https://doi.org/10.5194/egusphere-2023-2774
Preprint. Discussion started: 19 December 2023

# **Brief communication:** On the potential of seismic polarity reversal to detect a thin low-velocity layer above a high-velocity layer in ice-rich rock glaciers

Jacopo Boaga (1), Mirko Pavoni (1), Alexander Bast (2)(3), Samuel Weber (2)(3)
*(1) Department of Geosciences, University of Padova, Via Gradenigo 6, 35131 Padova, Italy*
*(2) WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, 7260 Davos Dorf, Switzerland*
*(3) Climate Change, Extremes and Natural Hazards in Alpine Regions Research Center CERC, Flüelastrasse 11, 7260 Davos Dorf, Switzerland*

*Correspondence to*: Jacopo Boaga (jacopo.boaga@unipd.it)

**Abstract.** Seismic refraction tomography is a commonly used technique to characterize rock glaciers, as the boundary between unfrozen and ice-bearing layers represents a strong impedance contrast. In several rock glaciers, we observed a reversed polarity of the waves refracted by an extended ice-bearing layer compared to direct wave arrivals. This phase change is due to the presence of a thin low-velocity, i.e. fine- to coarse-grained sediments with ice, above a thicker high-velocity ice layer. Our results are confirmed by modelling and analysis of synthetic seismograms to demonstrate that the presence of a low-velocity layer produces a polarity reversal on the seismic gather.

## 1. Introduction

Rock glaciers are prominent landforms in permafrost environments that pose a potential mass movement hazard, endangering communities and infrastructure in high mountain regions. As their kinematics are strongly dependent on the presence of ice and water, various geophysical methods have been used in recent decades to map, characterise, and monitor the internal structure of these permafrost-related landforms. Seismic methods are one of the most frequently and earliest applied methods to investigate the near subsurface of rock glaciers (e.g., Barsch 1973), besides electrical methods such as electrical resistivity tomography (ERT; e.g., Hilbich et al. 2010), induced polarization (e.g., Duvillard et al 2018) or electro-magnetic methods (e.g., Boaga et al., 2020; Pavoni et al 2023b). Recently, refraction seismic tomography (SRT; e.g., Musil et al 2002) has regained popularity, as joint-inversion algorithms provide a more detailed insight into the ice, water, rock and air composition within a rock glacier (e.g., Hauck et al. 2011; Pavoni et al. 2023a).

SRT is a very suitable method because the refracted seismic wave travels along the ice-bearing layer at higher seismic velocities compared to the upper sediments. Usually, higher velocities in depth imply higher impedance contrast, which is the acoustic impedance Z:

$$Z = \boldsymbol{\sigma} * v \qquad (1)$$

the product of density (**σ**) and seismic velocity (***v***). The energy reflection at the boundary is influenced by the reflection coefficient R:

https://doi.org/10.5194/egusphere-2023-2774
Preprint. Discussion started: 19 December 2023

$$R = (Z2 - Z1)/(Z2 + Z1) \quad (2)$$

where Z1 is the acoustic impedance of the overlying media, and Z2 is the acoustic impedance of the bottom one. If the reflection coefficient (*R)* is positive, the boundary generates critically refracted waves (Harvey et al 2011). From the first arrival times of the direct and refracted waves, we can retrieve the seismic velocity structure of the rock glacier (Leopold et al 2011). Since critically refracted waves are generated in case of a positive reflection coefficient, i.e. a higher seismic velocity layer below a slower one, a possibly occurring low-velocity layer (LVL) in between two faster ones is not visible using the seismic refraction technique. This represents the main drawback of the methodology. However, different wave attributes may be analyzed in the seismic shot gather. A polarity reversal, or so-called phase change, is an example of a local amplitude seismic attribute anomaly that can indicate the presence of a low-velocity layer between two faster media. In seismic hydrocarbon exploration, phase polarity inversion is considered a direct hydrocarbon indicator. Polarity reversals have also been observed in glaciological studies (e.g. Anandakrishnan et al. 2003). The phase shift can also involve refracted waves, due to the interaction of the wave with a boundary or a change in the medium, as a phase lag generated by slow layers.

