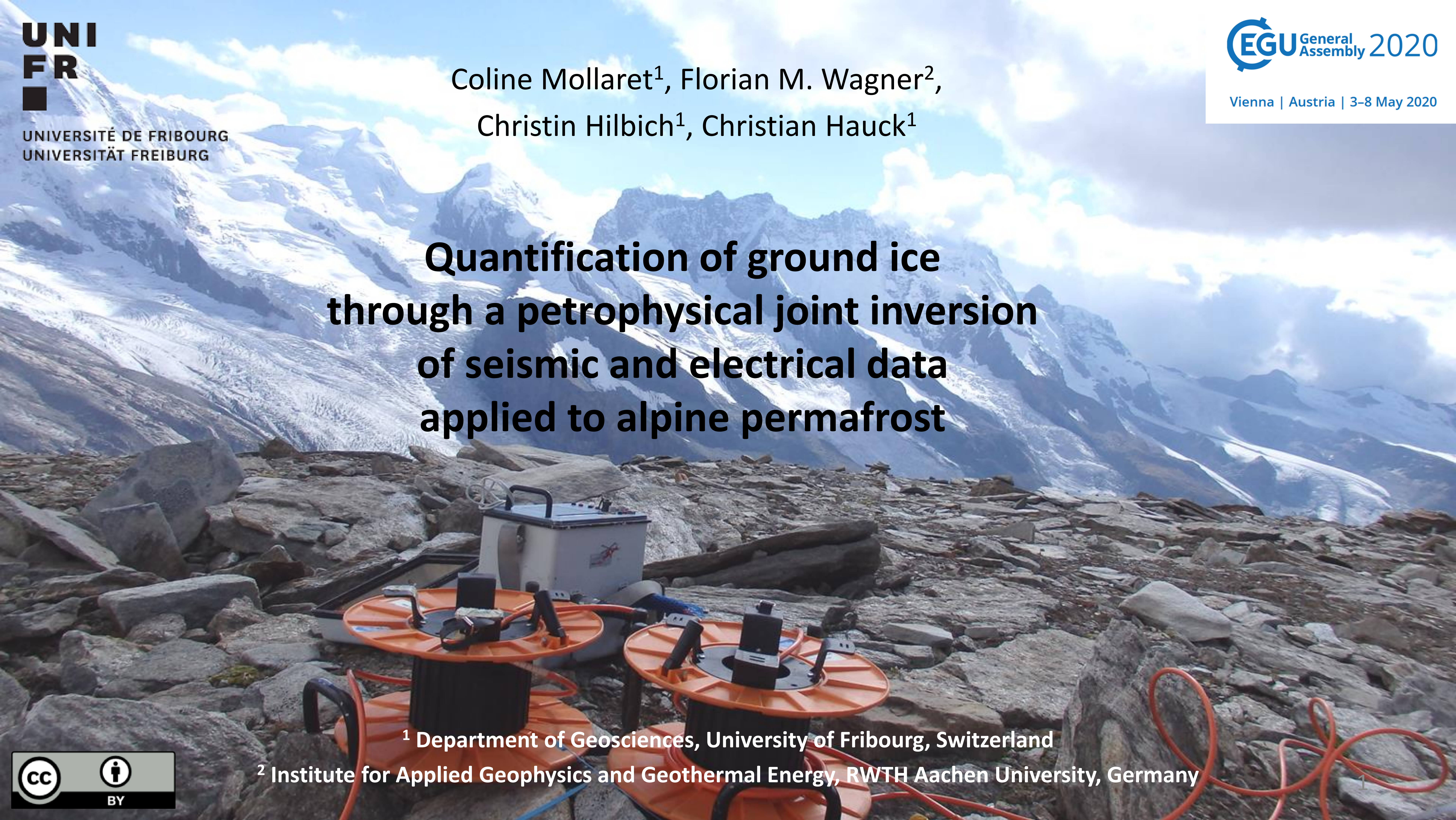

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Quantification of ground ice through a petrophysical joint inversion of seismic and electrical data applied to alpine permafrost

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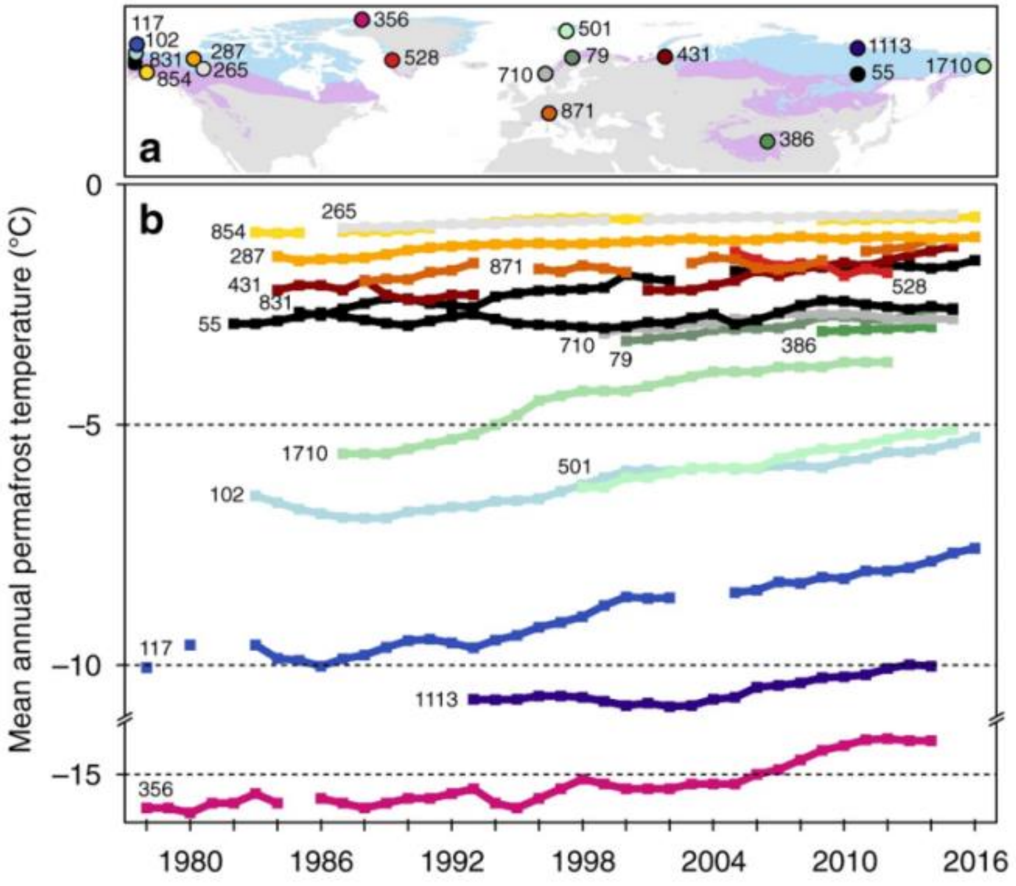
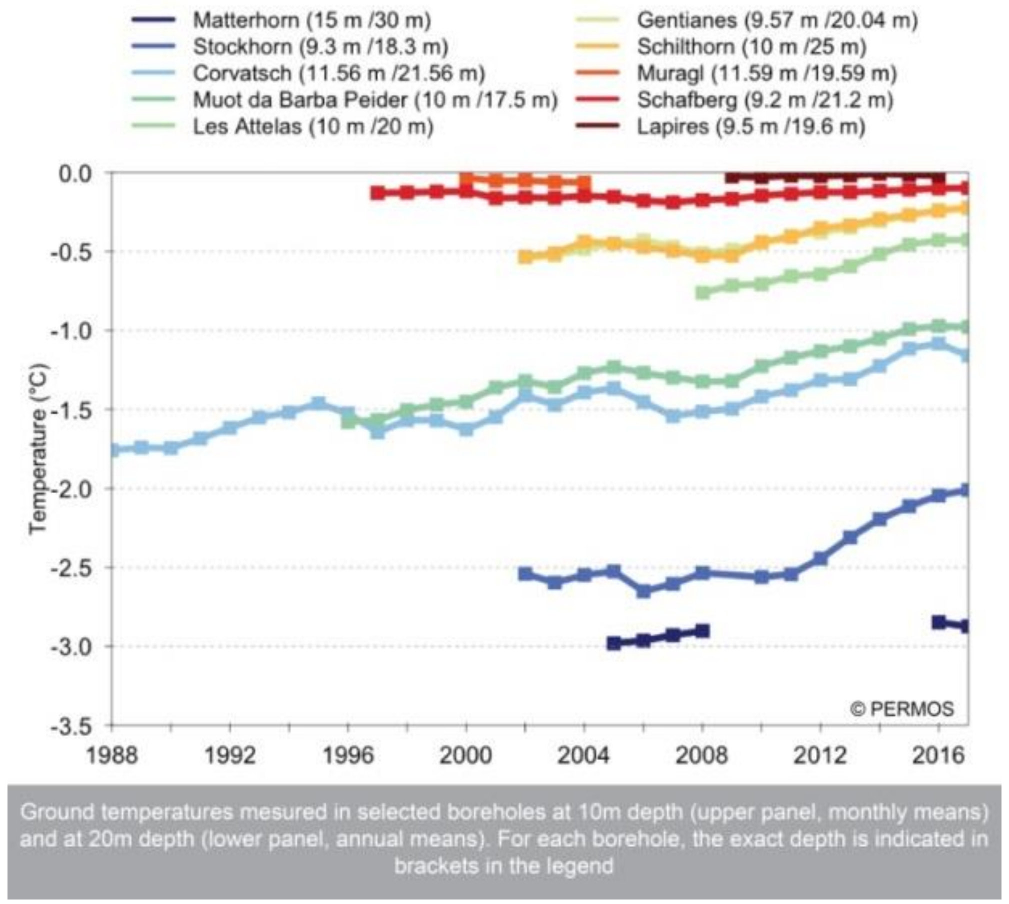
Climatic context: Increase of ground temperatures measured in boreholes

In the Northern Hemisphere...



