Seasonal and annual dynamics of frozen ground at a mountain permafrost site in the Italian Alps detected by spectral induced polarization

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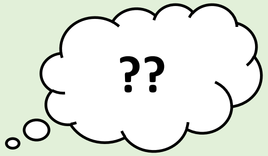
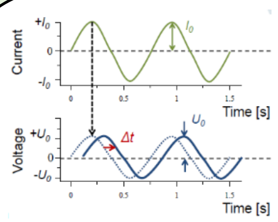
Content

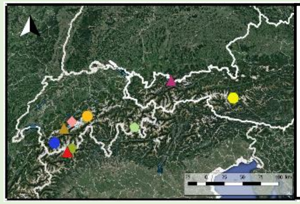
Objective





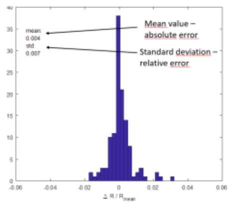
SIP

Mountain permafrost

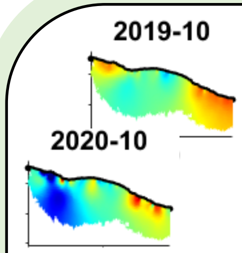


Site details & validation data

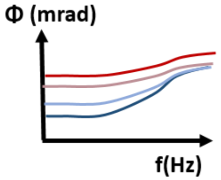
SIP measurement setup



Data processing



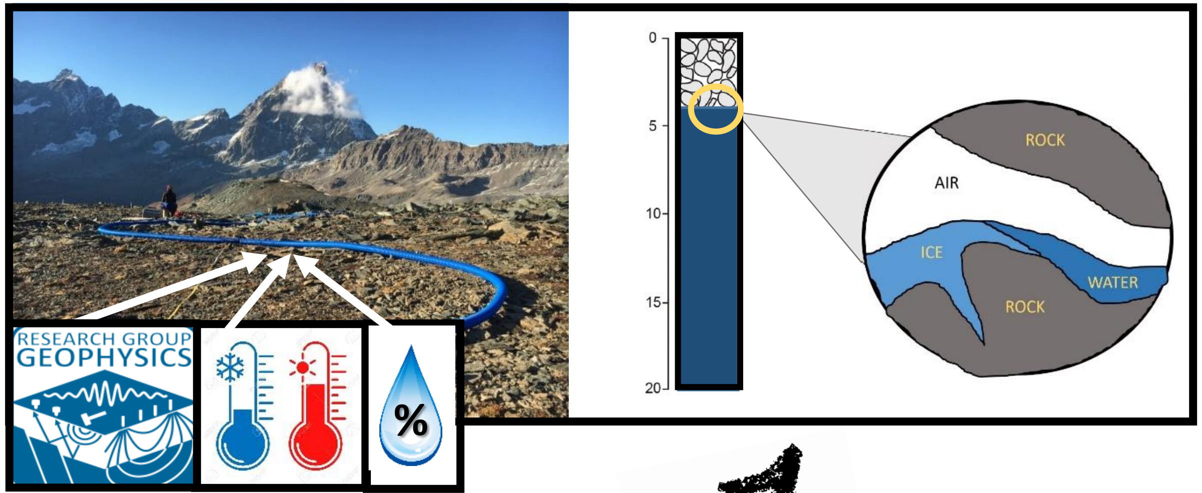
SIP field results for different times