We observed a reversal of the polarity of the refracted waves with respect to the direct wave phase in SRT datasets of different rock glaciers. Here we present two case studies from Switzerland, where two rock glaciers are characterized using ERT, SRT, and additionally in one case with borehole information. In both cases, the refracted wave shows a reversal polarity in correspondence with the buried ice-rich layer. We speculate that this phase change is due to the presence of a low-velocity layer (LVL), i.e. fine- to coarse-grained sediments with ice, overlying a high-velocity layer, i.e. a layer of massive ice or with ice-filled veins between coarse blocks. This layer is too thin to be detected by the ERT, and it is apparently undetectable by SRT. We then computed synthetic seismograms for two subsurface models, with and without the low-velocity layer (LVL) of fine sediments over a high-velocity ice layer. The synthetic modelling confirms that even the presence of a thin layer of fine sediments with low seismic velocity can induce a reversal in the polarity of the refracted waves.

## 2. Real data case studies: sites, methods, and results

In this study, we investigate the Schafberg and Flüelapass rock glaciers, Canton Grisons, Eastern Swiss Alps. At both sites, ERT and SRT data were collected in August 2022.

The ice-rich Schafberg rock glacier is located above Pontresina at 2’750 m a.s.l. (~ 46.49 N, ~ 9.93 E). In 1990, two boreholes were drilled and equipped with thermistors (Vonder Mühll and Holub, 1992), and in 2020, three further boreholes were drilled and equipped with piezometers, temperature sensors and a cross-borehole ERT setup (Phillips et al 2023). The stratigraphies recorded during drilling indicate a 3 – 4 m thick layer of boulders, above a layer of fines with ice (~ 1 m), over coarse sediments with ice, and a layer of ice and/or mud with ice (Phillips et al 2023). The internal structure was confirmed by ERT, SRT, and electro-magnetic soundings (Boaga et al 2020, Pavoni et al., 2023a). In both cases, the acquisition was performed with 48 channels and 3 m spacing between electrodes/geophones. The ERT survey was carried out with a Syscal Pro Switch georesistivimeter (Iris Instruments) and a multi-skip acquisition scheme (Pavoni et al., 2023a) with direct and reciprocal measurements to define a reliable expected data error (Binley, 2015). Seismic data were recorded with Geode seismographs

(Geometrics, USA) using vertical geophones (100 Hz). At each shot location, the impacts were performed with a 20 kg sledgehammer. The signal-to-noise ratio was improved by stacking the traces recorded twice at each location. In this way, we facilitated the manual picking procedure of the compressional wave's first-time arrivals and evaluated the data uncertainty (picking error) by performing repeated picking (Pavoni et al., 2023a).

The Flüelapass rock glacier is located at 2'400 m a.s.l., above the Flüelapass road (~ 46.75 N, ~ 9.95 E). The inverted tomograms suggested the presence of an ice layer beneath a 3-5 m thick layer of unfrozen debris. Data acquisition and processing were carried out in the same way as on the Schafberg rock glacier. However, on the Flüelapass a 2 m electrode/geophone spacing was used.

In the raw seismograms of both rock glaciers, we observed a reversal polarity of the refracted waves' first arrivals with respect to the direct waves' first arrivals, corresponding to the presence of a ice-bearing layer. Figures 1 and 2 show the Schafberg case study and the Flüelapass case study, respectively. The appendant panels *a* and *b* show the results of the inversion processes of the SRT and ERT datasets realized with the open-source C++/Python-based library pyGIMLi (Rücker et al., 2017). The inverted models reveal the internal structure of the rock glaciers, and the estimated ice-bearing layer boundary (dashed lines), estimated by applying the steepest gradient method to the ERT results (Pavoni et al., 2023c). The panels *c* and *d* show the raw seismograms in amplitude and wiggle mode with red (+) and blue (-) phase colors of the shot gather to highlight the polarity reversal.