Biskaborn, 2019

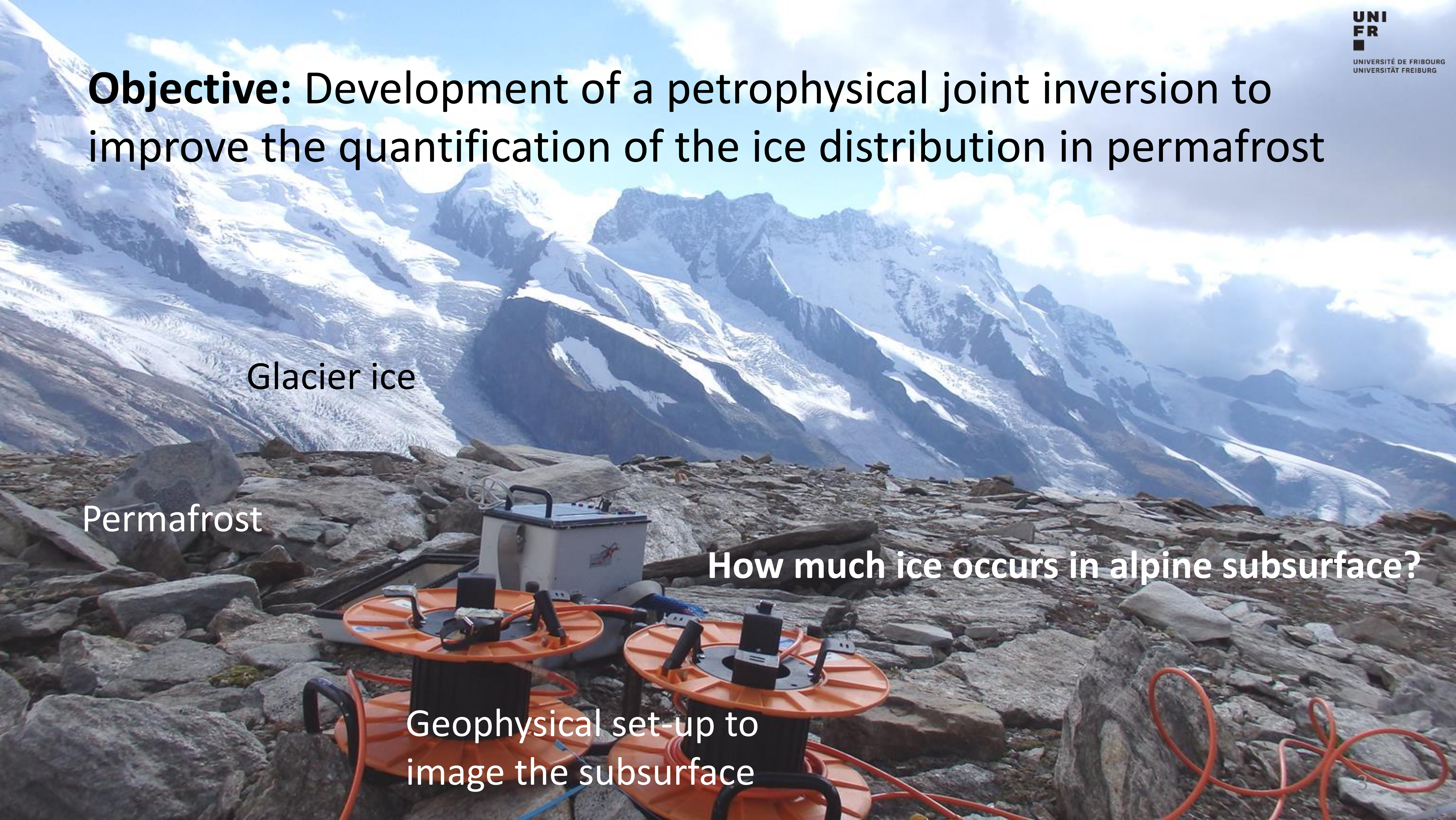
... and at a local scale (e.g. Switzerland)



Permos (2020) permos.ch

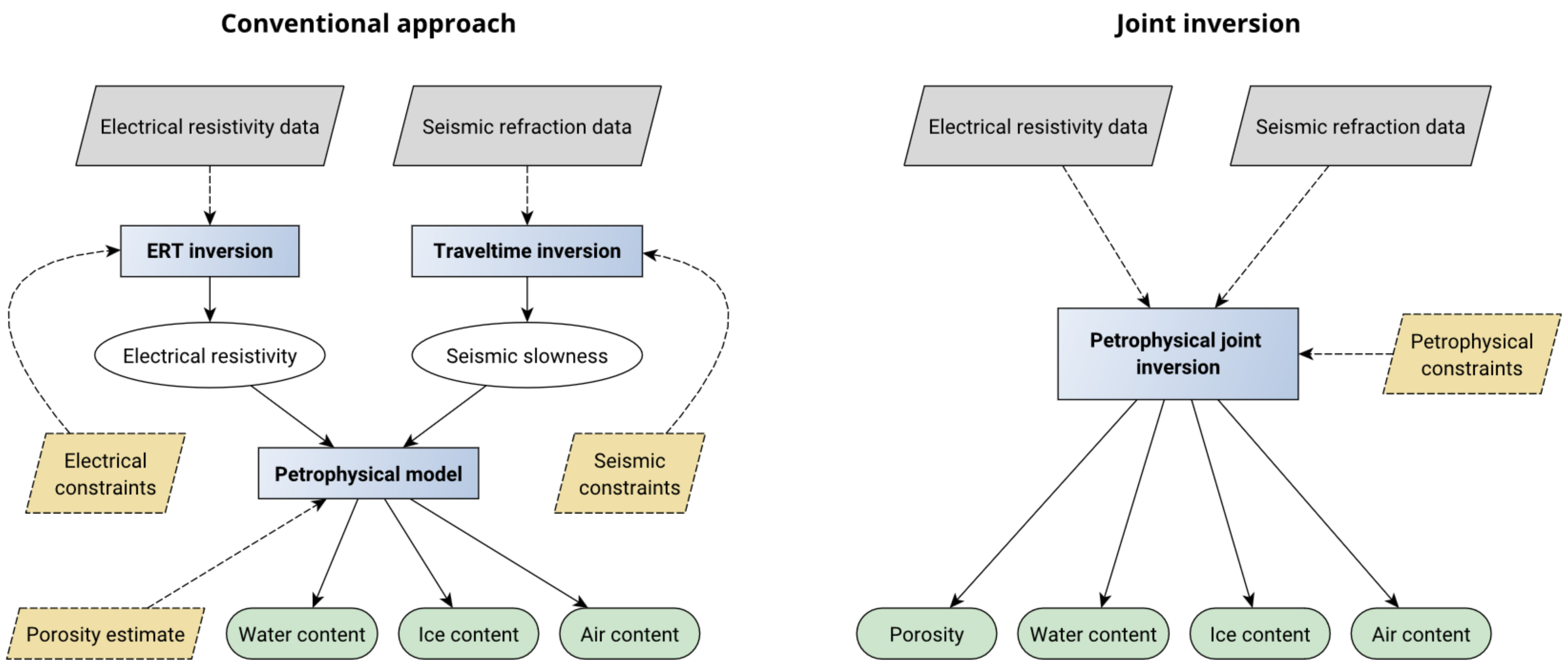
But, temperatures are unable to provide any **ice content quantification**.
The ice content, however, plays a major role in the ground stability and ongoing thaw processes.
Geophysical methods have been extensively used to qualitatively characterize the permafrost occurrence and the ice content.

