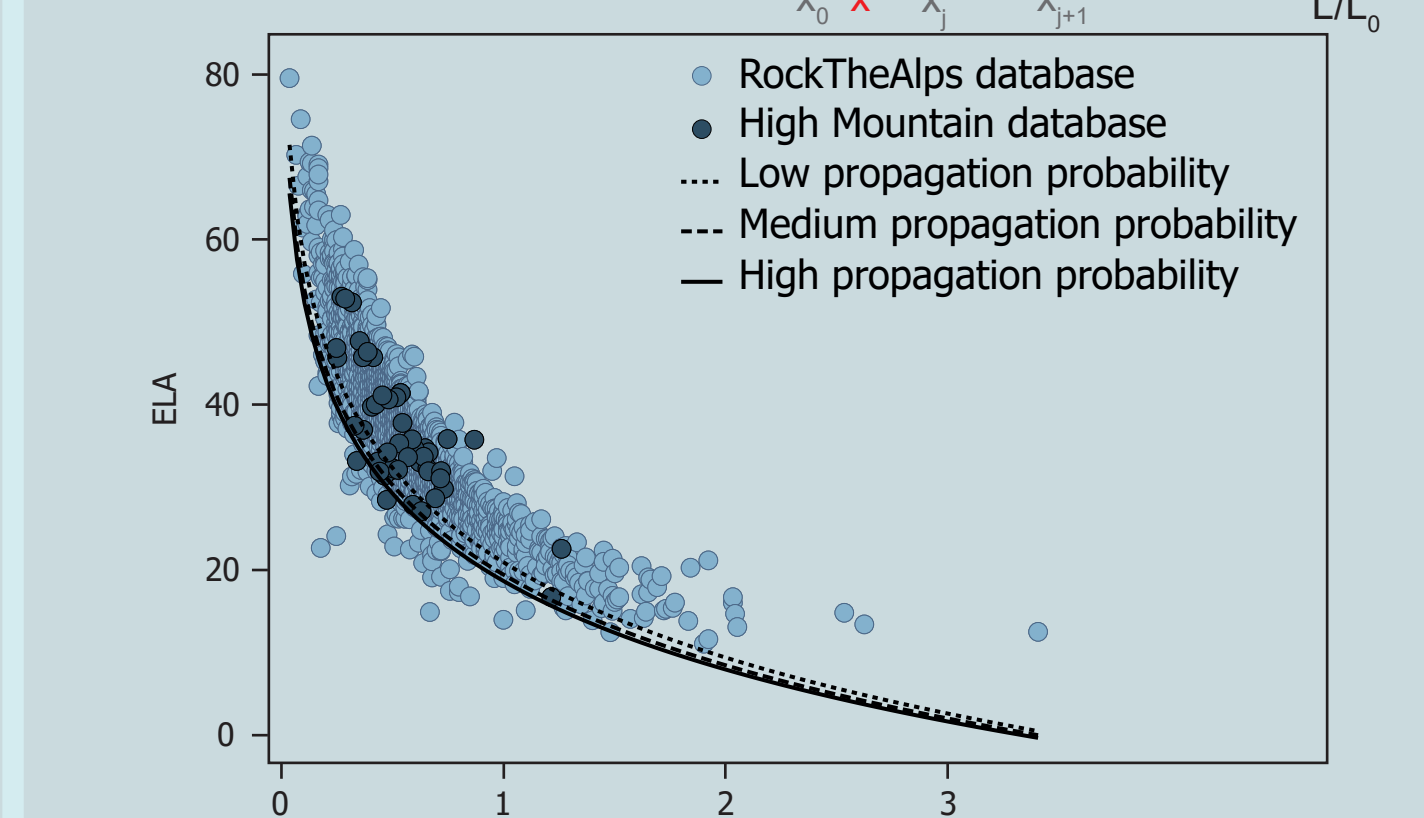
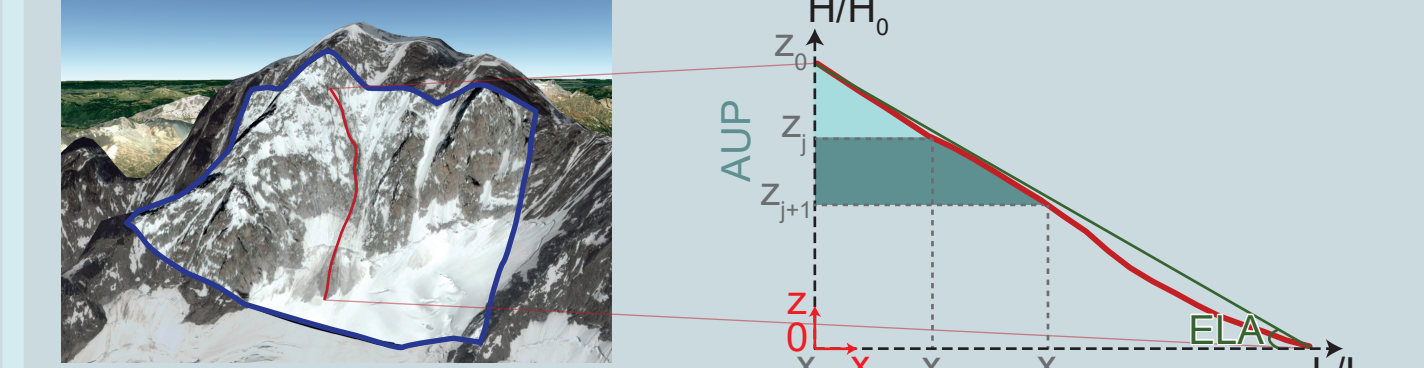
The MBM rockfall database is used to analyse the **distribution of rock slopes failures** according to the **permafrost (MARST)** in the slopes >30°. The results allow to determine the conditions the most prone to trigger rock slope failures according to permafrost conditions.