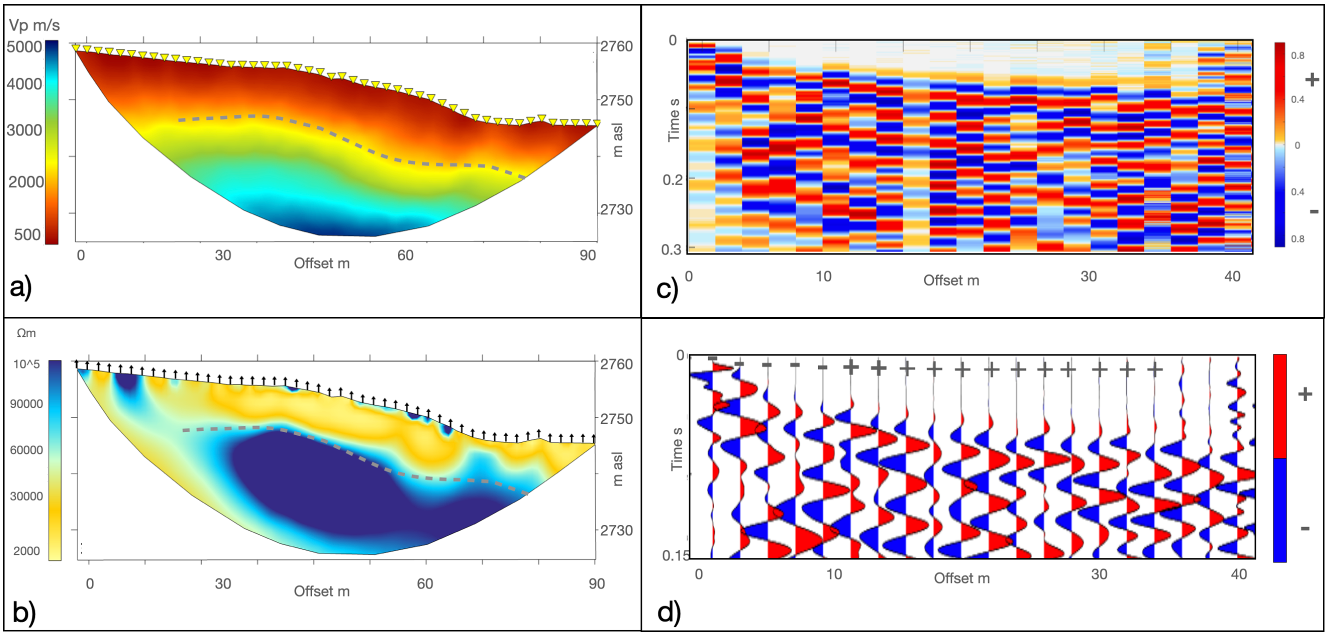

**Figure 1: a) Schafberg SRT inverted section (estimated picking error 1 msec) and b) Schafberg ERT inverted section (expected data error 10%). The dashed line represents the ice-bearing layer boundary evaluated with the steepest gradient method applied to the resistivity section; c) amplitude and d) wiggle modes (zoom) seismograms above the ice-bearing layer. The seismograms clearly highlight the reversal polarity of the refracted waves: first arrivals of the direct wave have blue-negative polarity (-), while refracted wave first-arrivals switch to red positive polarity (+).**