Objective: Development of a petrophysical joint inversion to improve the quantification of the ice distribution in permafrost



Method: Petrophysical joint inversion (PJI)

- Based on petrophysical relationships (inspired by the four-phase model (4PM), Hauck et al. 2011)
- Uses the complementarity of the seismic and electric data
- Constrains the volume conservation during parameter estimation
- Allows incorporation of petrophysical constraints / non-geophysical data



Wagner at al. (2019)

- The PJI code implementation is mainly written in python and uses the library pyGIMLi
- Open-source and available on github

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Petrophysical relationships

r, w, i, a	Rock, water, ice, air
$f_{\mathrm{r,w,i,a}}$	Volumetric fraction
$v_{\mathrm{r,w,i,a}}$	Velocity
$\rho_{\mathrm{r,w,i,a}}$	Resistivity
m, n	Archie's parameters
ε	Surface conduction factor
ρ_{g}	Grain density
B	Apparent mobility of the counterions for surf. conduction
CEC	Cation exchange capacity

$$f_{\mathrm{r}} + f_{\mathrm{w}} + f_{\mathrm{i}} + f_{\mathrm{a}} = 1$$

Volume conservation

$$\frac{1}{v} = \frac{f_{\mathrm{r}}}{v_{\mathrm{r}}} + \frac{f_{\mathrm{w}}}{v_{\mathrm{w}}} + \frac{f_{\mathrm{i}}}{v_{\mathrm{i}}} + \frac{f_{\mathrm{a}}}{v_{\mathrm{a}}}$$

Time average equation (Timur, 1968)

Four different resistivity model were implemented and compared:

$$\rho = \rho_{\mathrm{w}} \, (1 - f_{\mathrm{r}})^{-m} \left(\frac{f_{\mathrm{w}}}{1 - f_{\mathrm{r}}} \right)^{-n}$$

Archie's second law (Archie, 1942)

$$\rho = \frac{\rho_{\mathrm{w}}}{1 + \varepsilon \, \rho_{\mathrm{w}}} (1 - f_{\mathrm{r}})^{-m} \left(\frac{f_{\mathrm{w}}}{1 - f_{\mathrm{r}}} \right)^{-n}$$

Archie's law with surface conduction factor (Sen et al. 1988)

$$\rho = \frac{1}{b \, f_{\mathrm{w}}} \quad \text{with} \quad b = \rho_{\mathrm{g}} \, B \, CEC$$

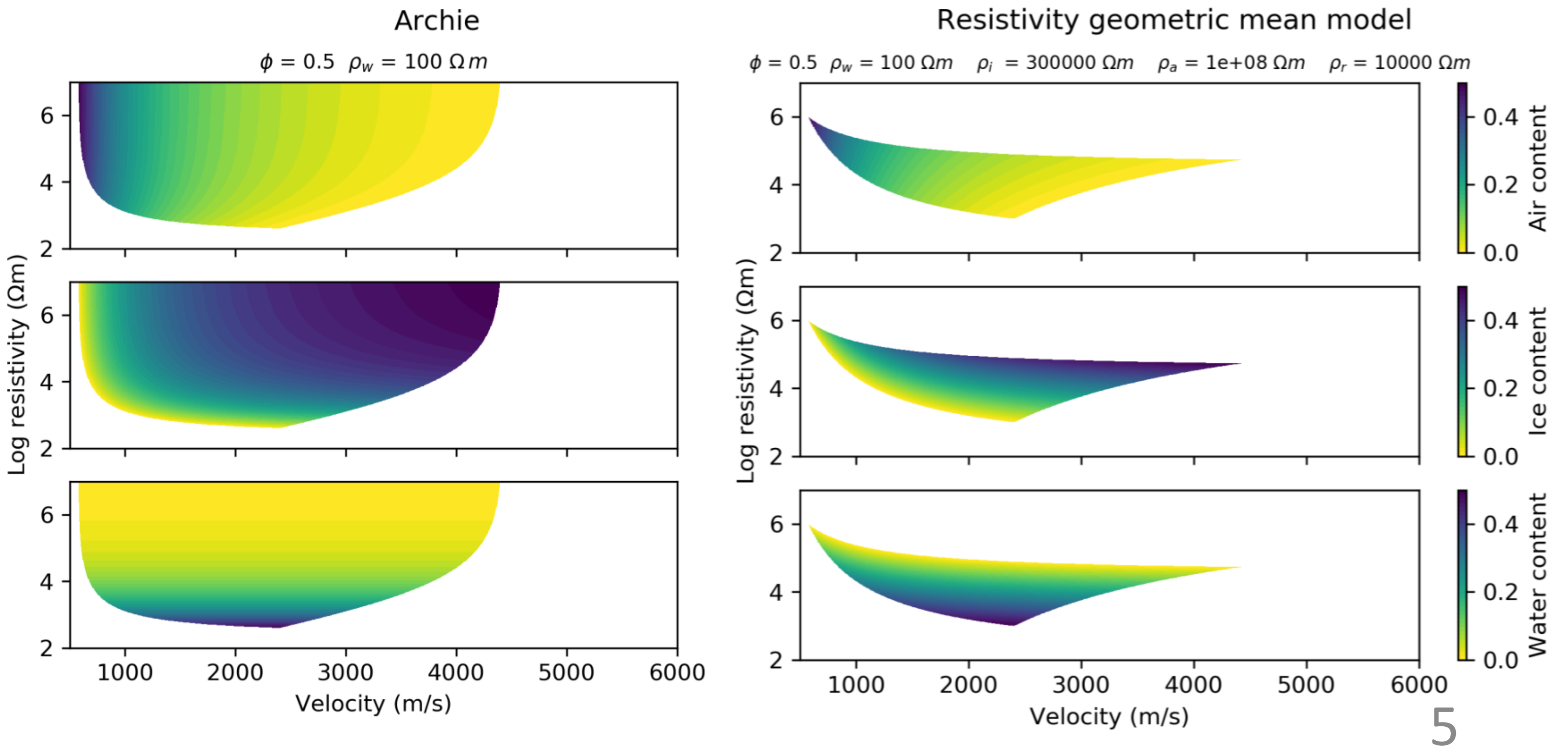
Surface conduction (Duvillard et al. 2018)

Similar solution space as Archie's case

$$\rho = \rho_{\mathrm{r}}^{f_{\mathrm{r}}} \cdot \rho_{\mathrm{i}}^{f_{\mathrm{i}}} \cdot \rho_{\mathrm{w}}^{f_{\mathrm{w}}} \cdot \rho_{\mathrm{a}}^{f_{\mathrm{a}}}$$

Geometric mean model (Glover , 2010)

Analytic solution space



The geometric mean model exerts a stronger constraint on the four phases than the other models (narrower solution space).

Application to field data

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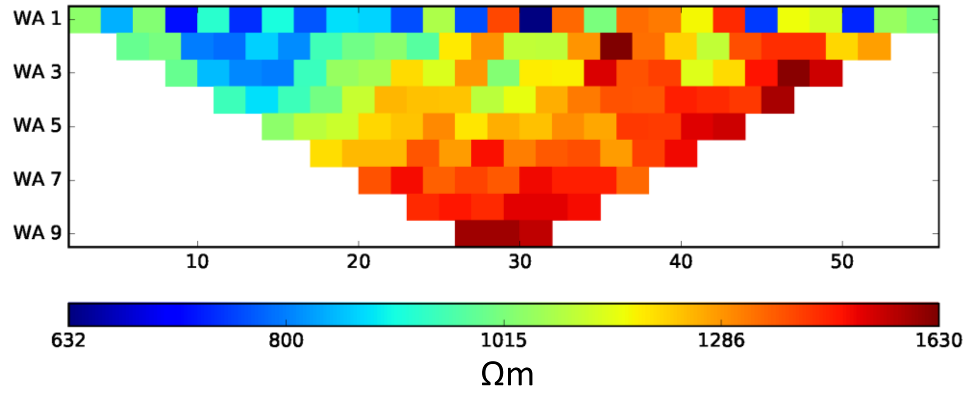
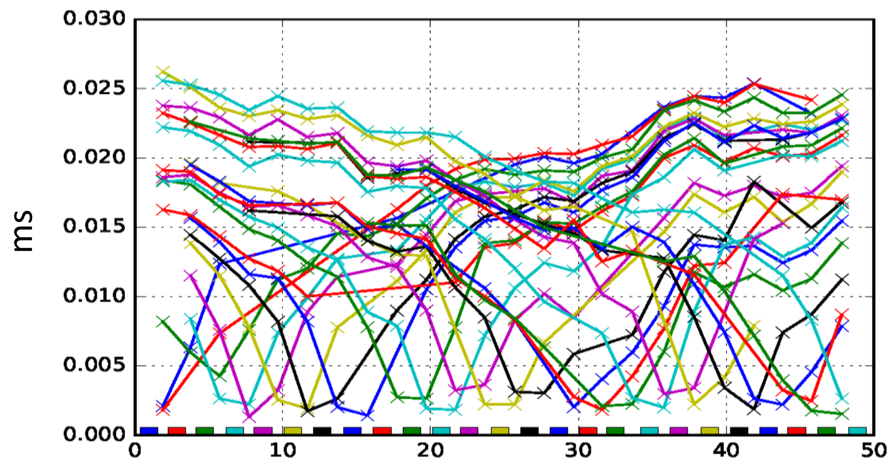
Apparent resistivity data



