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A 'subsurface weather station' to measure boulder-mantle heat fluxes on Murtèl rock glacier

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[1] Key points

- 'Permafrost Meltwater Assessment eXpert Tool' (PERMA-XT).
- Innosuisse collaboration between Uni Fribourg and GEOTEST.
- Project duration: 2020–2023.
- Aim: *More reliable ice-rich permafrost runoff forecasts by improved process understanding of heat exchange between atmosphere and permafrost body*.
- Strategy: Thermal degradation + ice-content estimate → quantification of permafrost melt

[2] Research idea and methods

- We installed a weather station on the rock-glacier surface and a subsurface 'mirror' array of sensors placed in natural cavities in the open-framework boulder mantle: *'as above, so below'*.
- The subsurface array captures conduction in boulders, air and water flow, radiation, and energy storage in the active layer.
- We study heat exchange processes between atmosphere and permafrost table at a high level of detail.
- This process understanding will also improve predictions on downwasting rates of debris-covered glaciers.

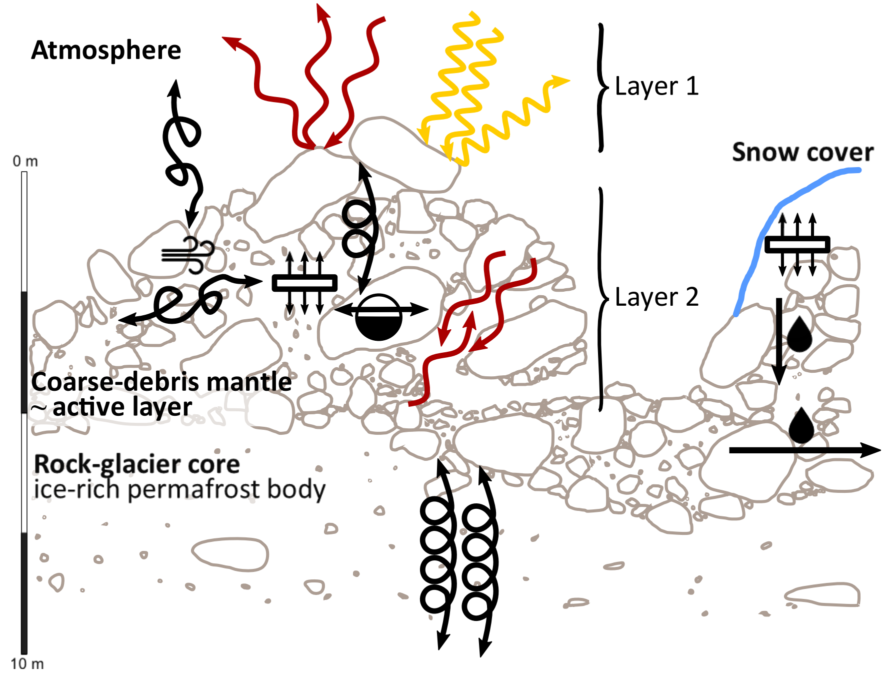

Fig. 1: Idealized cross-section through the open-framework boulder mantle with a furrow-and-ridge micro-topography. Fluxes (symbols in **Tab. 1**, on sheets 2, 3) and measurement design: (i) fluxes at the surface (atmosphere, snow; **Layer 1: 'as above'**), and (ii) fluxes within the boulder mantle (including water; **Layer 2: 'so below'**).

