Integrating UAV photogrammetry and Ground Penetrating Radar to monitor the Forni Glacier tongue (Stelvio National Park, Italy)

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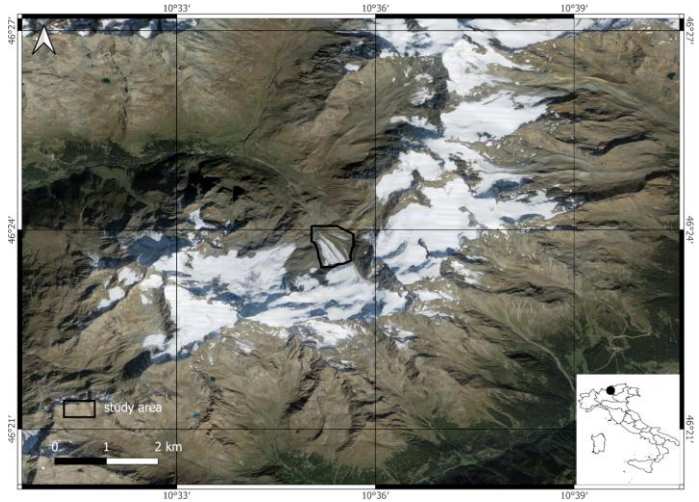
[3] Leica Geosystems AG

11th EARSeL WS Land Ice and Snow 2026

Outline

- Aim of the work and study area
- Previous UAV ånd GPR campaigns
- UAV and GPR data collection
- UAV and GPR data processing
- Results
- Conclusions and future works

Study area: Forni Glacier (Stelvio National Park, Italy)





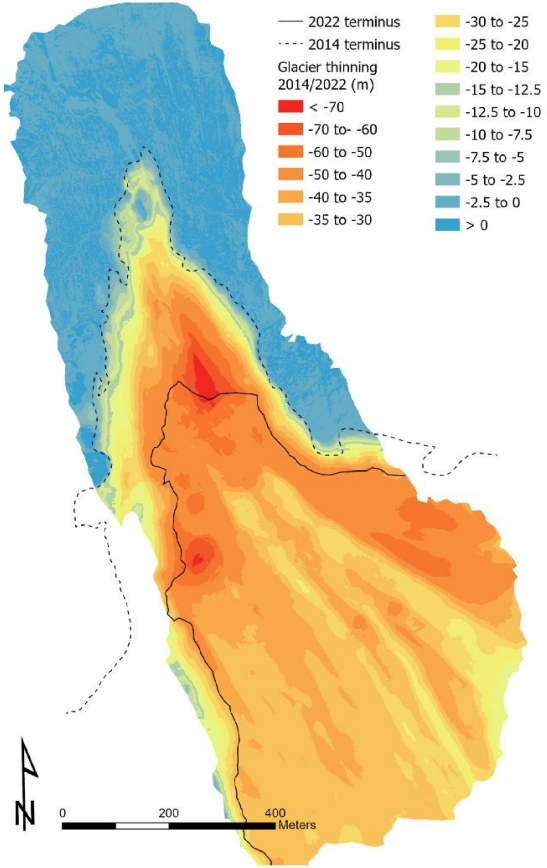
Overview

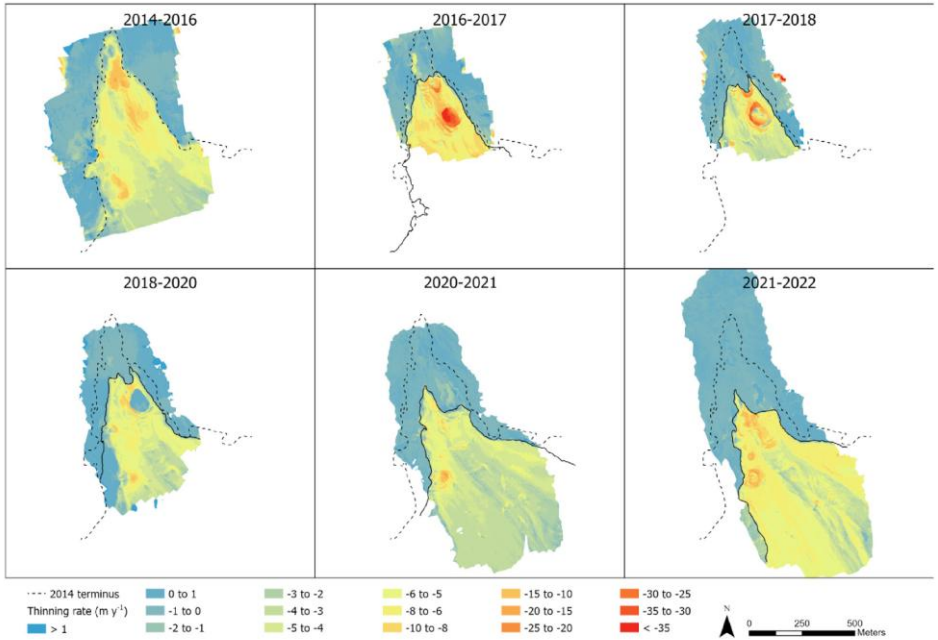
- One of the largest valley glaciers in the Alps
- Rapid retreat and morphological changes in recent years
- Data available from 2014 to 2025

Goals of 2024 UAV and GPR campaign

- Detect ice thickness in the glacier tongue
- Compare results with previous surveys
- Provide reference for future geophysical data