Seismic travel time data



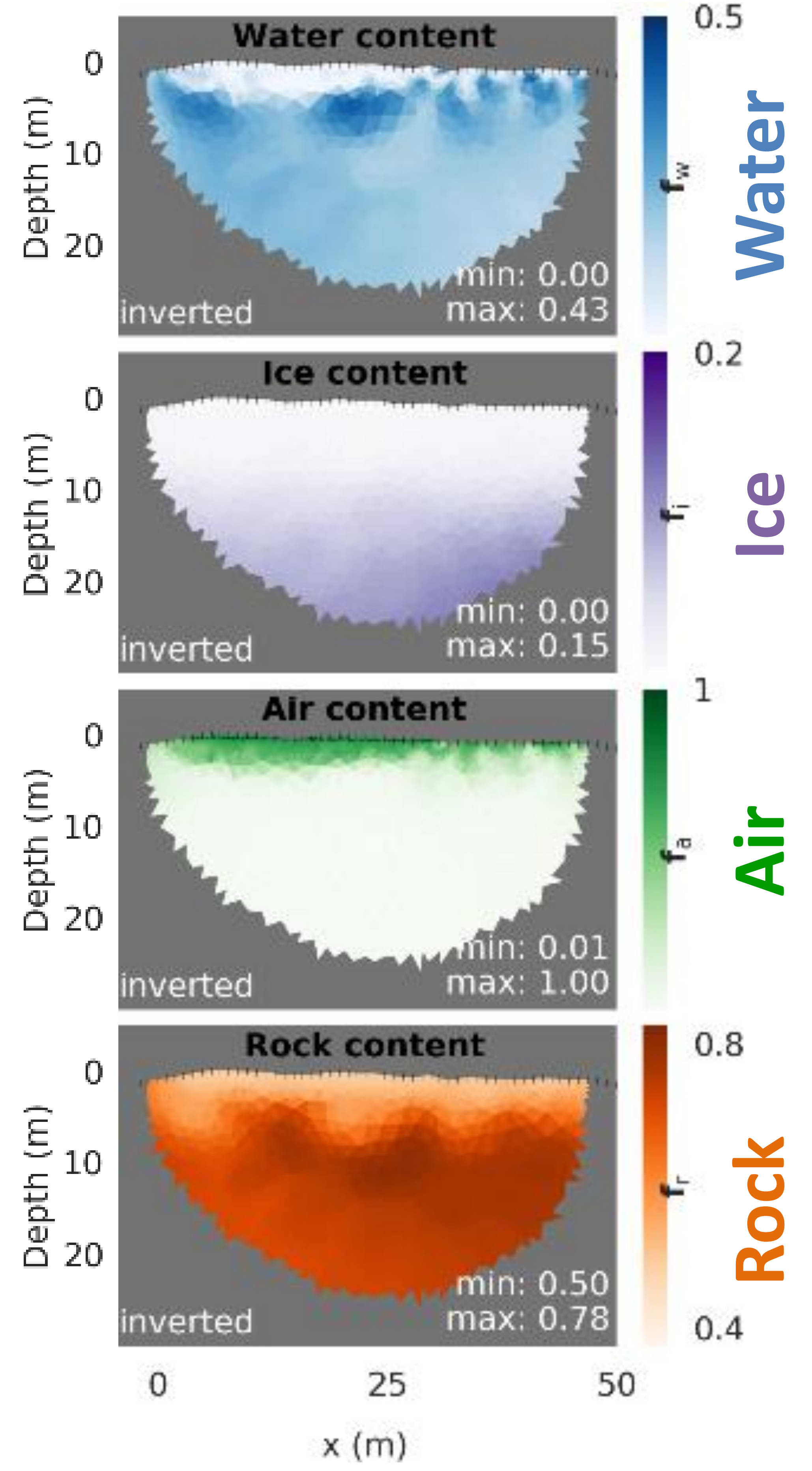
Petrophysical equations

$$f_\mathrm{r} + f_\mathrm{w} + f_\mathrm{i} + f_\mathrm{a} = 1$$

$$\frac{1}{v} = \frac{f_\mathrm{r}}{v_\mathrm{r}} + \frac{f_\mathrm{w}}{v_\mathrm{w}} + \frac{f_\mathrm{i}}{v_\mathrm{i}} + \frac{f_\mathrm{a}}{v_\mathrm{a}}$$

$$\rho = \rho_\mathrm{r}^{f_\mathrm{r}} \cdot \rho_\mathrm{i}^{f_\mathrm{i}} \cdot \rho_\mathrm{w}^{f_\mathrm{w}} \cdot \rho_\mathrm{a}^{f_\mathrm{a}}$$

Petrophysical Joint Inversion



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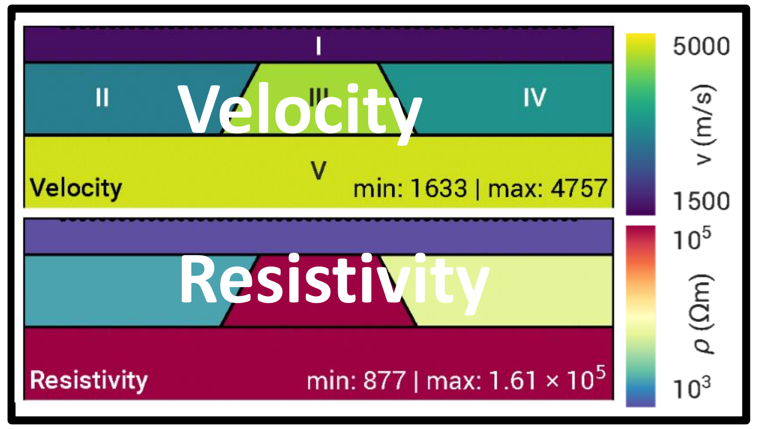
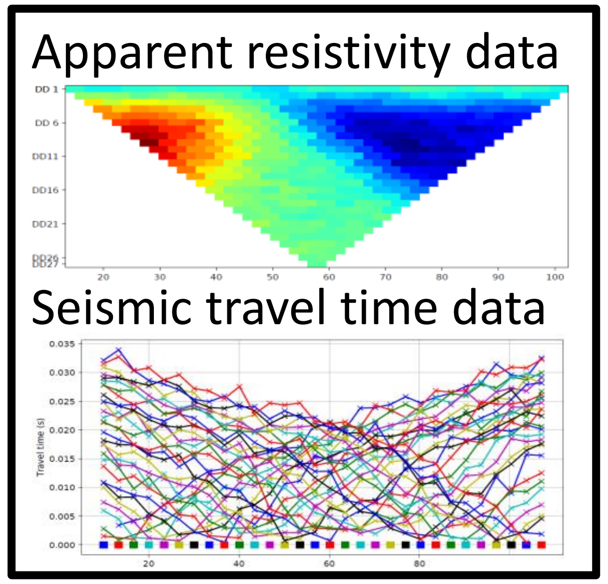
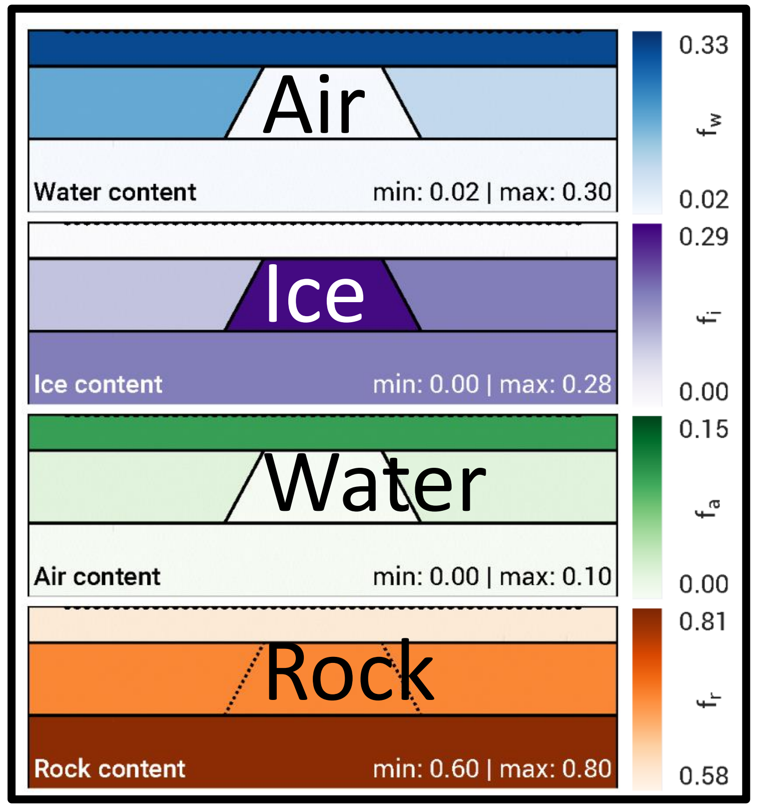
Validation with synthetic data

This slide present the step-by-step process to validate the joint inversion approach to determine the spatial distribution of the air, ice, water, and rock in the subsurface.