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[3] Sensor deployment

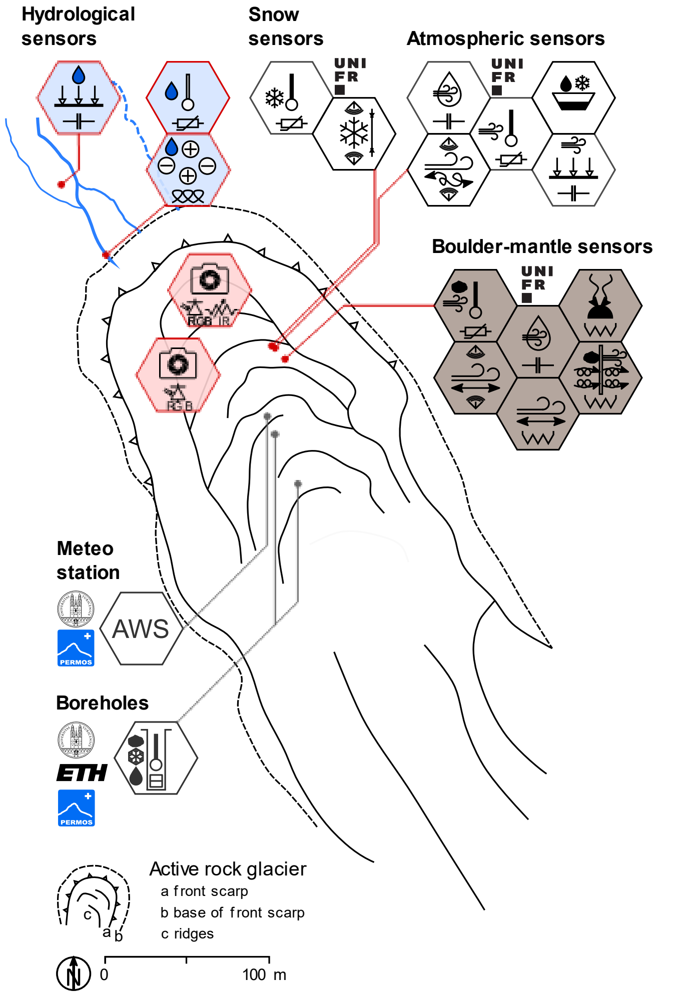
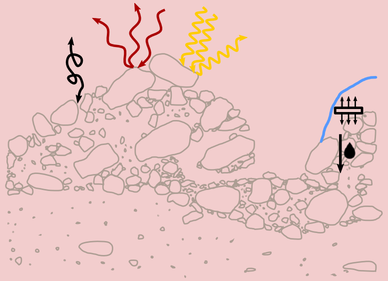


Fig. 2: Sketch map of the Murtèl rock glacier showing the locations of the existing sensors (meteo station and boreholes) and newly deployed sensors (cameras, hydrological, snow, atmospheric and boulder-mantle sensors. Installation in August 2020).