Forni Glacier – Previous geomatic campaigns 2014-2022





Q. Mean ice thickness reduction of 5 m per year but how deep is the glacier bed?
A. Maybe GPR can help…

Belloni et al., 2025, *International Journal of Applied Earth Observation and Geoinformation*

Forni Glacier – Previous GPR campaigns 2012-13

- 2012 - A **Radio Echo Sounding** survey operating at 40 MHz identified a maximum **ice thickness** of **120 m** in the western accumulation basin, while in the glacier tongue bedrock echoes are not well identifiable, though its depth is expected to be around 100 m or more
  (Urbini et al. 2017, Annals of Geophysics)
- 2013 - A **Radio Echo Sounding** system at 70 MHz together with **passive seismic recordings** in the higher part of the tongue detected the bedrock at an approximate **depth** of **70-80 m**
  (Picotti et al. 2017, Journal of Glaciology)

Bedrock depth is highly variable in this area

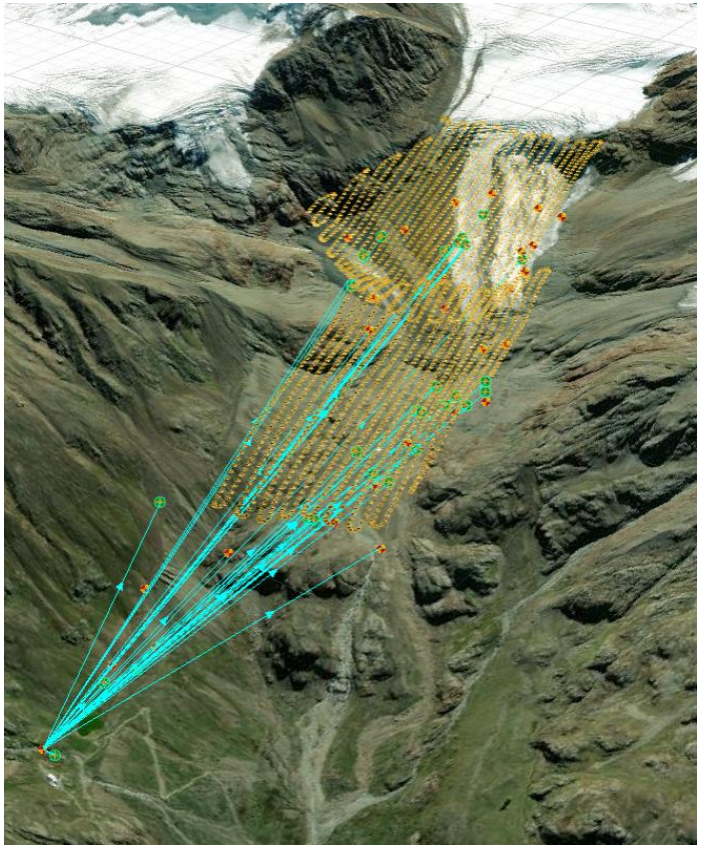
Forni Glacier – 2024 campaign: UAV data collection

- **DJI Mavic 3E UAV** with a 20 Mpx camera
- **D-RTK 2** high-precision **GNSS mobile station** for RTK-assisted UAV navigation
- Centimeter-level RTK GNSS receivers for positioning Ground Control Points (GCPs)/Check Points (CPs)
- A **GNSS base station** outside the glacier for continuously recording satellite observations, used for post-processing and precise positioning of the UAV D-RTK 2 station and the GCPs/CPs