Comparison field and laboratory data

Conclusion and Outlook

Objective


RESEARCH GROUP
GEOPHYSICS
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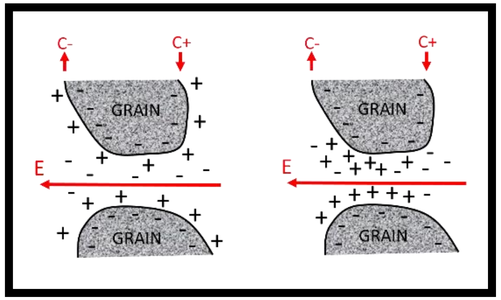
ROCK
AIR
ICE
WATER
ROCK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C+
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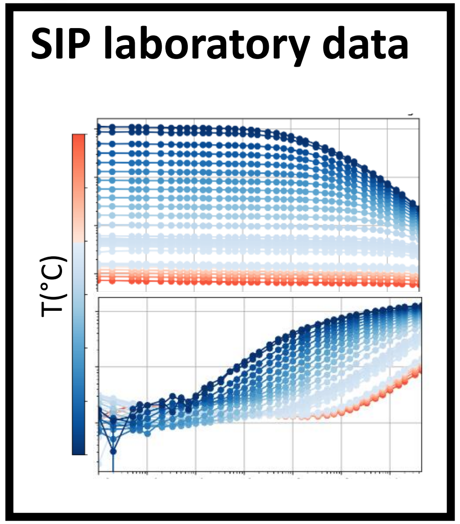
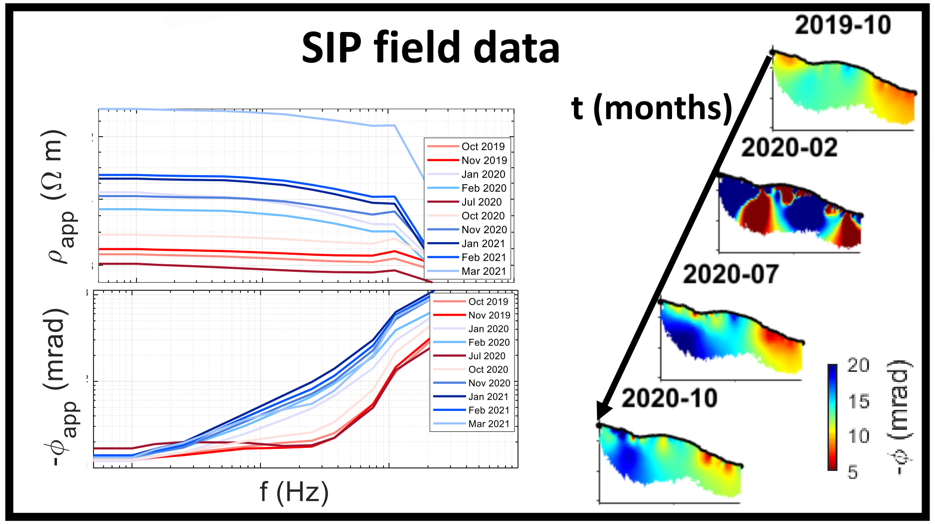
Flores Orozco et al., 2021


SIP laboratory data
T(°C)


SIP field data
ρ_{app} (Ω m)
$-\phi_{app}$ (mrad)
f (Hz)
Oct 2019
Nov 2019
Jan 2020
Feb 2020
Jul 2020
Oct 2020
Nov 2020
Jan 2021
Feb 2021
Mar 2021
t (months)
2019-10
2020-02
2020-07
2020-10
20
15
10
5
$-\phi$ (mrad)