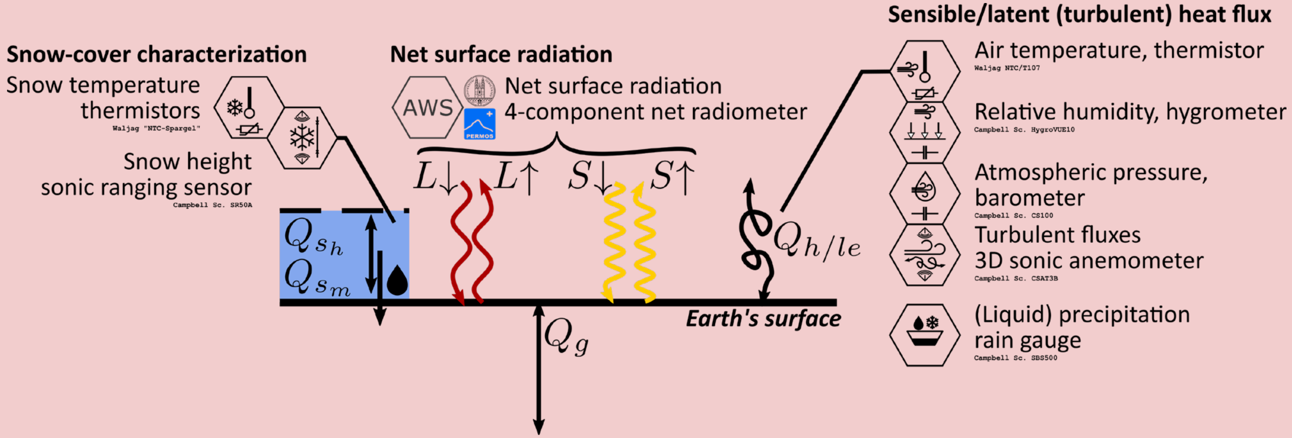


[4a] Measurement design: Layer 1

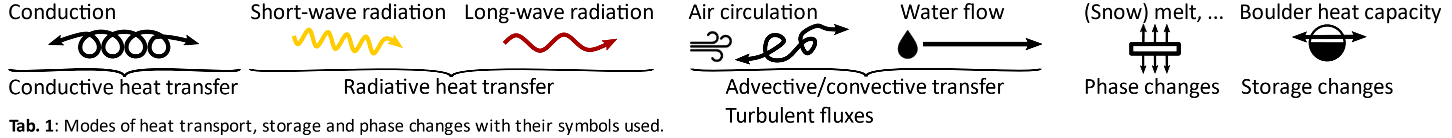
'AS ABOVE'

Atmosphere & snow sensors

The existing automatic weather station (AWS) is complemented with a sonic anemometer system to capture turbulent heat fluxes (eddy correlation) and snow pylons to characterize the snow cover.



Schematized cross-sections through the surface–lowermost atmosphere with involved heat transport modes (**Tab. 1**, below) and sensors. The ground heat flux, Q_g, is the link to the layer 2 ('so below').



Tab. 1: Modes of heat transport, storage and phase changes with their symbols used.

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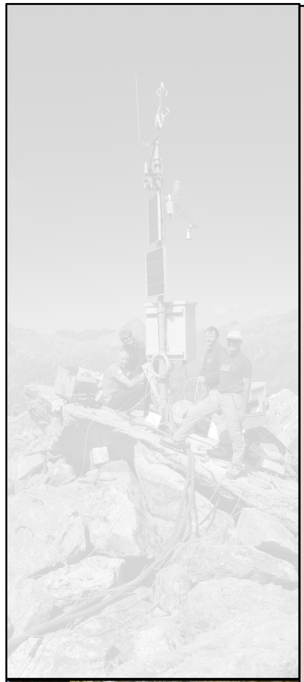
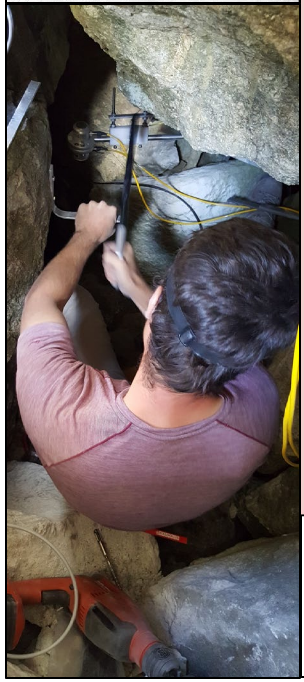
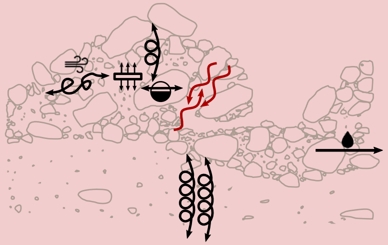