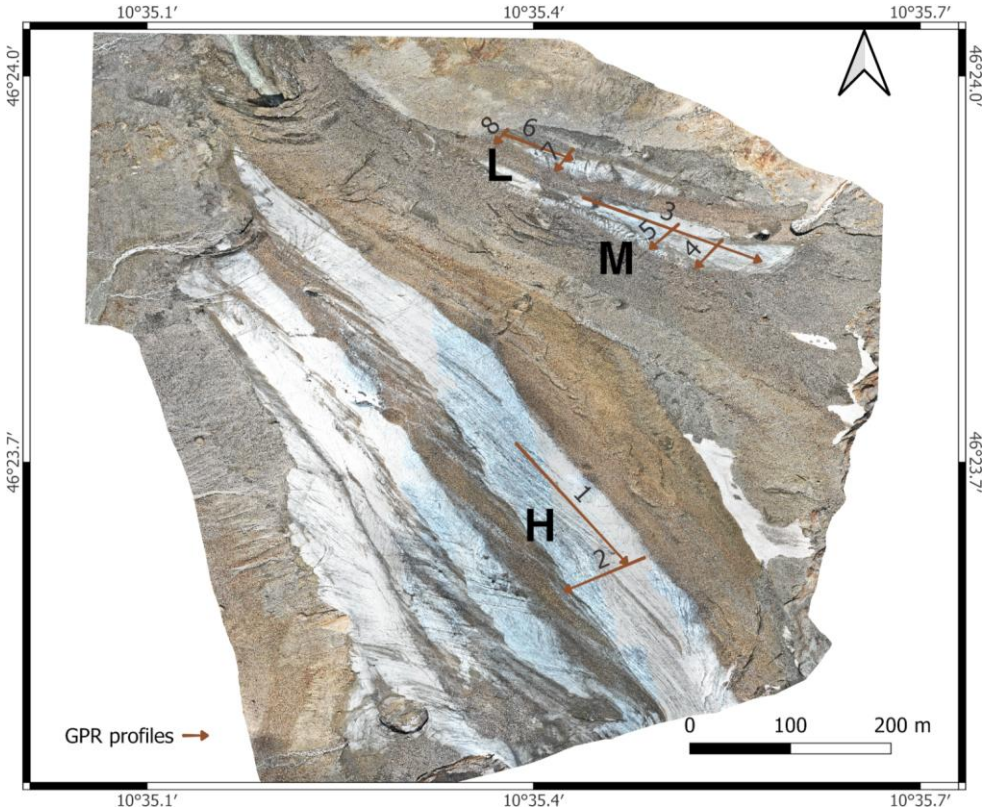




Forni Glacier – 2024 campaign: GPR data collection

- **3 sites** (H, M and L) and **8 GPR profiles**
- **200 MHz IDS antenna** (bistatic)
- Trace length: 1.5 ms, 8192 samples
- Positioning through GNSS receiver

Site H	
Profile	**Length [m]**
1	210
2	90
Site M	
Profile	**Length [m]**
3	200
4	45
5	38
Site L	
Profile	**Length [m]**
6	80
7	35
8	25



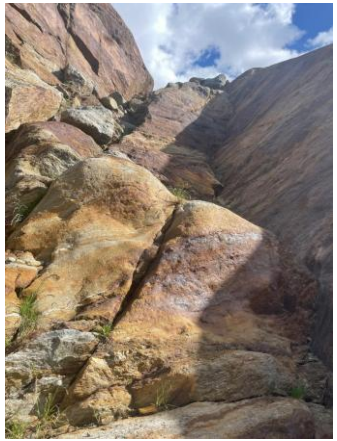
Forni Glacier – 2024 campaign: GPR data collection

Q. Why the 200 MHz antenna?

A. Because this antenna is low frequency being **light enough** (compared to the 80 MHz) to be backpacked (total weight of equipment ~ 30 kg: 2x15kg backpacks with also aux. equipment/spare parts etc.)











Forni Glacier – 2024 campaign: UAV data processing

- **GCPs/CPs** and **UAV track data** post-processing using the GNSS receiver outside the glacier, once this was corrected with data from static known reference stations
- **UAV image** processing using a **Structure-from-Motion** approach implemented in **Leica Infinity** software to model in 2D and 3D the area by generating:
  - Dense Point Cloud (DPC)
  - Digital Surface Model (DSM)
  - orthophoto

Forni Glacier – 2024 campaign: GPR data processing

Data processing (standard)

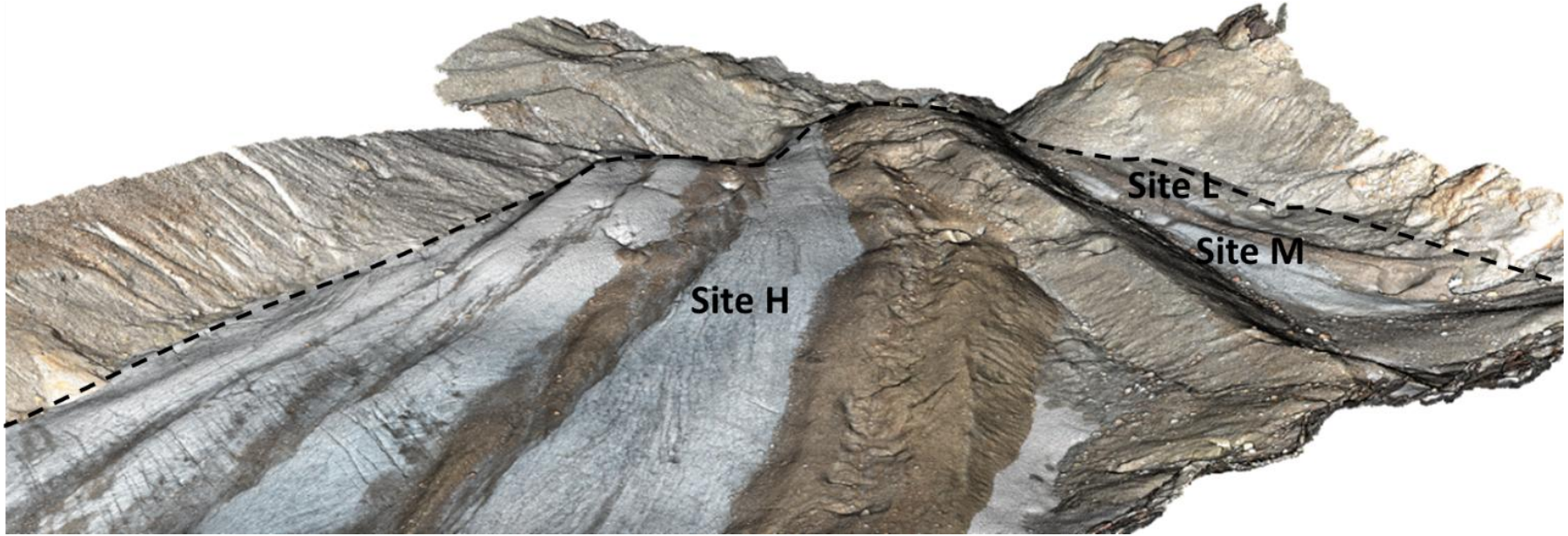
- De-wowing removal
- Zero-time correction
- Background removal
- Spectral analysis and filtering
- Amplitude analysis and recovery
- Topographic correction
- Time-to-depth conversion equation:

$$z = v\,\frac{TWT}{2}$$

where z is the depth, TWT is the two-way-travel time and v is the EM-wave velocity (ice) set to 0.16 m/ns (Forte et al. 2012, EarthDoc) for each GPR trace