②


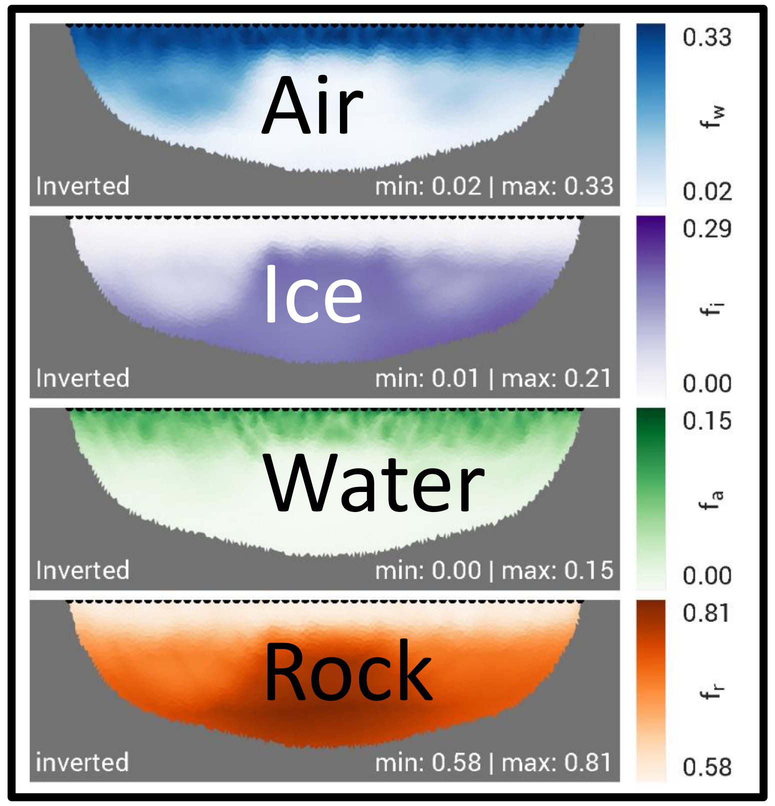
③


① **True synthetic model**



⑤ comparison

④ **Estimated parameters by the joint inversion**



These tomograms represent 2D images of the subsurface

- Calculation through the **4PM** (Hauck et al., 2011)
- Numerical **simulation**
- Petrophysical **joint inversion**

Modified after Wagner at al. (2019)
Implementation with pyGIMLi (Rücker et al. 2017)

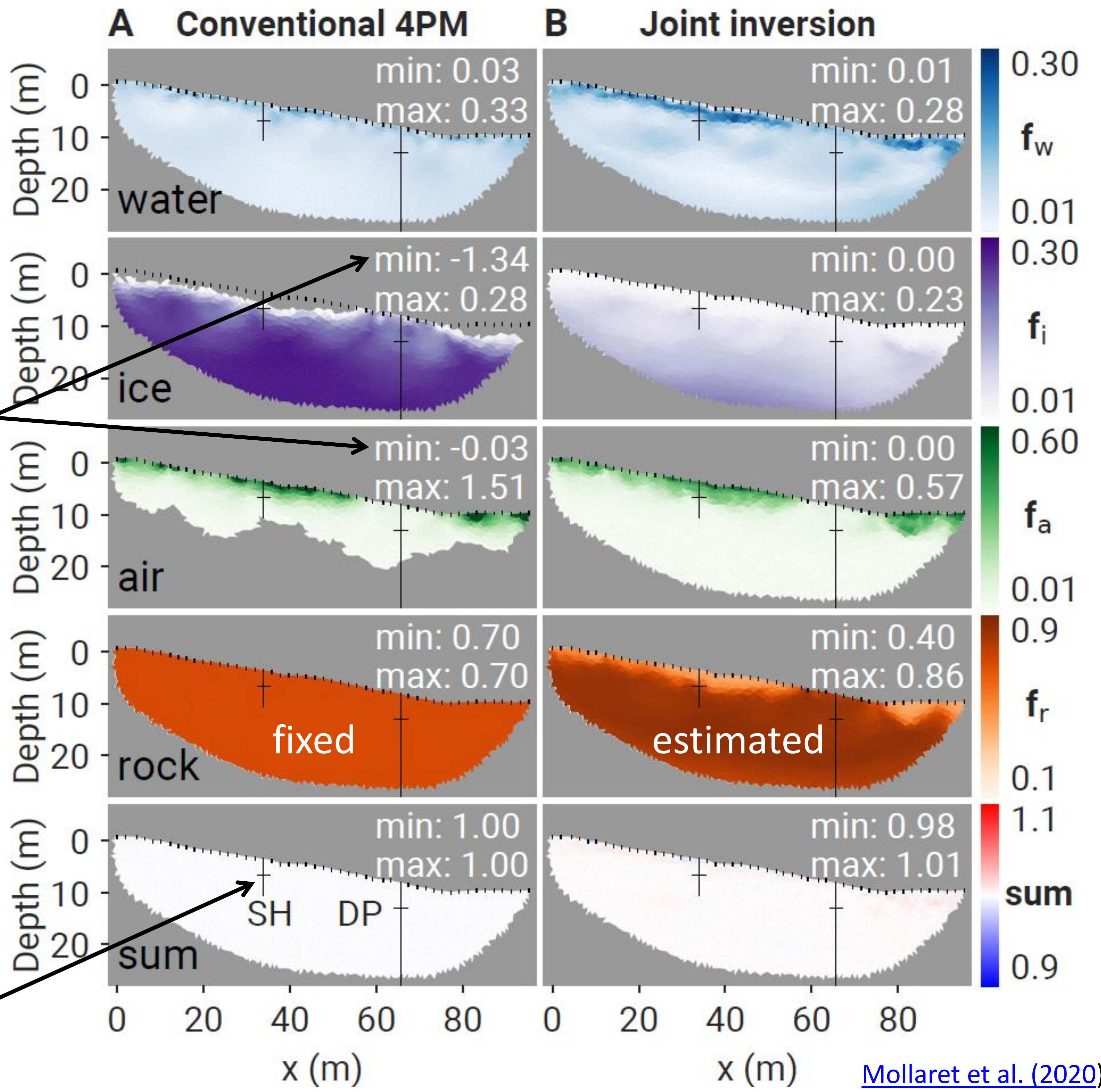
Comparison of the conventional 4PM and the petrophysical joint inversion at Cervinia

In the conventional four-phase model (4PM), one of the phase has to be fixed (a set of 3 equations is solved to find 3 unknows). The porosity is prescribed to 0.3.

Each phase are not constrained individually and may lead to non-physical results (e.g. $f_i < 0$)

The sum of fractions is exactly 1.

Borehole and thaw depth



Mollaret et al. (2020)

In the petrophysical joint inversion (PJI), the four phases are estimated.

The content of each phase is physically-possible ($0 < f_{w,i,a,r} < 1$)

The differences in porosity directly lead to large differences in ice content.

The spatial variation in the rock content is highlighted by the joint inversion.