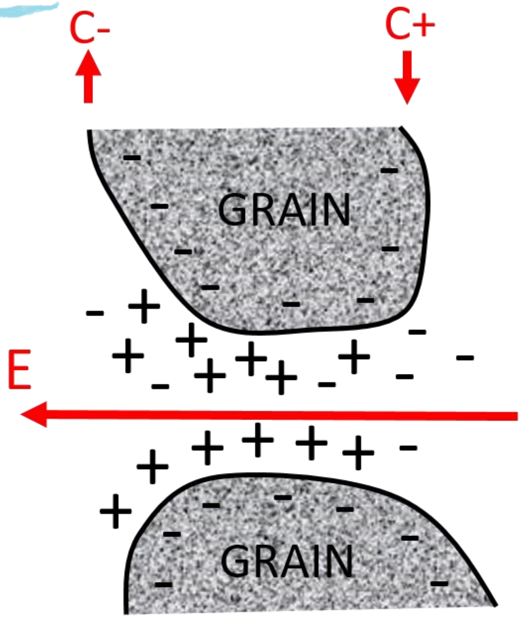
Objective

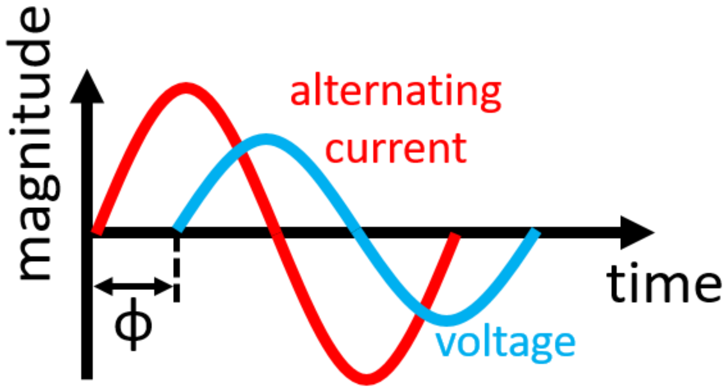
- Climate change – permafrost degradation → monitoring of the ice content has become an essential task also in the European Alps
  - Borehole temperatures (only point information)
  - Geophysical measurements: Electrical Resistivity Tomography (ERT), Refraction Seismic Tomography (RST) – standard measurement techniques in permafrost

- Additional information is needed → a few recent studies address the polarization response of soils and rocks under freezing conditions (Grimm and Stillman, 2015; Doetsch et al., 2015; Wu et al., 2017; Duvillard et al., 2018, Duvillard et al., 2020), Coperey et al., 2019 extended the Stern layer model for freezing conditions and Auty and Cole, 1952 found that ice exhibits a relaxation behaviour at higher frequencies (1 kHz – 45 kHz)

- Aim of our study:
  - To investigate the in situ frequency dependence of the induced polarization response for a representative permafrost site in the Italian Alps
  - To gain information about the seasonal and annual changes of the frequency dependence of the complex resistivity covering a 1.5-year monitoring period
  - To validate field data with borehole information and SIP laboratory analysis on rock samples

Spectral Induced Polarization





Induced Polarization

In Frequency Domain:

- An alternating current is injected at low frequencies (commonly below 1 kHz)

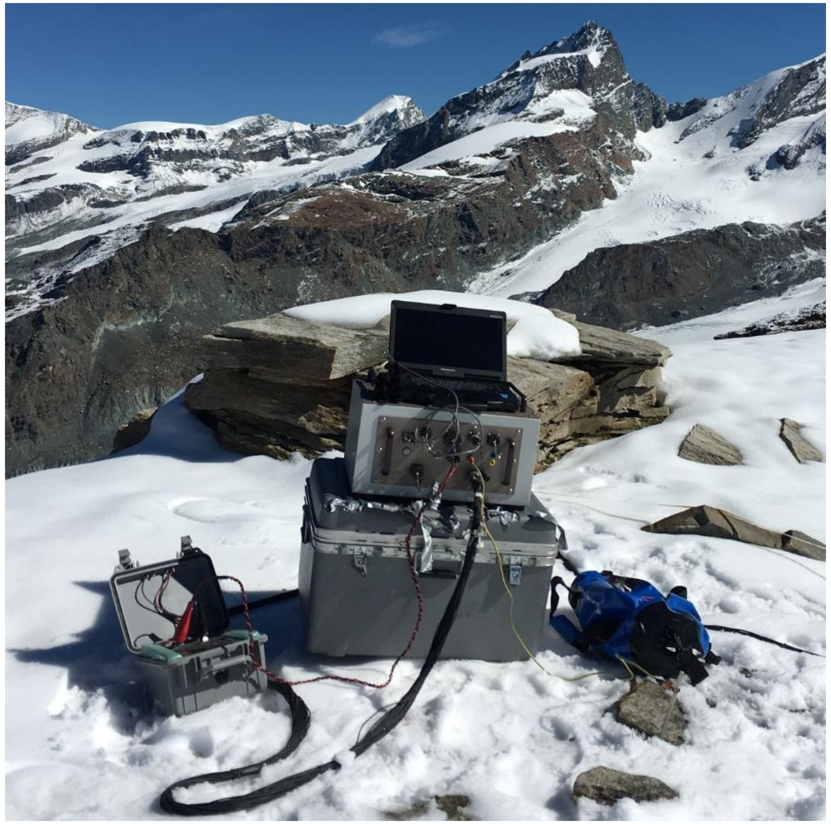
- **DATA:** In subsurface materials we observe a phase-shift (ϕ) between the injected current and measured voltage