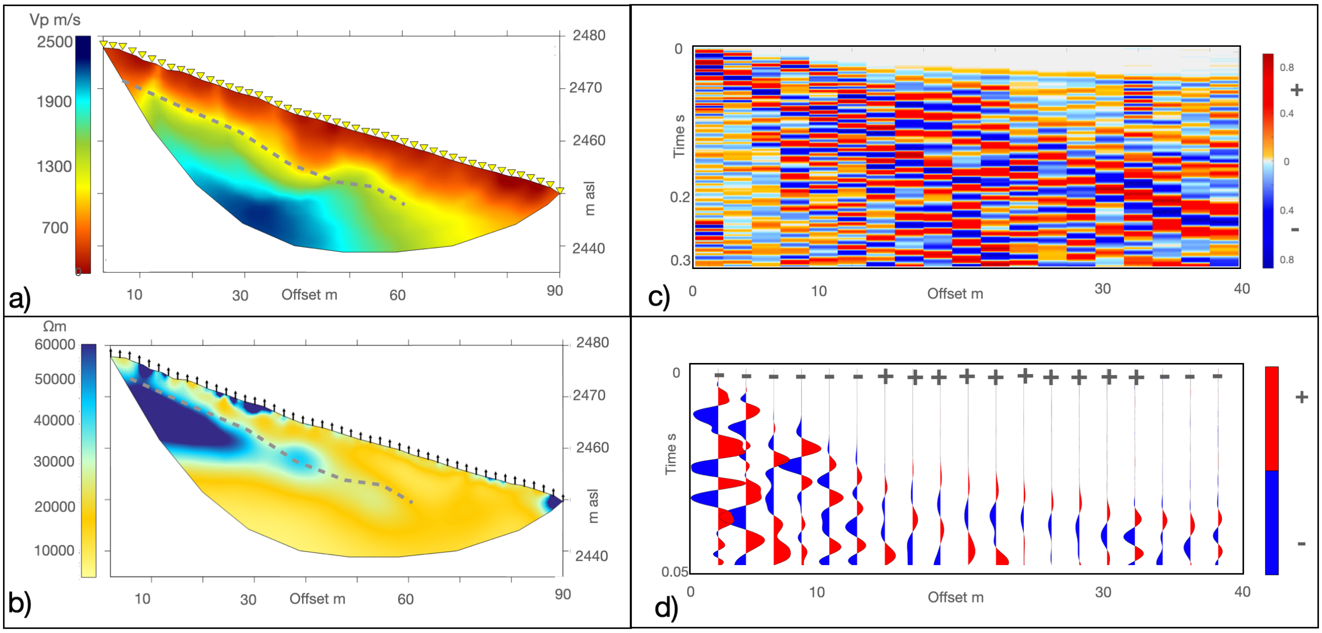

**Figure 2: a) Flüelapass SRT inverted section (estimated picking error 1 msec) and b) Flüelapass ERT inverted section (expected data error 5%). The dashed line represents the ice-bearing layer boundary evaluated with the steepest gradient method applied to the resistivity section; c) amplitude and d) wiggle modes (zoom) seismograms above the ice-bearing layer. The seismograms highlight the reversal polarity of the refracted waves: first arrivals of the direct wave have negative polarity indicated with blue (-), while the refracted waves' first arrivals switch to positive polarity indicated with red(+).**

At both sites, the shot gathers show a clear phase change from negative to positive between the direct waves' first arrivals (blue, negative polarity), and the refracted waves' first arrivals (red, positive polarity) generated by the ice-bearing layer boundary.

We hypothesize that the observed reversal polarity can be attributed to the presence of a thin, low-velocity layer of fine- to coarse grained sediments with ice above a high-velocity ice-rich layer, as confirmed by the documented stratigraphy of the Schafberg rock glacier (Phillips et al. 2023).