*1 The relative frequency is calculated according to the rockwalls area for each slope and MARST classes.

Propagation analysis

The mobility of each rockfalls of the propagation database and the Rock the Alps database is given by the **Energy Line Angle**^{*2} (ELA) **normalize by the dimensionless area under profile**^{*3} (AUP)



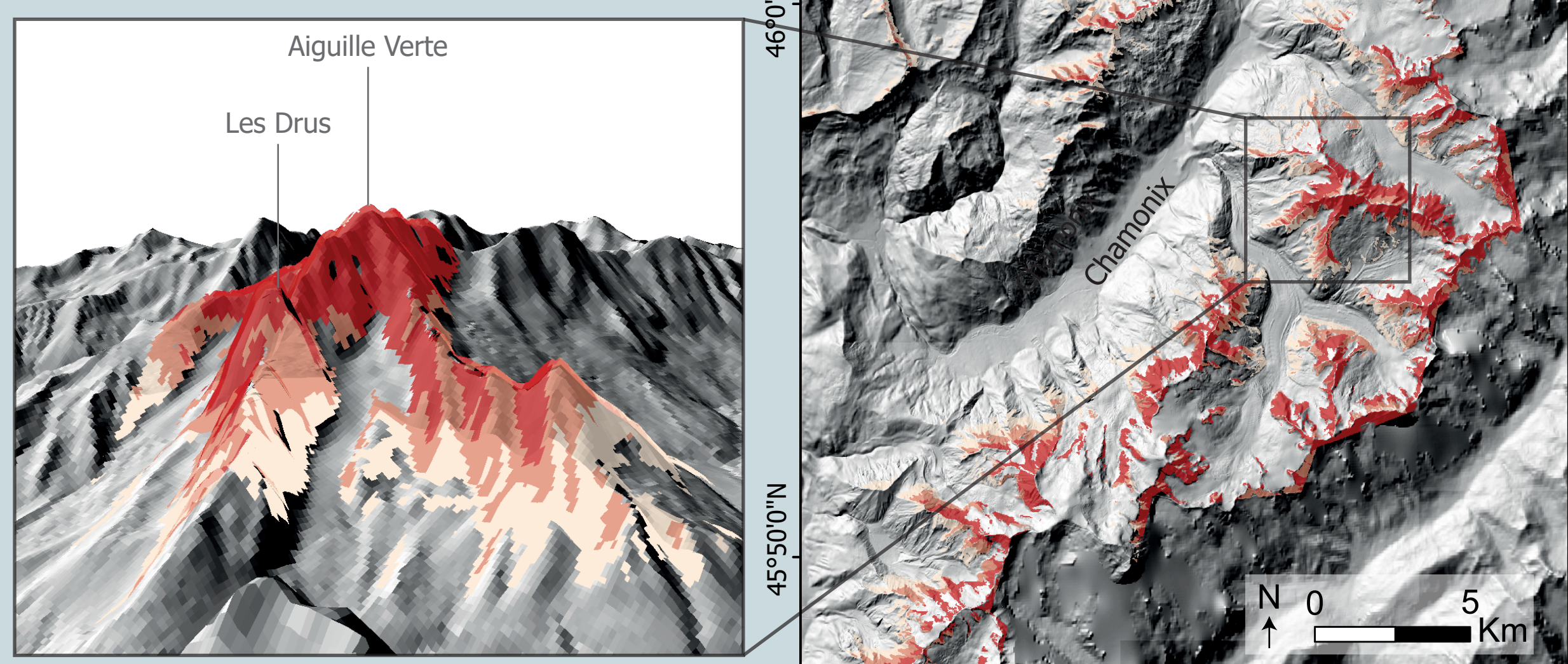
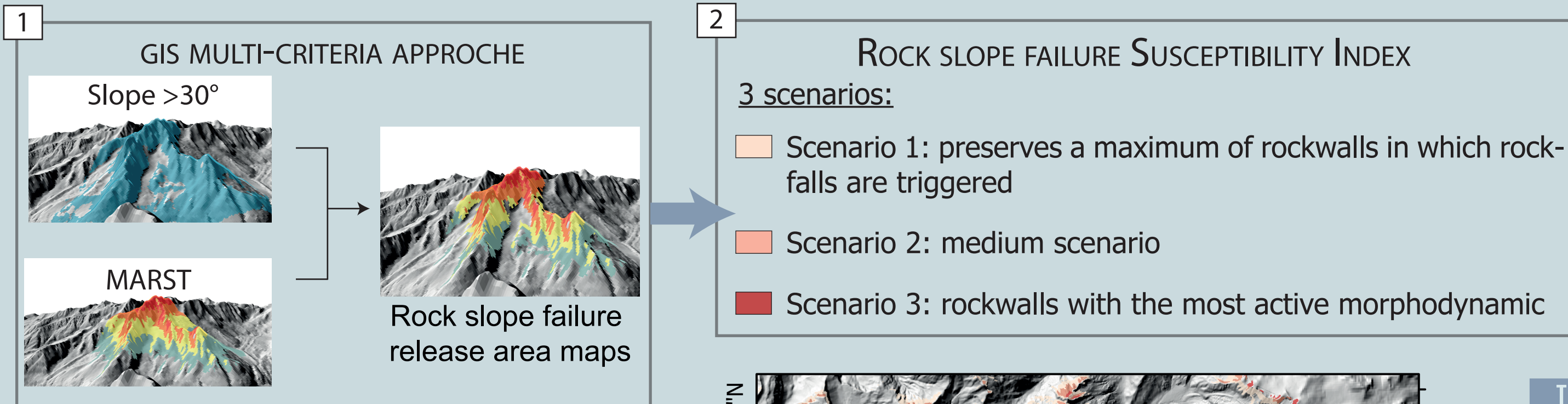
*2 Angle between the maximum drop height and the maximum horizontal deposition distance (from the top of the scar to the tip of the deposit)

*3 The dimensionless area is calculated with the area under the profile of each rockfall