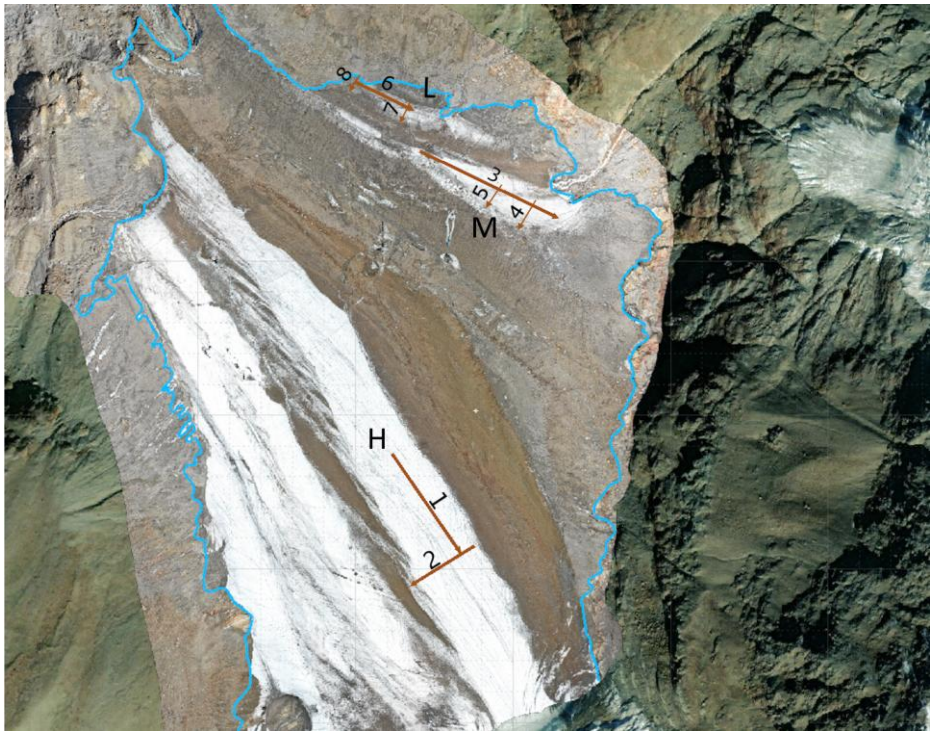
Forni Glacier – 2024 campaign: UAV results

- **GCPs** - Mean of 3D residuals is 3.4 cm with a standard deviation of 1.4 cm
- **CPs** **-** Mean of 3D residuals is 6.4 cm with a standard deviation of 3.1 cm

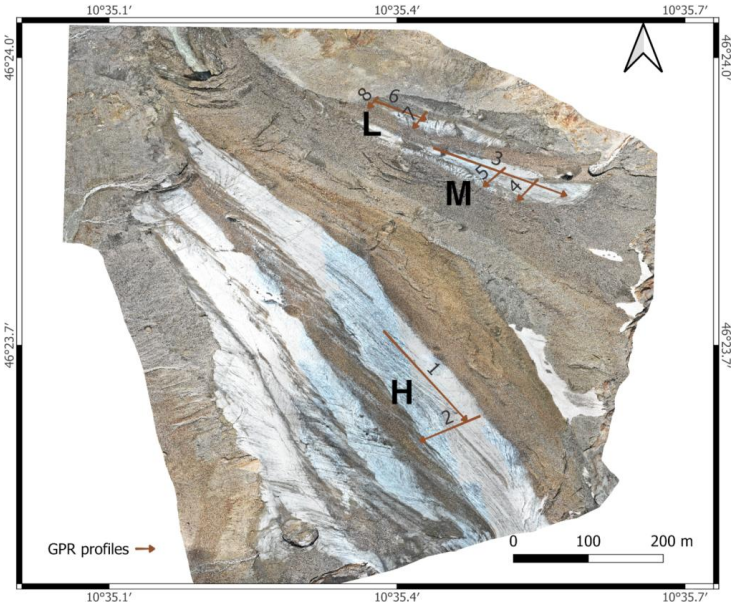


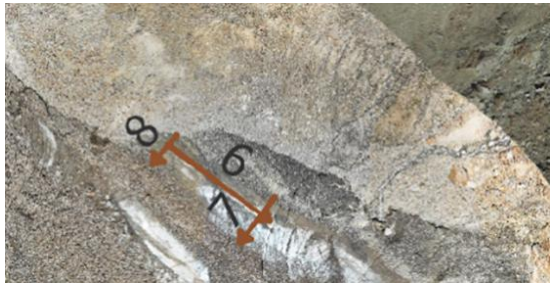
Forni Glacier – 2024-2025 campaign: UAV results

- GPR sites are still inside the 2025 outline of the glacier (cyan)