## 3. Representation in a synthetic model

To verify this hypothesis, we computed synthetic seismograms based on information derived from the Schafberg borehole information, SRT and ERT data. The forward problem was implemented using the advanced full-waveform spectral element solver Salvus (by the Mondaic ETH spin-off; see Afanasiev et al. 2019). Figure 3 shows a schematic layered model of the Schafberg near-subsurface structure. A Ricker wavelet source signal recorded by 100 receivers spaced 1 m apart was simulated, in one case without low velocity layers within the structure (Fig. 3, panels *a* and *c*), and then adding a 1 m thick low velocity layer with Vp= 400m/s (Fig. 3, panels *b* and *d*). For both the models the upper debris has Vp = 600 m/s, the ice layer has Vp= 3000 m/s and the bottom layer has Vp = 4000 m/s.

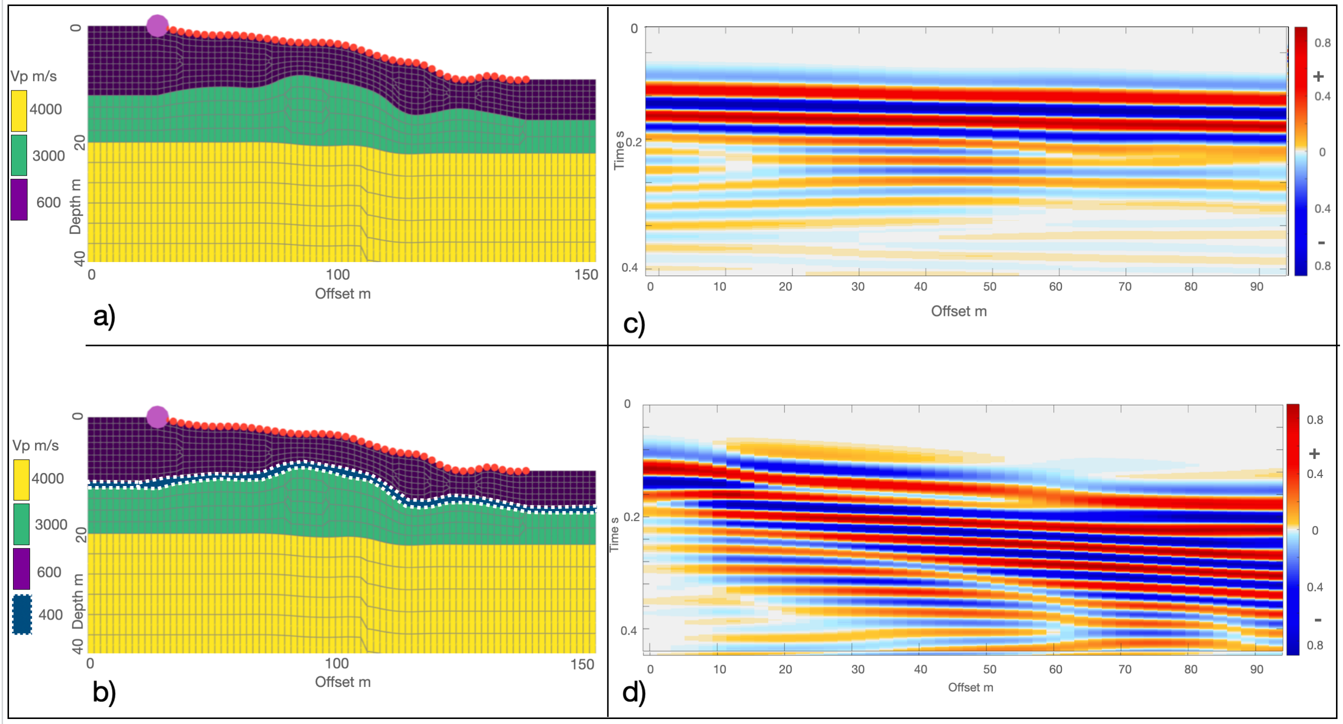

**Figure 3. Synthetics models of the Schafberg rock glacier a) without and b) with the fine sediments 1 m thick LVL (blue zone between dashed white lines). The purple dot is the source position, and the red dots are the receivers. Debris has Vp = 600 m/s, Ice Vp= 3000 m/s, bedrock Vp = 4000 m/s. LVL in panel b) has Vp = 400 m/s. c) Synthetic seismograms computed without the LVL presence; d) synthetic seismograms computed with the LVL presence.**