RELEASE AREAS AND RUNOUT DISTANCES: REGIONAL MAPPING

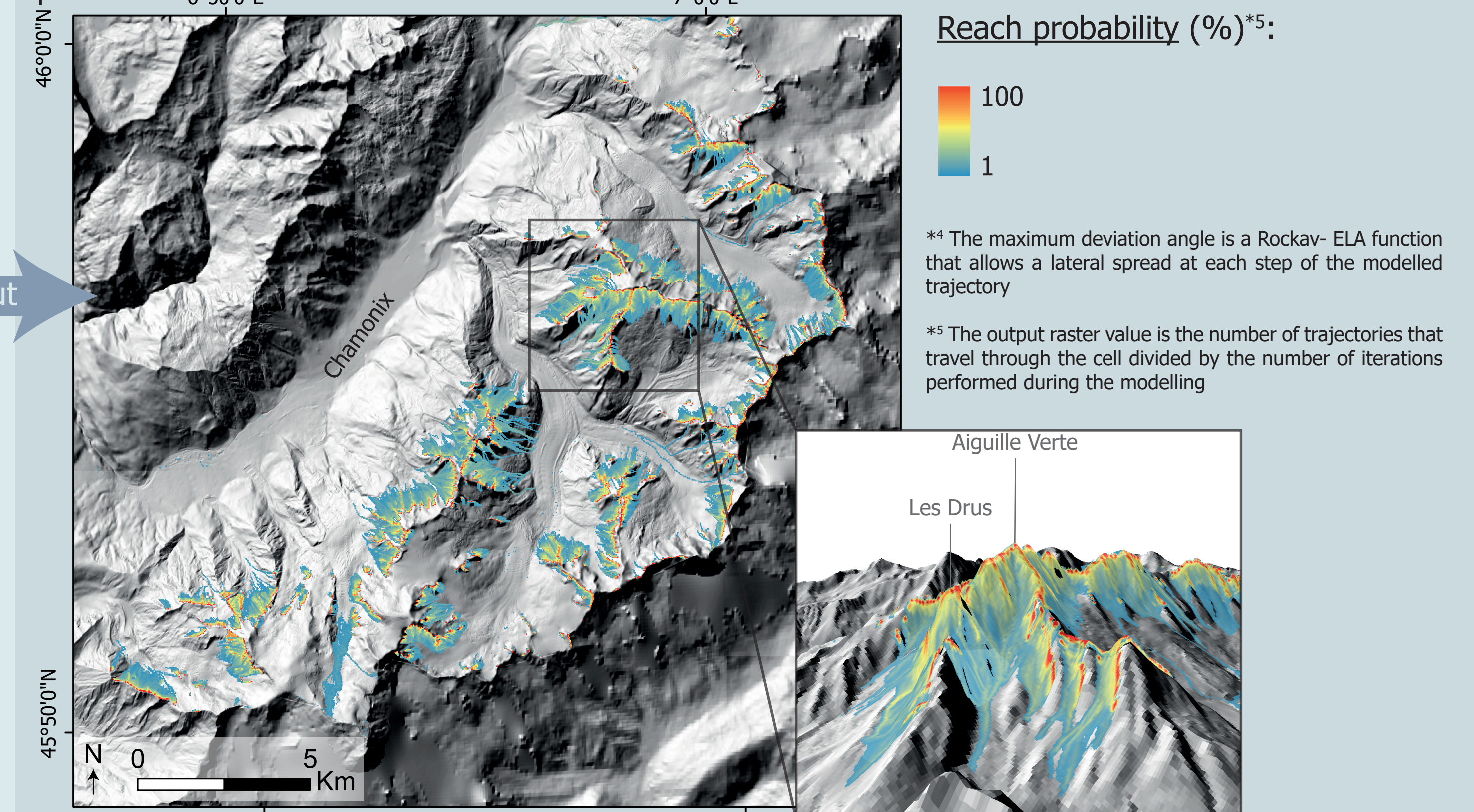
RELEASE AREAS MAPPING

The statistical distribution of the rockfalls according to slope and MARST are used to set up a multi-criteria GIS scheme to map potential release areas.

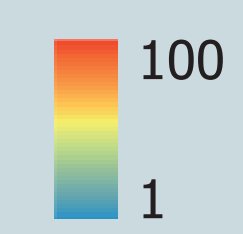


RUNOUT DISTANCES MODELLING

The RockavELA model (Rock avalanche Energy Line Angle) is used to map at a regional scale the potential runout distances of rockfalls. The model is based on the **Energy Line Angle** and the **Area Under Profile** principles to calculate stopping threshold and a **deviation angle**^{*4} allows a lateral spread.