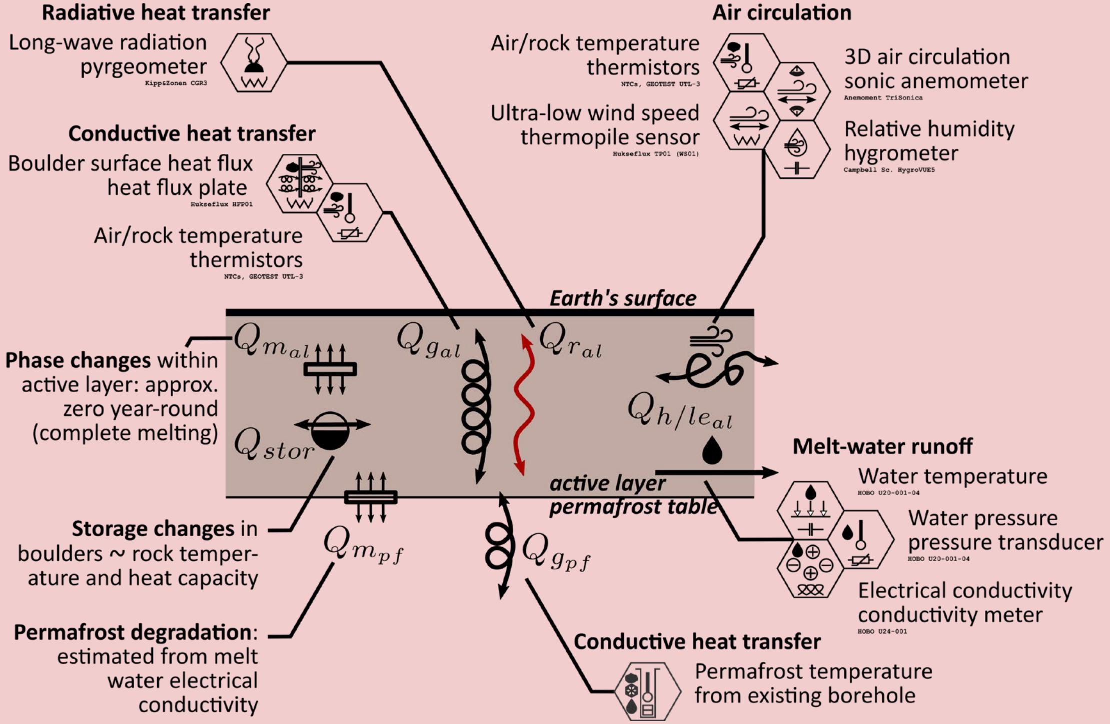


[4b] Measurement design: Layer 2

'SO BELOW'

Boulder-mantle & hydrological sensors

The ground heat flux, Q_g, is more than simple conduction, because all energy transfer modes (**Tab. 1**) occur in the coarse-debris mantle. The debris cover leads to a non-linear, slowed response of the permafrost body to atmospheric warming.



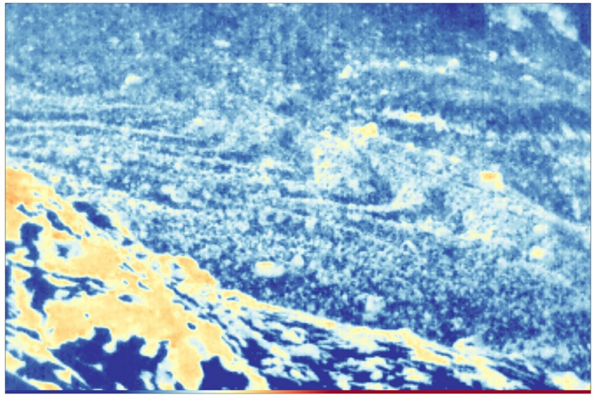
Schematized cross-sections through the active layer with involved heat transport modes (**Tab. 1**, below) and sensors.

Conduction	Short-wave radiation	Long-wave radiation	Air circulation	Water flow	(Snow) melt, ...	Boulder heat capacity
Conductive heat transfer	Radiative heat transfer		Advective/convective transfer Turbulent fluxes		Phase changes	Storage changes

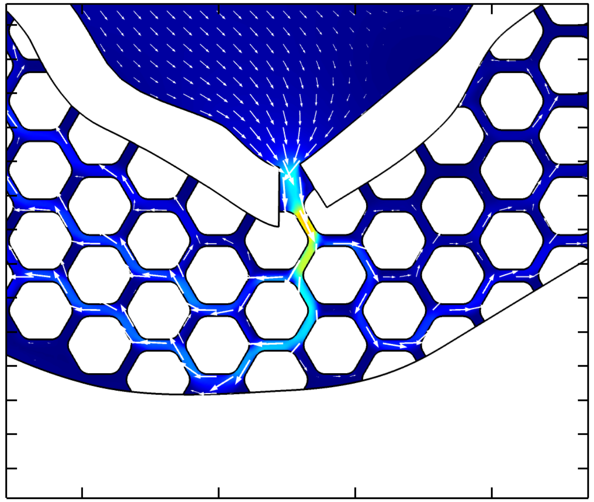
Tab. 1: Modes of heat transport, storage and phase changes with their symbols used.