- **RESULTS:** Complex electrical resistivity/conductivity expressed in terms of the real and imaginary components or by its magnitude (ratio voltage/current) and phase (shift between voltage/current)
  - Real part: Conduction mechanisms
  - Imaginary part: Polarization processes

$$\rho^* = \rho' + i\rho'' = \log |\rho| + i\phi$$

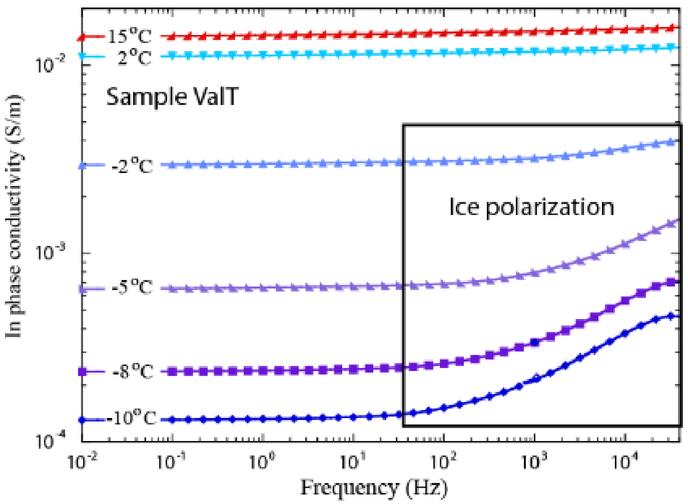
Spectral Induced Polarization

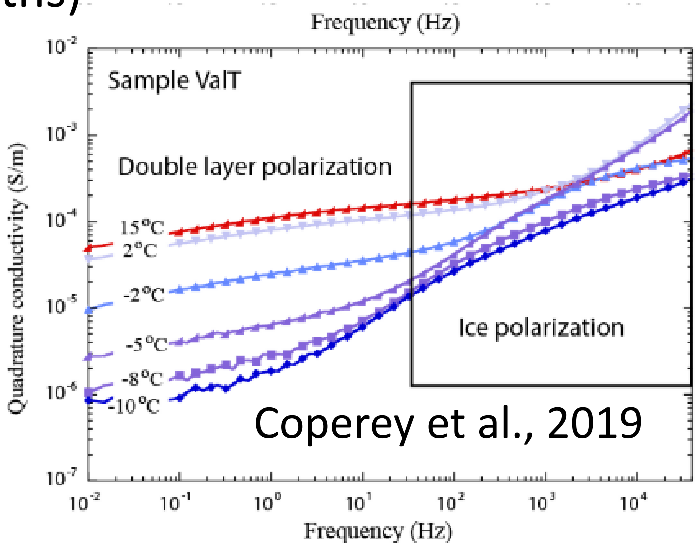
Spectral Induced Polarization



DAS-1 (TDIP and FDIP measurements at frequencies between 0.01-225 Hz)