Reach probability (%)^{*5}:

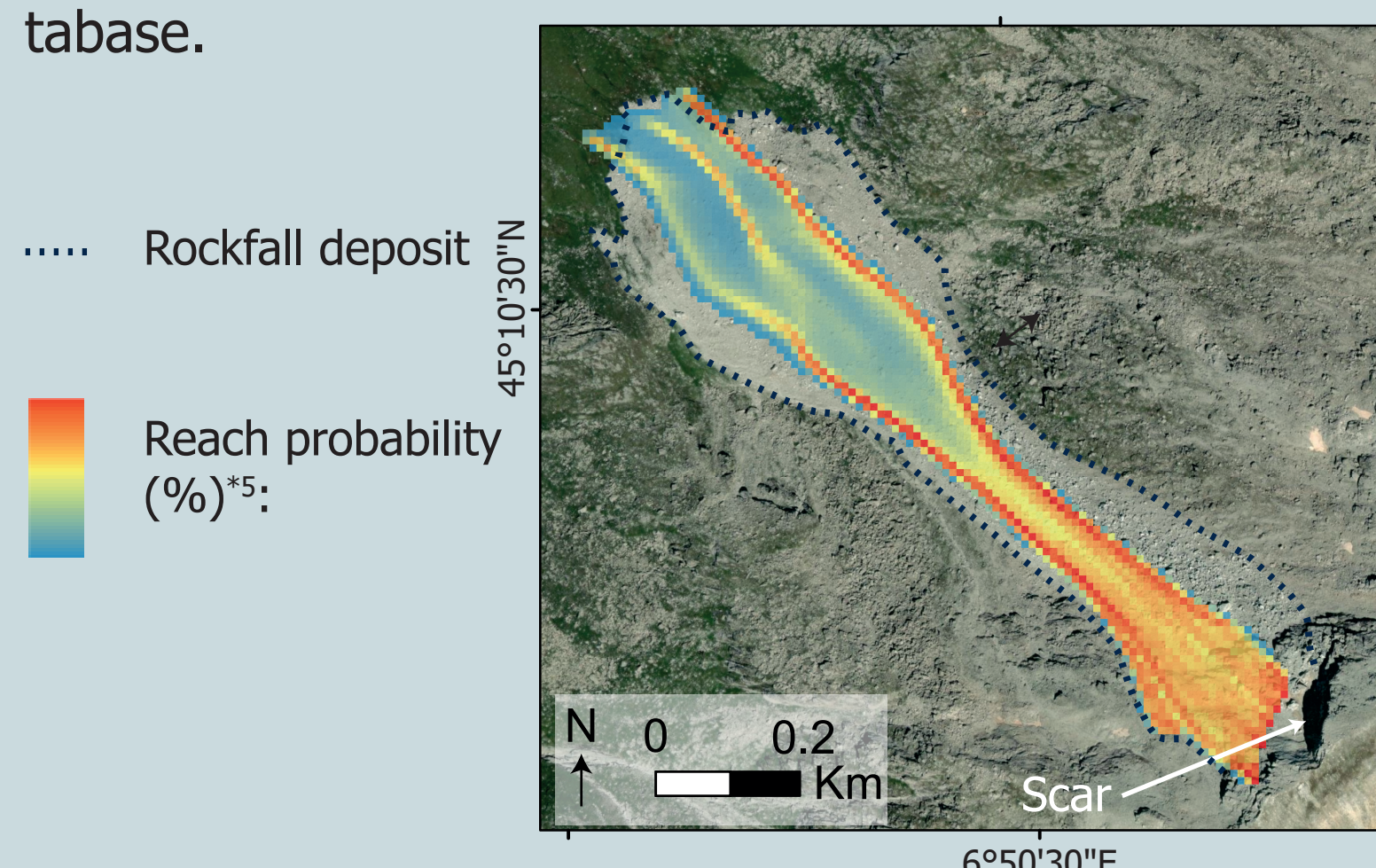


*4 The maximum deviation angle is a Rockav-ELA function that allows a lateral spread at each step of the modelled trajectory

*5 The output raster value is the number of trajectories that travel through the cell divided by the number of iterations performed during the modelling