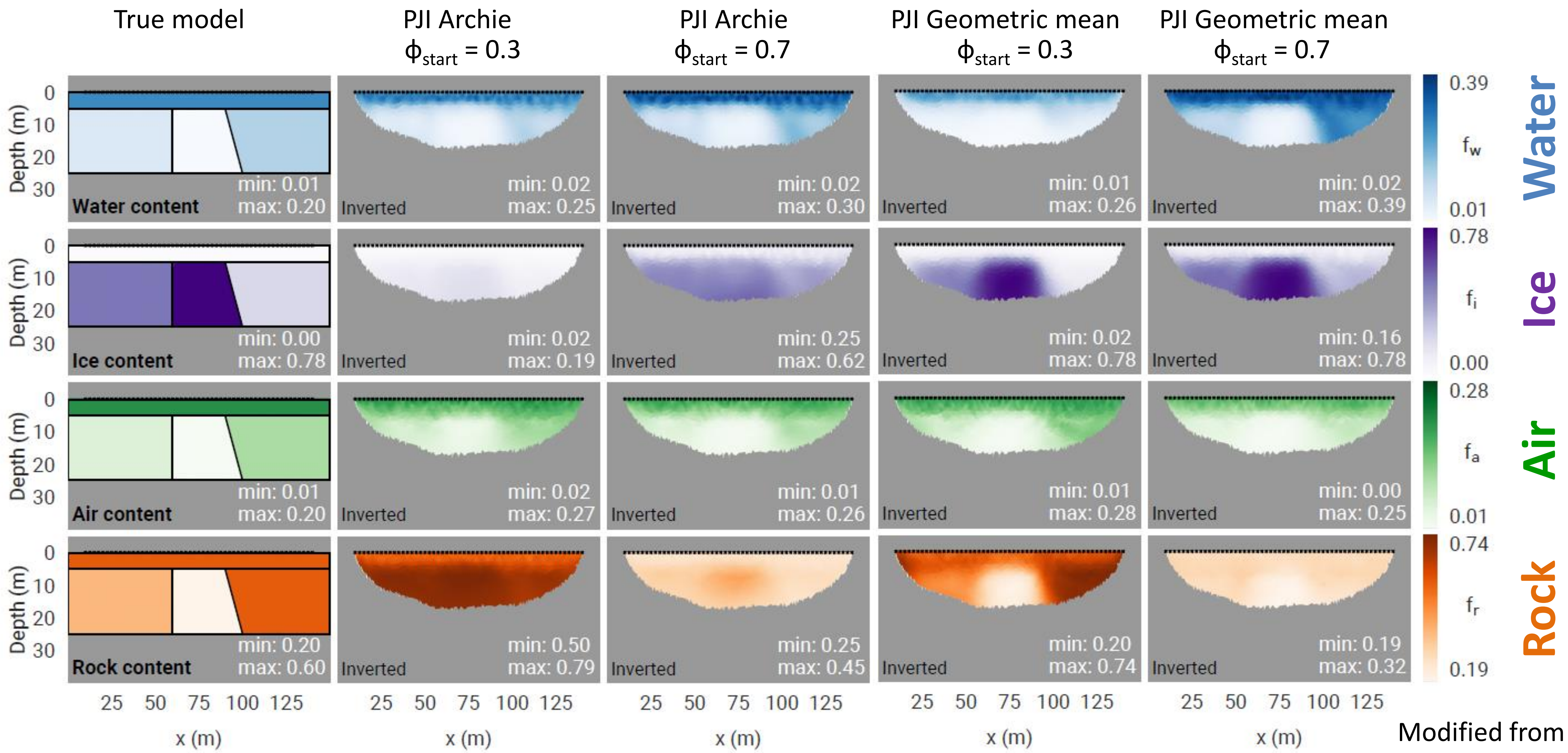
The sum of fractions is approximately 1 (and depends on the volume conservation regularisation parameter).

Synthetic models analysis

We compare here the petrophysical joint inversion results using Archie's law and the geometric mean resistivity model and using a start porosity model ϕ_{start} of 0.3 and 0.7.

The geometric mean model constrains all four phases, whereas Archie's law exerts no explicit constraint on the ice and air contents (cf. the equations and the solution spaces).

The air content is well constrained, mainly through the refraction seismic data.



Modified from Mollaret (2020)

In this synthetic example, the use of the geometric mean results in a much more realistic ice distribution.

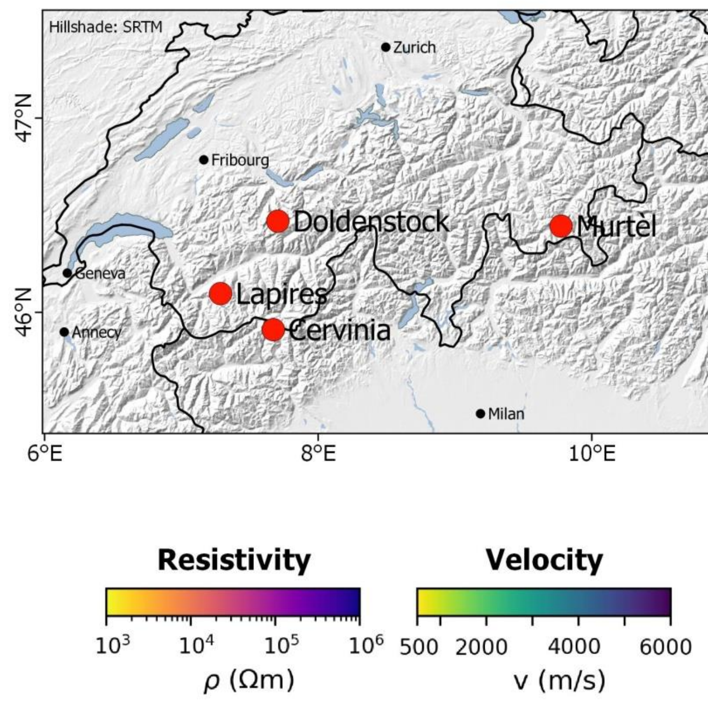
Archie's law leads to a rock-ice ambiguity, whereas the geometric mean model leads to a rock-water ambiguity (this also depends on the petrophysical parameters such as the pore water resistivity).

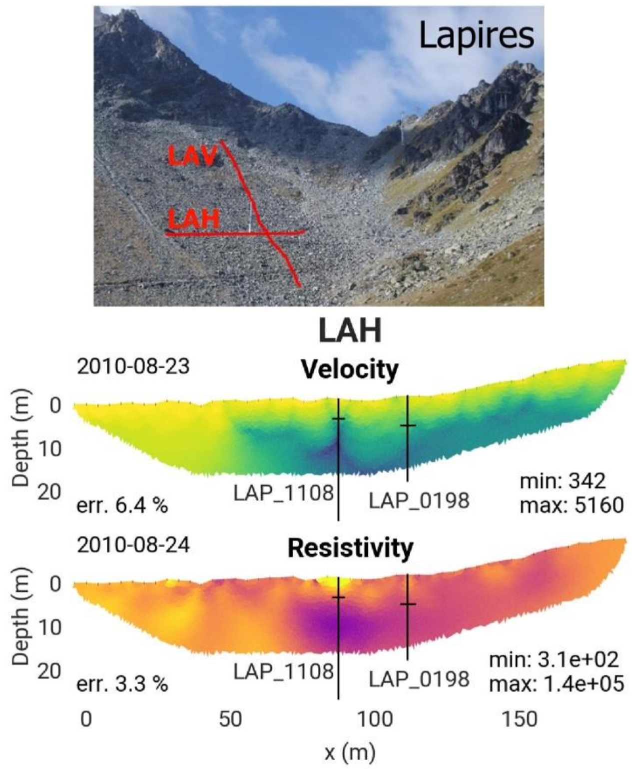
→ Additional data and/or laboratory measurements are needed.