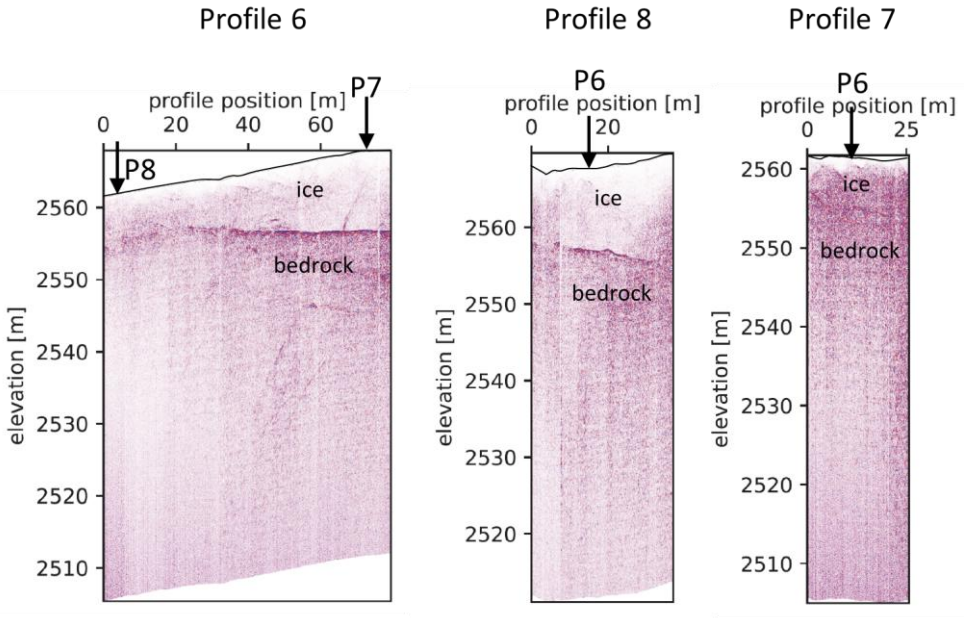
Forni Glacier – 2024 campaign: GPR results



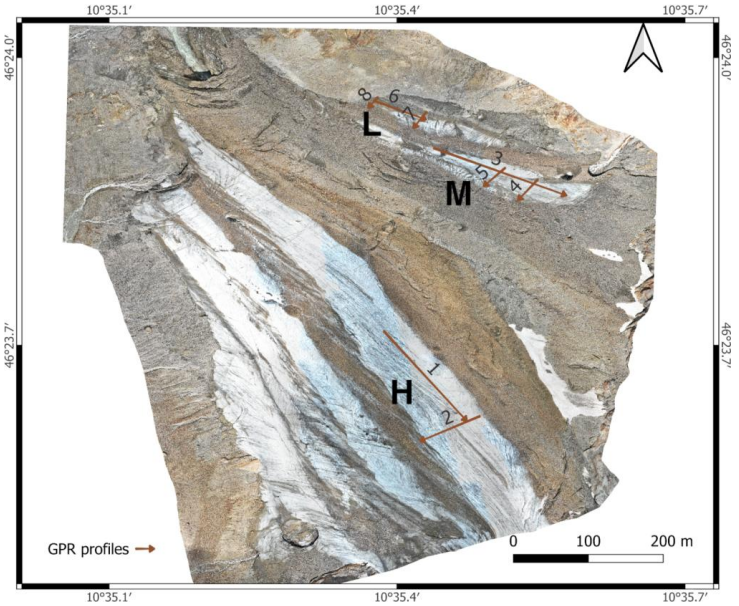


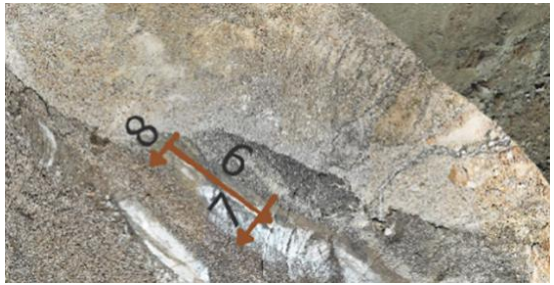
Site L

Bedrock depth ~ 5-15 m



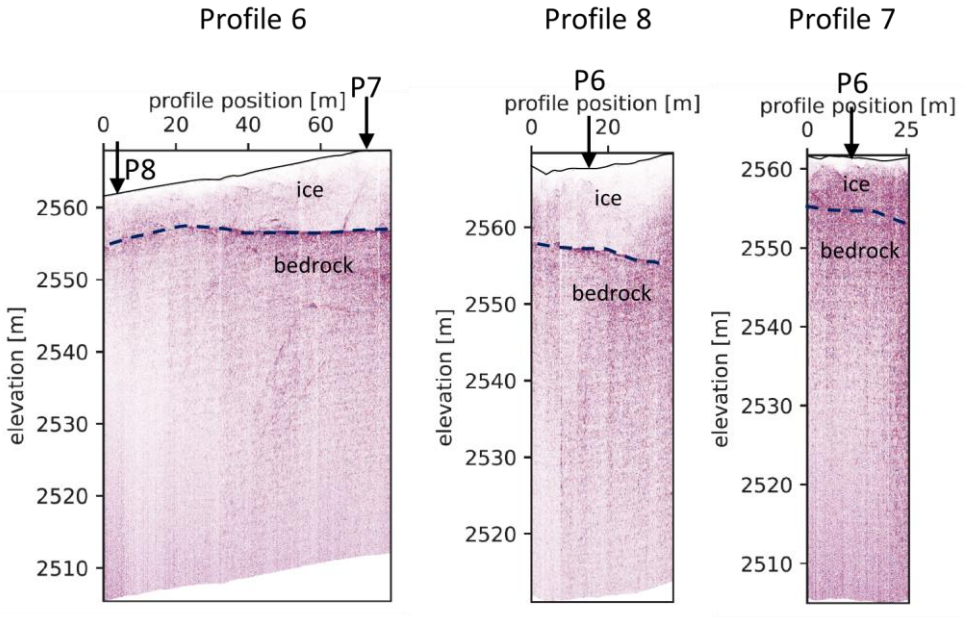
Forni Glacier – 2024 campaign: GPR results