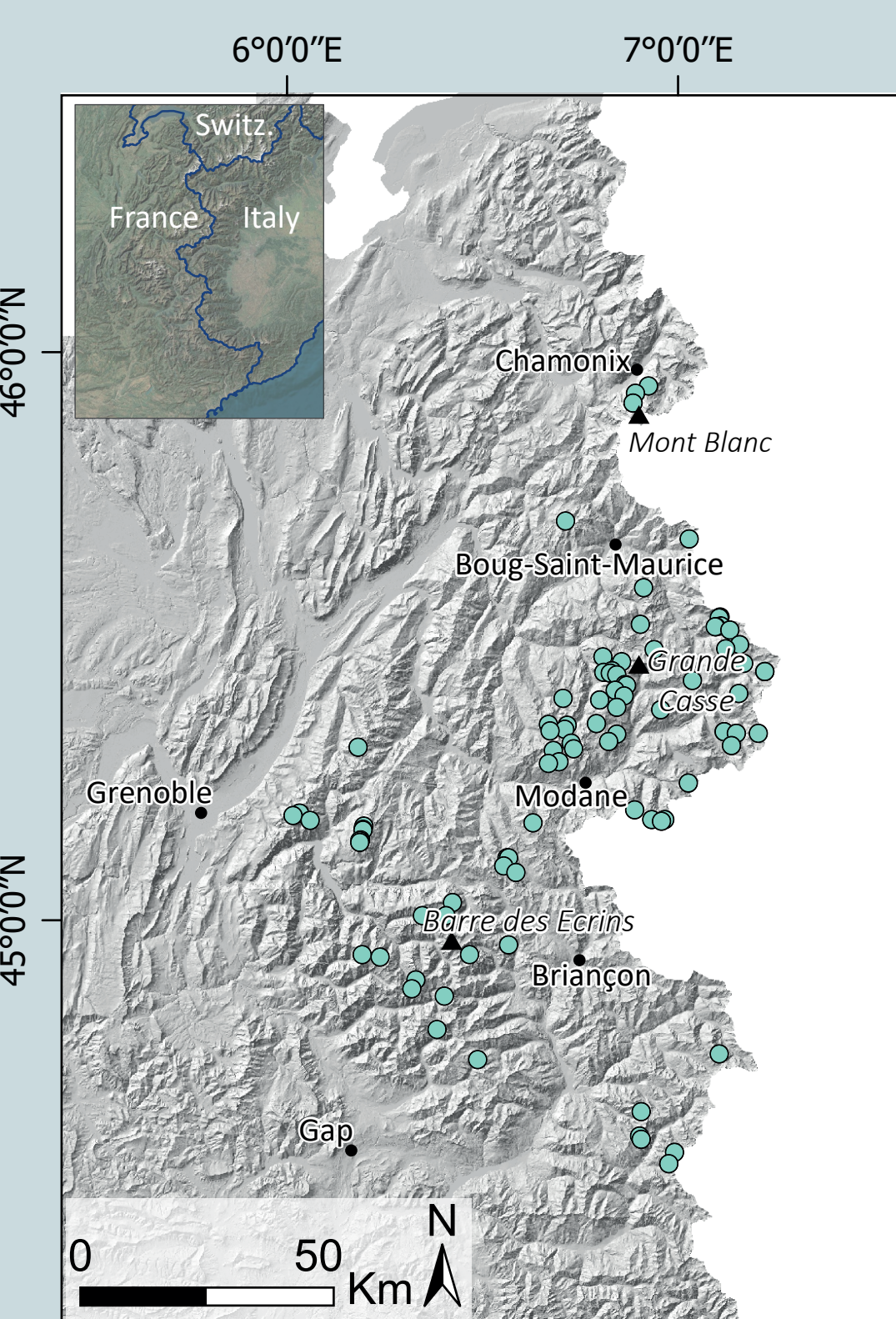