[5] Complementary investigations

- Thermistors distributed across rock glacier.
- Time-lapse visible images for snow conditions.
- Time-lapse thermal infrared images (TIR) for surface temperature (*Fig.* ↓).



- Electrical resistivity tomography (ERT) for near-surface active layer characterization.
- GPR, qualitative smoke tracer tests.
- Numerical modelling of small-scale air circulation (*Fig.* ↓).



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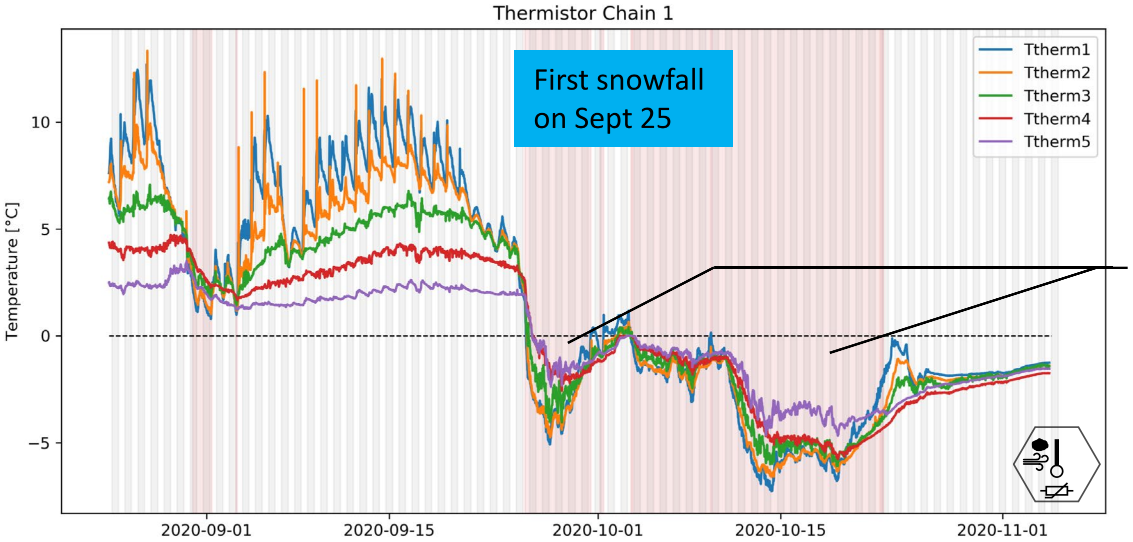
[6] Preliminary data from below: The rock glacier enters the winter mode!

- Data since late August allow a glimpse into the different cooling mechanisms of the rock glacier.

[6a] Thermistors

- 5 Thermistors from surface (‘Ttherm1’, blue) to bottom of cavity at 2.5 m depth (‘Ttherm5’, purple).
- Decoupling from surface conditions and air stratification in cavity.
- Temperature inversions in cavity (shown in red) lead to instable stratification and air motion.

Air temperature on vertical profile



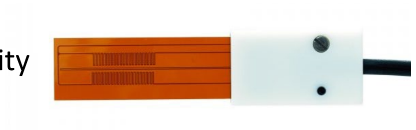
- Temperature inversions: Cold near surface, warmer at depth

[6b] Thermo-anemometer

- Wind speed estimate from cooling rate of an intermittently heated plastic foil (‘wind-chill effect’).
- ‘WS01/1’ near ‘Ttherm5’ (purple) at cavity floor, ‘WS01/3’ (blue) at surface.
- Processes: Daily cycles, natural convection, wind pumping (forced convection).
- Opposing diurnal cycles in different heights of cavity.

Cavity air circulation

- Daily cycles with peak in early morning



Surface air circulation

- Daily cycles with peak in late afternoon (katabatic wind?)

- Natural circulation due to temperature inversion
- Wind pulse: wind pumping
- No wind pumping beneath thick snow cover

[6c] Pyrgeometer

- A pair of pyrgeometers measures long-wave radiation in cavity.
- Slow shift from net downward (heat gain) to upward radiative flux (heat loss/cooling)?

Long-wave radiation

- Upward radiative flux