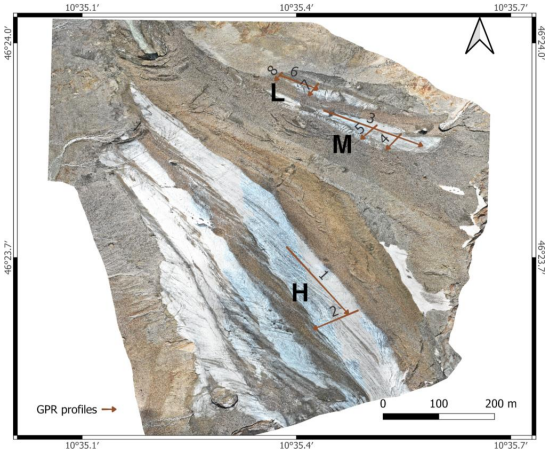


Site L

Bedrock depth ~ 5-15 m



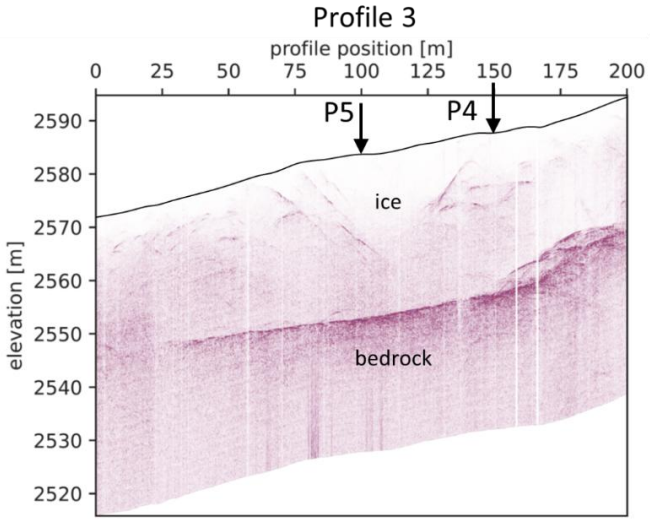
Forni Glacier – 2024 campaign: GPR results

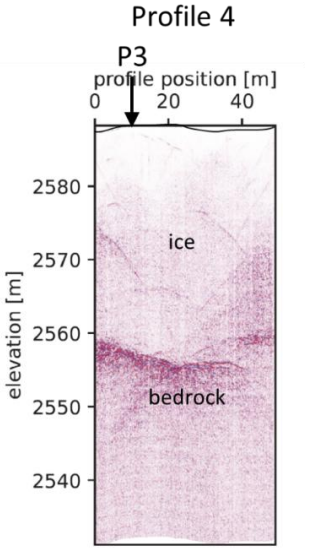


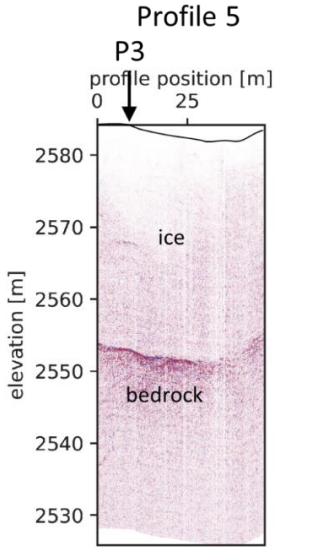


Site M

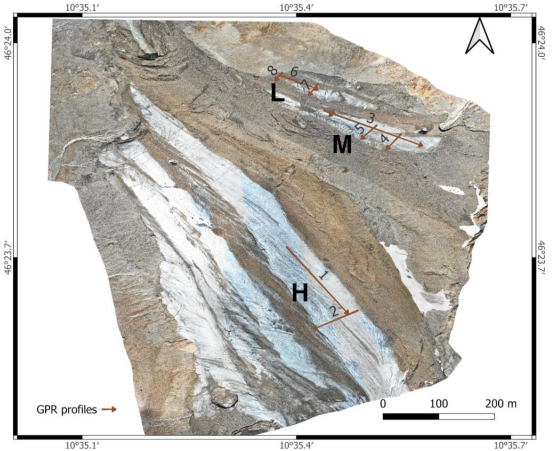
Bedrock depth ~ 25-30 m







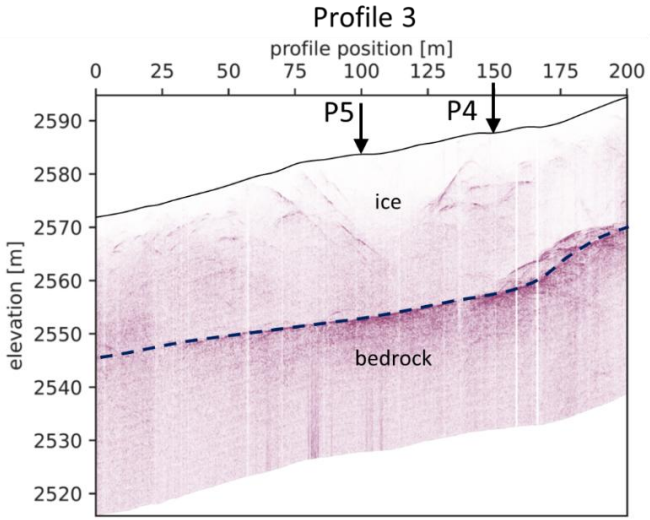
Forni Glacier – 2024 campaign: GPR results