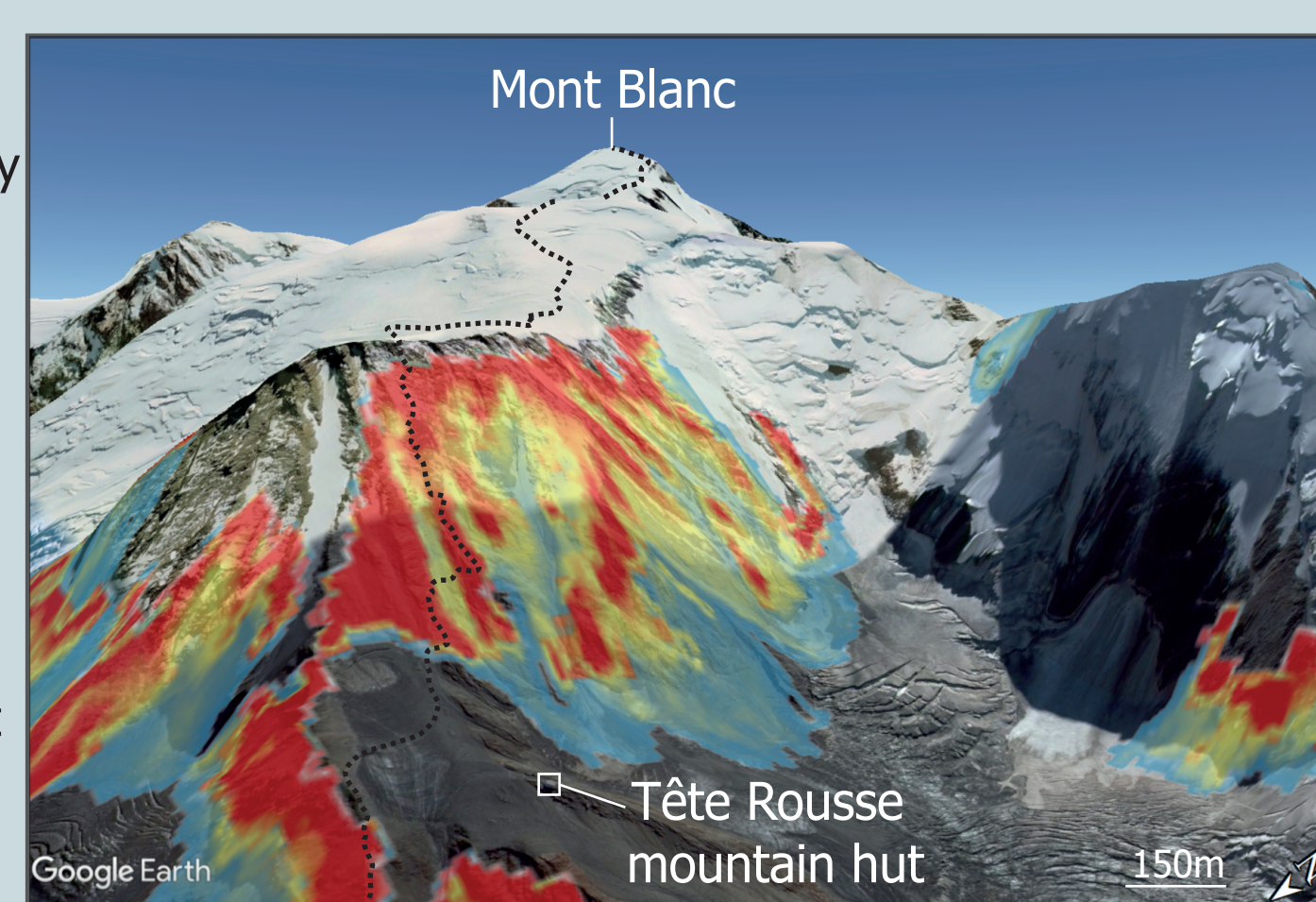
VALIDATION