## 4. Discussion and Conclusions

We demonstrated that a thin low-velocity layer (LVL) consisting of fine sediments increases the complexity of the shot gather (see panels *b* and *d in* Figure 3). However, we are able to identify this LVL as it generates a polarity reversal of the refracted waves' first arrivals in contrast to the direct waves' phases (from the negative phase in blue to the positive phase in red). On the contrary, in the absence of a LVL, the direct and refracted waves retain the same negative (blue) polarity without any change in phase (see Figs. 3a and 3c). Furthermore, the synthetic shot gather in Fig. 3d is very similar to the actual shot gather collected at Schafberg (Figure 1c), where borehole stratigraphy confirmed the presence of a thin, fine- to coarse-grained sediment layer with ice above a high-velocity ice-rich layer (Phillips et al 2023). This observation indicates that the observed reversal polarity at Schafberg and Flüelapass (also observed at other sites not presented here for the sake of brevity) may be attributed to the presence of a low-velocity layer (LVL) of finer sediments accumulated upon the ice-rich layers. This thin LVL is hardly detectable with geophysical imaging as conventional ERT does not have the necessary resolution, and SRT is not compatibel to velocity inversion at depth. This thin LVL may play a relevant role in the hydrological behavior of the suprapermafrost water fluxes in rock glaciers (Jones et al., 2019), which are most likely composed of low-permeability fine sediments. This LVL may, for example, help the ice-rich layer to act as an aquiclude (Pavoni et al 2023c) or favour local water accumulation (Haeberli et al 2001). Hence, the simple observation of phase reversal in the shot gather of the seismic refraction dataset can be interpreted as a proxy of the very interesting presence of fine- to coarse-grained sediments with ice overlying the ice-rich / massive ice zone. Once the possible presence of an LVL has been detected by reversal polarity evidence in the shot gather, future perspectives may include its characterization, both in terms of thickness and continuity, by specifically designed surveys as very high-resolution ERT or detailed surface waves analyses (Barone et al., 2021).

*Author contributing.* JB developed the concept of the study, AB, JB, SW, MP have been involved in data acquisition; MP and JB performed the data processing; all authors contributed to the writing and editing of the manuscript.

The authors declare that they have no conflict of interest.

## References

Anandakrishnan S (2003) Dilatant till layer near the onset of stream- ing flow of Ice Stream C, West Antarctica, determined by AVO (amplitude vs offset) analysis. Ann. Glaciol., 36, 283–286

Afanasiev, M., Boehm, C., van Driel, M., Krischer, L., Rietmann, M., May, D. A., et al. Modular and flexible spectral-element waveform modelling in two and three dimensions. Geophysical Journal International, 216(3), 1675–1692, 2019

Barone, I., Boaga, J., Carrera, A. et al. Tackling Lateral Variability Using Surface Waves: A Tomography-Like Approach. Surv Geophys 42, 317–338, 2021.

Haberkorn A, Kenner R, Noetzli J and Phillips M. Changes in Ground Temperature and Dynamics in Mountain Permafrost in the Swiss Alps. Front. Earth Sci. 9:626686, 2021

Boaga, J.; Phillips, M.; Noetzli, J.; Haberkorn, A.; Kenner, R.; Bast, A.. A Comparison of Frequency Domain Electro-Magnetometry, Electrical Resistivity Tomography and Borehole Temperatures to Assess the Presence of Ice in a Rock Glacier. DOI:10.3389/feart.2020.586430. In Frontiers in Earth Science - ISSN:2296-6463 vol. 8, 2020