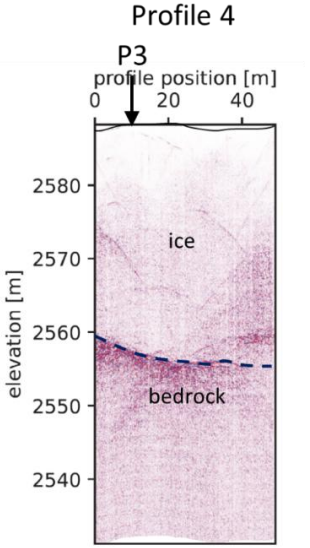


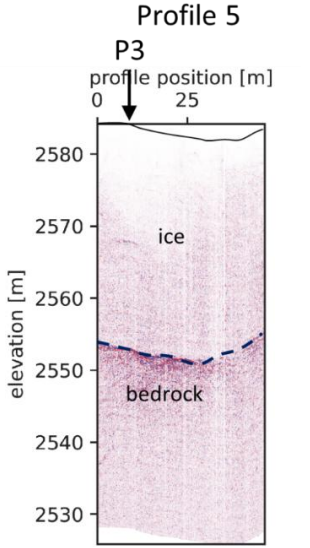


Site M

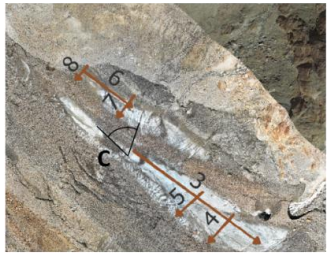
Bedrock depth ~ 25-30 m



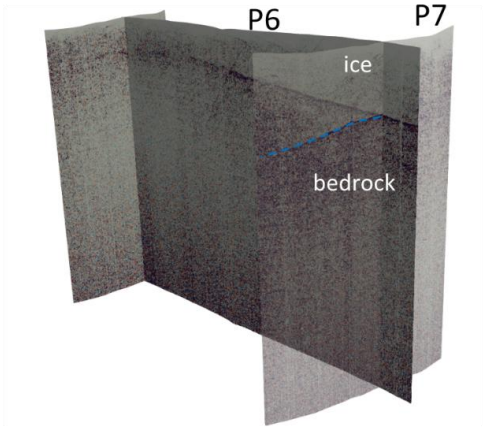




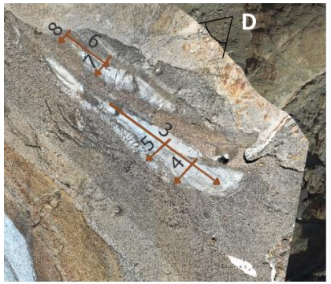
Forni Glacier – 2024 campaign: GPR results