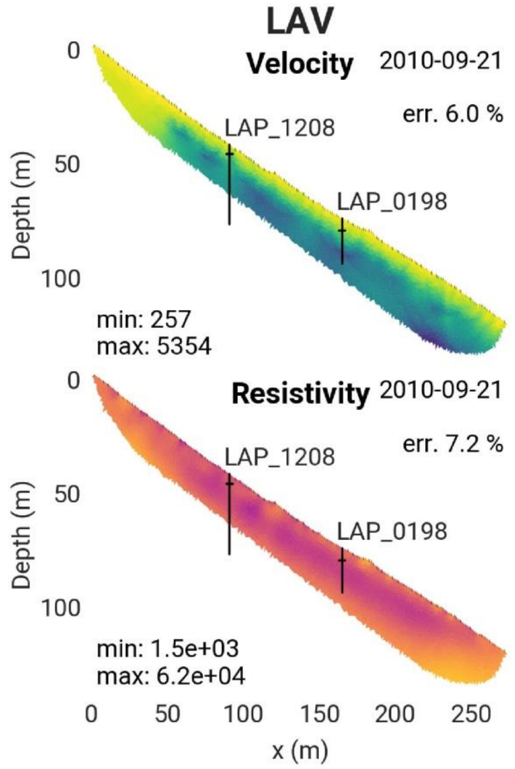
Sites of investigation

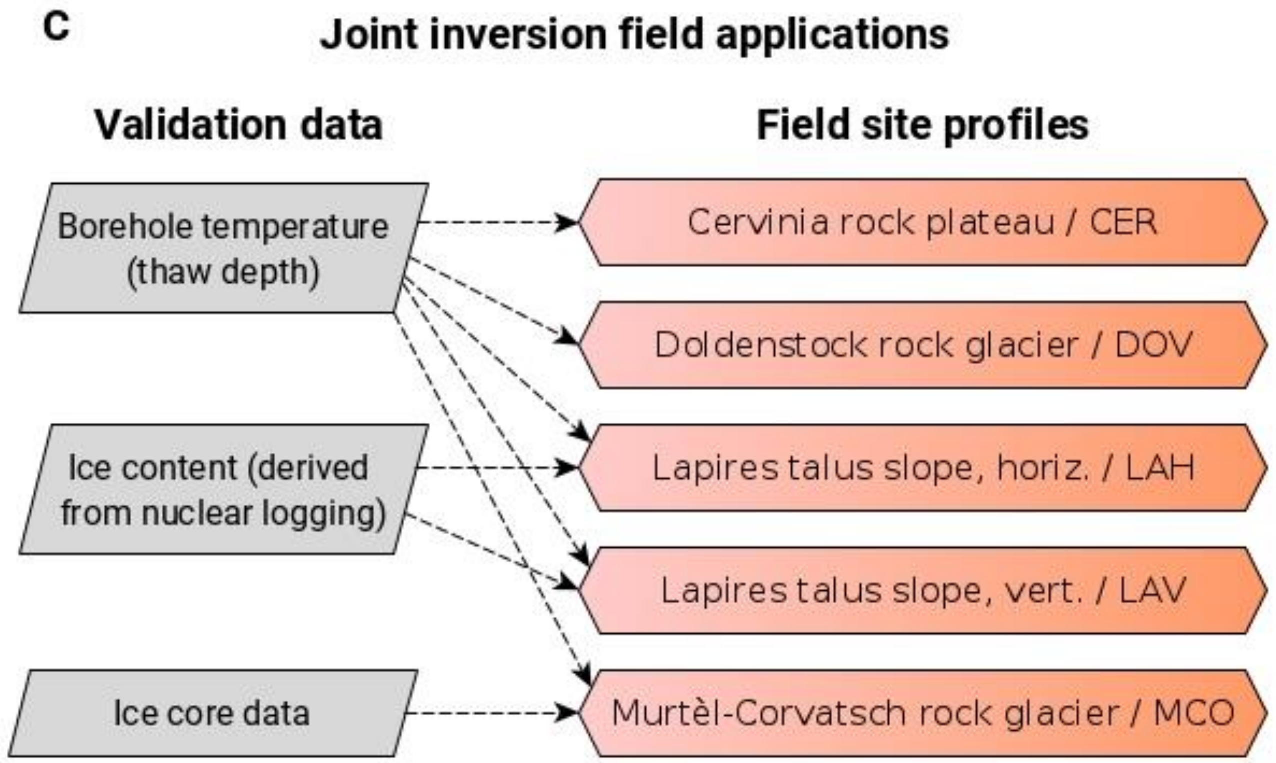
This slide presents the location of the alpine field sites, as well as exemplary refraction seismic and electrical resistivity tomograms.

The available validation data is shown below and further described in Mollaret et al. (2020).

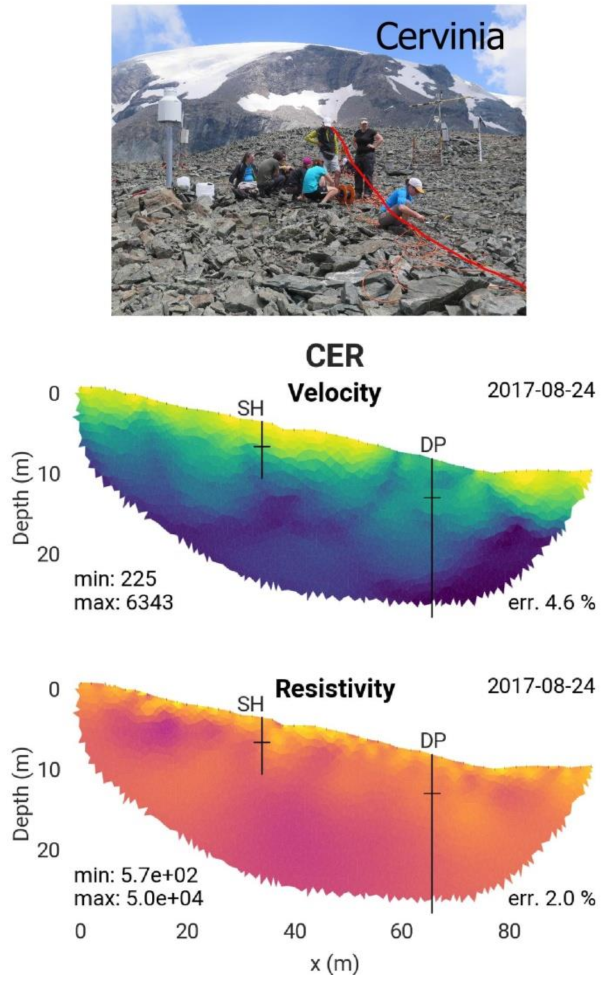


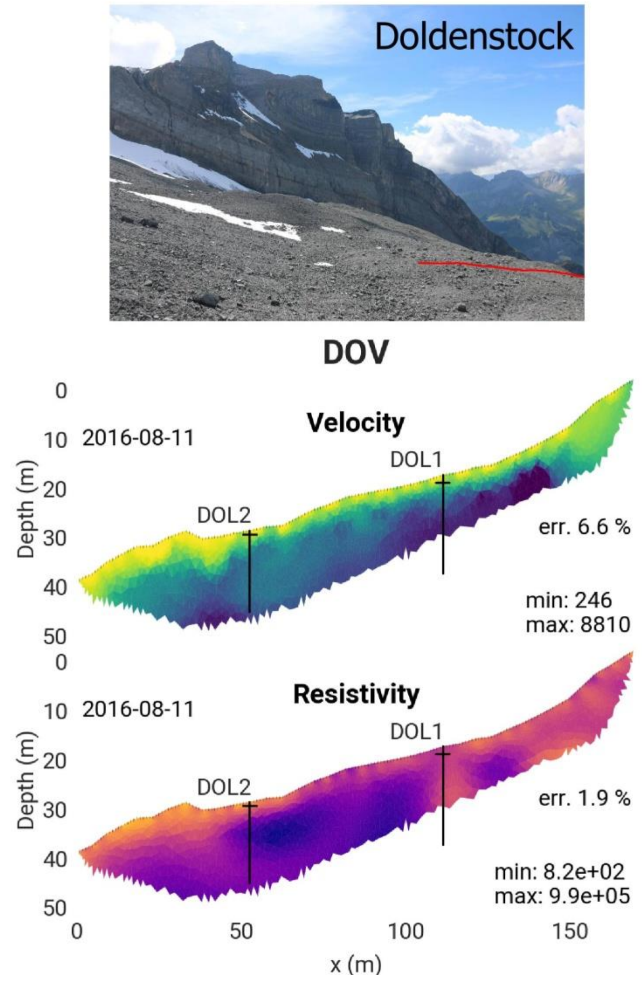


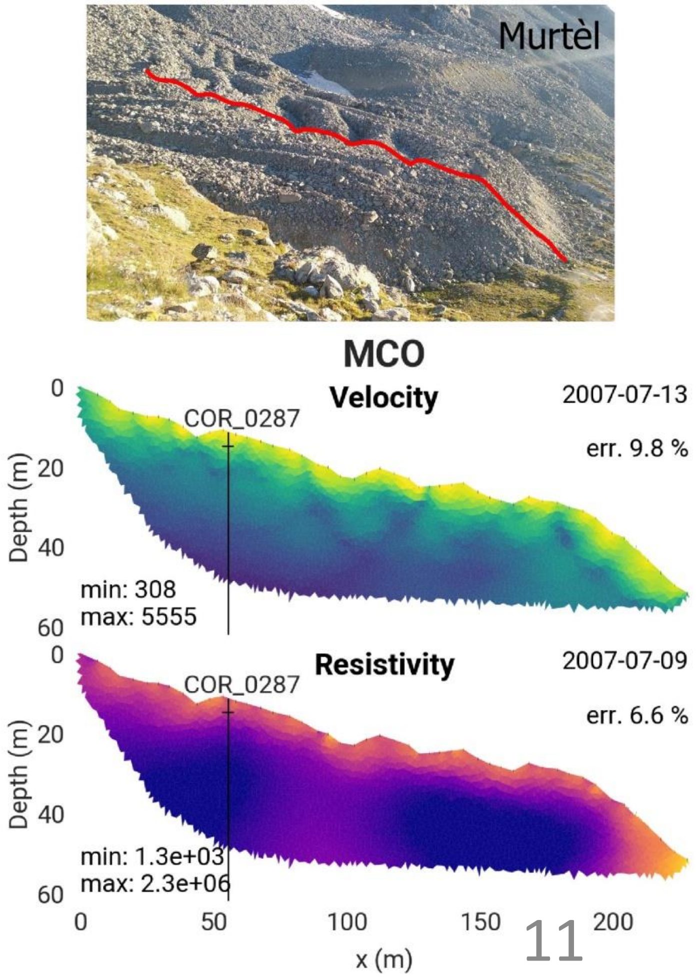




Mollaret et al. (2020)