The validation of the model will be realised by a **sensitivity study** of the different settings (e.g. lateral spread, segment length) and by measuring the frontal and lateral error (vertical/horizontal distance) between the modelled deposition trajectories rockfall deposit from the propagation database.



HAZARD ASSESSMENT

This study is a first step to anticipate the location of potential rockfalls trajectory at regional scale and **identify hotspots** where **human issues** (e.g. mountaineering routes, infrastructure, tourism areas) or **glacial lakes** could be impacted. More in-depth studies should be conducted at a local scale for risk mitigation.



● Lakes formed on a potential rockfall trajectory in the French Alps (High propagation mobility scenario)

CONCLUSIONS

This work provides a first overview to **assess the susceptibility of rock slope failures and their potential trajectory** at a regional scale for **risk mitigation** in current and future conditions of permafrost degradation. The method presented here is relevant to be reproducible in other mountain ranges and nordic environments.

REFERENCES

GAPHAZ 2017: Assessment of glacier and permafrost hazards in mountain regions. Prepared by Allen, S., Frey, H., Huggel, C. et al. Standing Group on Glacier and Permafrost Hazards in Mountains (GAPHAZ) of the International Association of Cryospheric Sciences (IACS) and the International Permafrost Association (IPA). Zurich, Switzerland / Lima, Peru, 72 pp.

PERSPECTIVES