3D View C

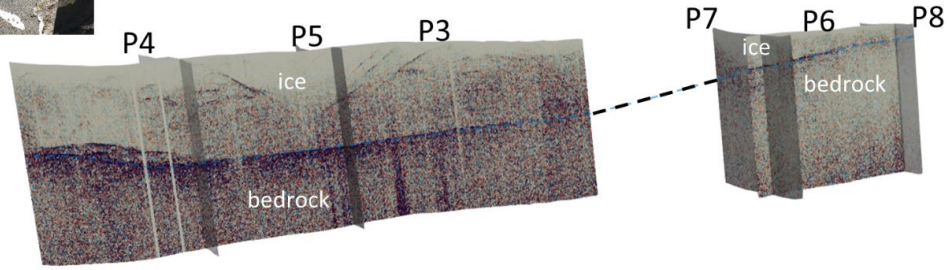


Site L

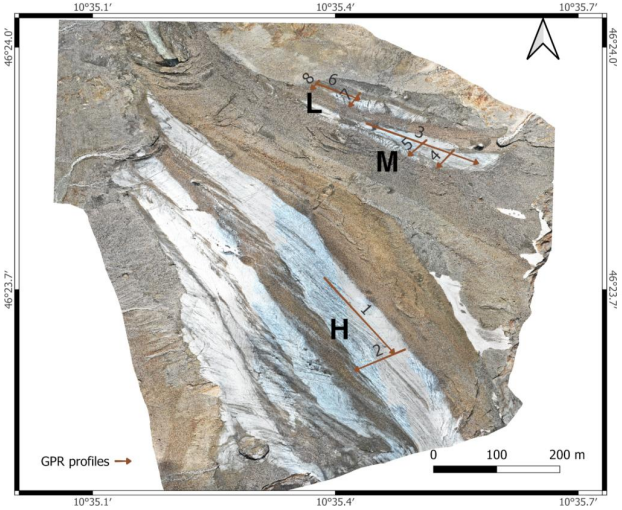


3D View D

Site M



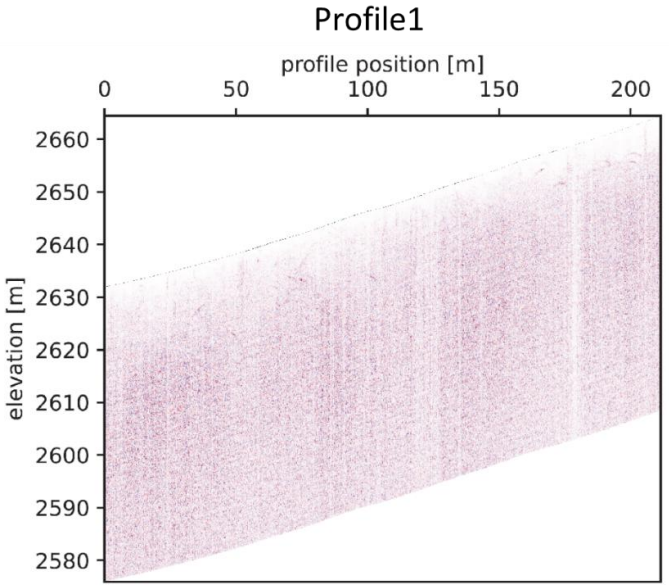
Forni Glacier – 2024 campaign: GPR results

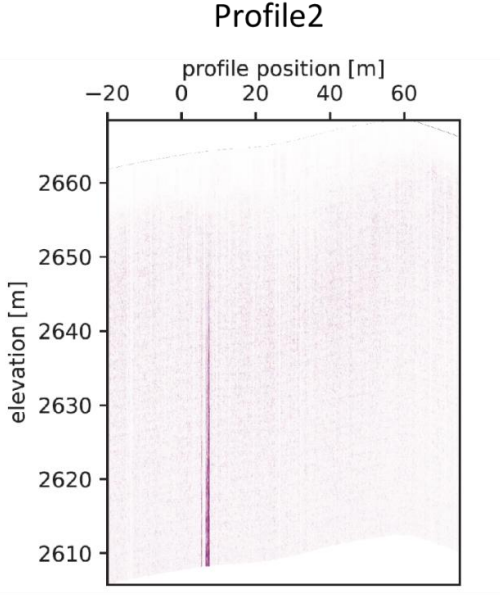




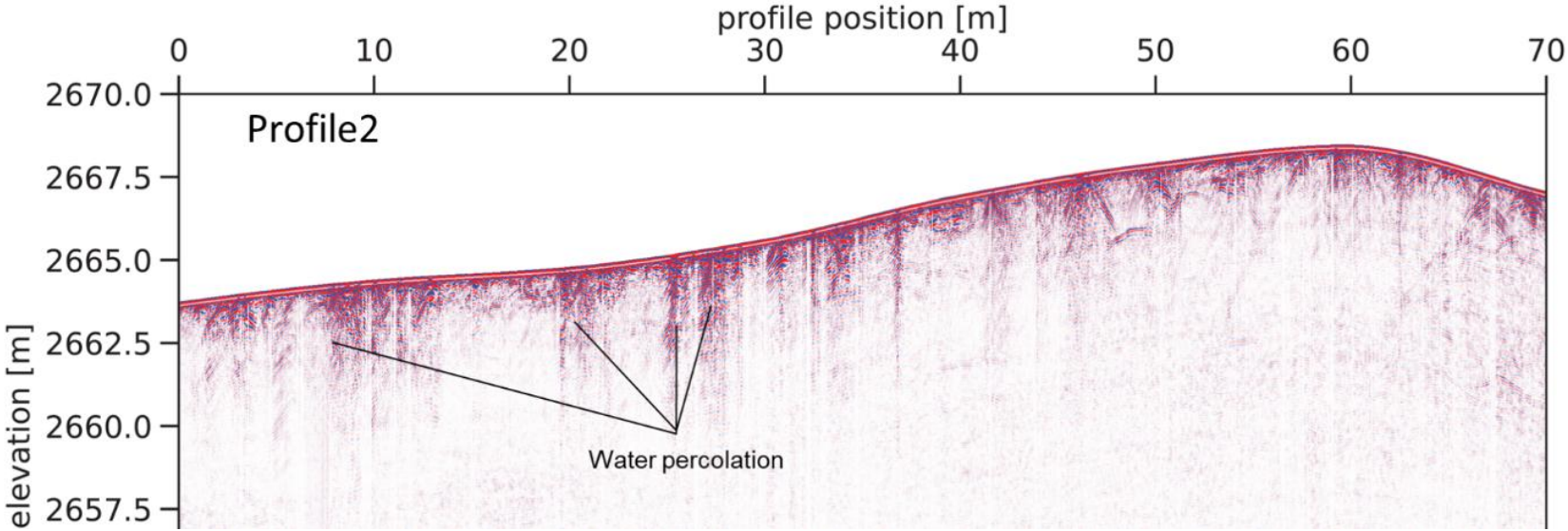
Site H

Bedrock is too deep for the detection at this site (expected depth > 60 m)





Forni Glacier – 2024 campaign: GPR results



Final remarks

Conclusions

- We detected the **ice thickness** in 3 sites of the tongue
- Ice thickness increases from margin (L) to central tongue (M)
- UAV and GPR integration enables surface and depth reconstruction and is effective for glacier monitoring

Future work

- Supporting future high-resolution drone mapping of entire glacier tongue with a **lower** antenna frequency
- Investigate **UAV GPR** equipment

Thanks for your attention