Duvillard P.A., A. Revil, Y. Qi, A. Soueid Ahmed, A. Coperey, L. Ravanel. Three-Dimensional Electrical Conductivity and Induced Polarization Tomography of a Rock Glacier, Journal of Geophysical Research, vol 123, issue 11, 2018

Haeberli, W., Kääb, A., Vonder Mühll, D. and Teysseire, P., Prevention of outburst floods from periglacial lakes at Grubengletscher, Valais, Swiss Alps. Journal of Glaciology, 47(156): 111-122, 2001

Harvey, N. Seismic Refraction. In: Hopley, D. (eds) Encyclopedia of Modern Coral Reefs. Encyclopedia of Earth Sciences Series. Springer, Dordrecht, 2011

Leopold, M., Williams, M.W., Caine, N., Völkel, J., Dethier, D. Internal structure of the Green lake 5 rock glacier, Colorado Front Range, USA. Permafr. Periglac. Process. 22 (2), 107–119, 2011

Hilbich, C. Time-lapse refraction seismic tomography for the detection of ground ice degradation. Cryosphere 4 (3), 243–259, 2010

Musil, M., Maurer, H., Green, A.G., Horstmeyer, H., Nitsche, F.O., Mühill, D.V., Springman, S. Shallow seismic surveying of an Alpine rock glacier. Geophysics 67 (6), 1701–1710, 2002

Pavoni M., Boaga J., Wagner F.M. , Bast A., Phillips M., Characterization of rock glaciers environments combining structurally-coupled and petrophysically-coupled joint inversions of electrical resistivity and seismic refraction datasets, Journal of Applied Geophysics, Volume 215, 2023,105097, ISSN 0926-9851, 2023a

Pavoni, M.; Boaga, J.; Carrera, A.; Urbini, S.; de Blasi, F.; Gabrieli, J. Combining Ground Penetrating Radar and Frequency Domain Electromagnetic Surveys to Characterize the Structure of the Calderone Glacieret (Gran Sasso d'Italia, Italy). Remote Sens. 2023, 15, 2615. https://doi.org/10.3390/rs15102615, 2023b

Pavoni, M., Boaga, J., Carrera, A., (...), Carturan, L., Zumiani. Mountain permafrost acts as an aquitard during an infiltration experiment monitored with electrical resistivity tomography time-lapse measurements. The Cryosphere 17(4), pp. 1601-1607, 2023c

Phillips, M., Buchli, C., Weber, S., Boaga, J., Pavoni, M., and Bast, A.: Brief communication: Combining borehole temperature, borehole piezometer and cross-borehole electrical resistivity tomography measurements to investigate seasonal changes in ice-rich mountain permafrost, The Cryosphere, 17, 753–760, https://doi.org/10.5194/tc-17-753-2023, 2023.

Vonder Mühll, D. and Holub, P.: Borehole logging in Alpine permafrost, Upper Engadin, Swiss Alps, Permafrost and 230 Periglacial Processes, 3, 125-132, 1992.

Wagner, T., Brodacz, A., Krainer, K. et al. Active rock glaciers as shallow groundwater reservoirs, Austrian Alps. Grundwasser - Zeitschrift der Fachsektion Hydrogeologie 25, 215–230, 2020

Jones, D. B., Harrison, S., Anderson, K., and Whalley, W. B.: Rock glaciers and mountain hydrology: A review, Earth-Sci. Rev., 193, 66–90, https://doi.org/10.1016/j.earscirev.2019.04.001, 2019.

Barsch, D. Refraktionsseismische Bestimmungen an der Obergrenze des gefrorenen Schuttkörpers in verschiedenen Blockgletschern Graubündens. Zeitschrift für Gletscherkunde und Glaziologie, IX (1-2): 143 – 167, 1973

Hauck, C., Bottcher, M. and Maurer, H. A new model for estimating subsurface ice content based on combined and seismic data sets. The Cryosphere, 5: 453-468. doi: 10.5194/tc-5-543-2011, 2011