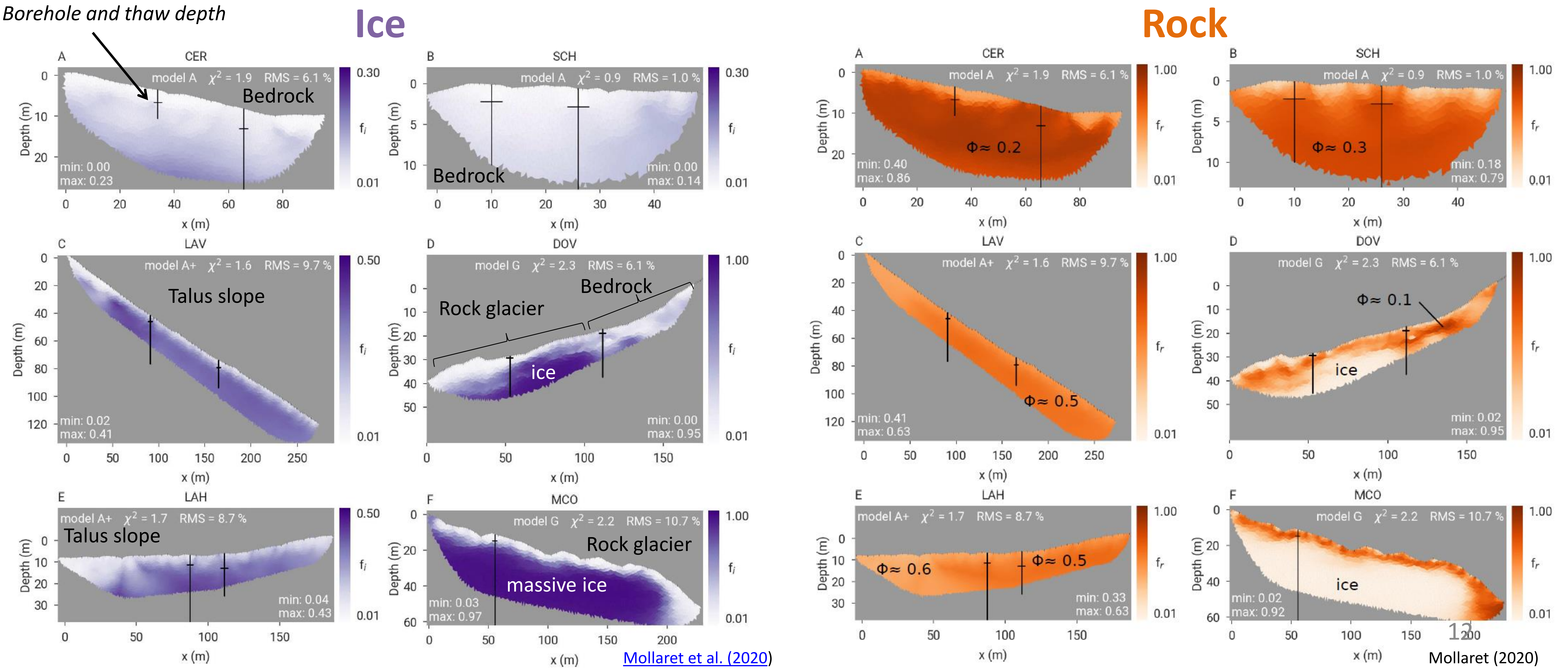






Ice and rock distribution estimated by the joint inversion

Best-guess estimation of ice and rock contents resulting from a regularisation parameter analysis and from the choice of the resistivity model matching the best the ground truth data.



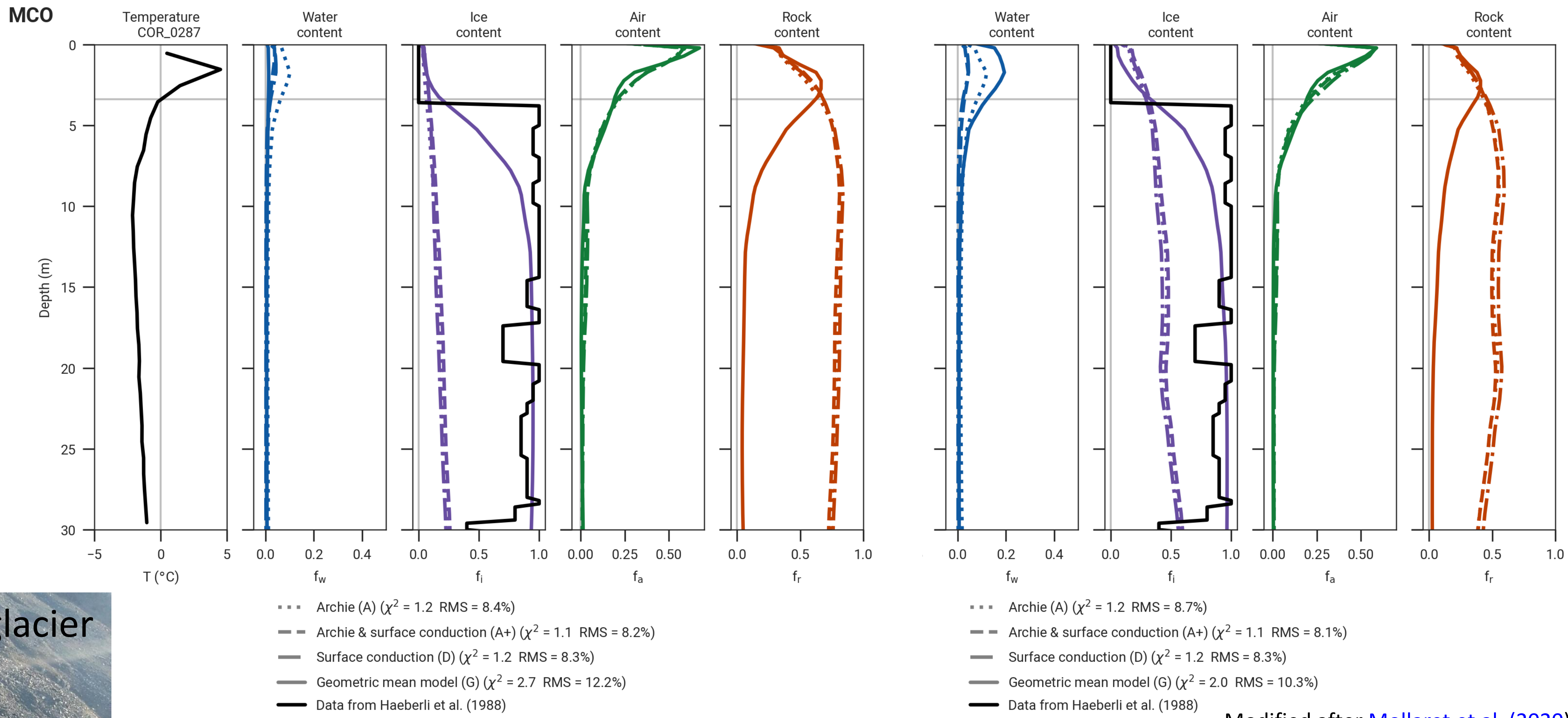
Mollaret et al. (2020)

Mollaret (2020)

Comparisaon to borehole data

We present the borehole temperature at Murtèl rock glacier and the associated four phase distribution estimated through the joint inversion for 2 values of initial porosity model.

Initial porosity model = 0.3 Initial porosity model = 0.7



Modified after Mollaret et al. (2020)

→ The use of the geometric mean model has 2 main advantages:
- Results in relative good agreement to the ice content validation data (in black)
- Low influence from the prescribed initial porosity model (on the contrary to all other resistivity models tested).

Conclusions

- The presented petrophysical joint inversion approach is **able to quantitatively estimate the composition of permafrost subsurface (including the ice content distribution)**.

- The presented petrophysical joint inversion approach is **applicable to various landforms** with ice content varying from near zero volumetric content to massive ice.

- The regularisation and petrophysical parameters strongly influences the results. Their determination has to be careful.

- The influence of the porosity initial model is significantly lower when using the geometric mean model (in comparison to the use of Archie's law or of the models taking into account the surface conduction, where no constraint is exerted on the ice and air contents).

- The resolution of the volumetric estimation directly depends on the geophysical methods resolution. Small-scale features (such as ice lenses) can, therefore, not be determined by the joint inversion method.

- The **joint inversion approach has increased the reliability of ice, water, and rock fraction estimations**, even though inherent uncertainties remain due to data errors, simplified petrophysical models and inversion imperfections.

Outlook

- A **time-lapse scheme** is currently implemented within a Master thesis (J. Klahold, RWTH Aachen University) and has the capacity to further reduce the uncertainties in the four phase estimation by adding an **additional time constraint**.

- **Additional geophysical data** such as available SIP (Spectral Induced Polarization) or SP (Self Potential) may be implemented to contribute to constrain the results.

- Further work on the petrophysical relations, petrophysical parameters , and their temperature dependency including site-specific calibration may further reduce the uncertainties.

Thank you for reading! We are looking forward to your comments.

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