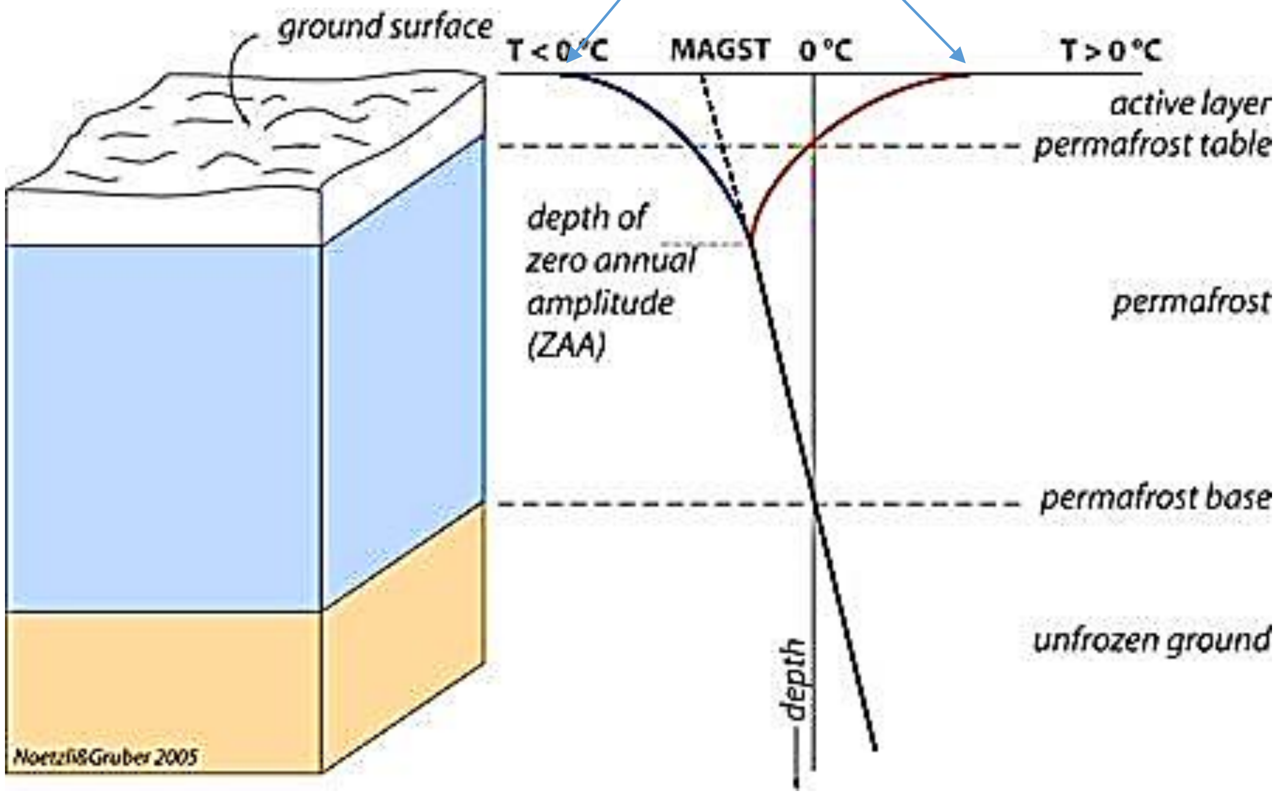
- Repetition of the measurement at different frequencies (0.01-40 000 Hz)
- To gain information about the frequency-dependence of the electrical properties (resistivity and IP)
  - Fast polarization effects – e.g., small grains – take place at high frequencies (small pulse lengths)
  - Slow polarization effects – e.g., big grains – take place at low frequencies (high pulse lengths)





Mountain permafrost - Thermal regime of permafrost

Annual maximum (summer) and minimum (winter) ground temperature during the year



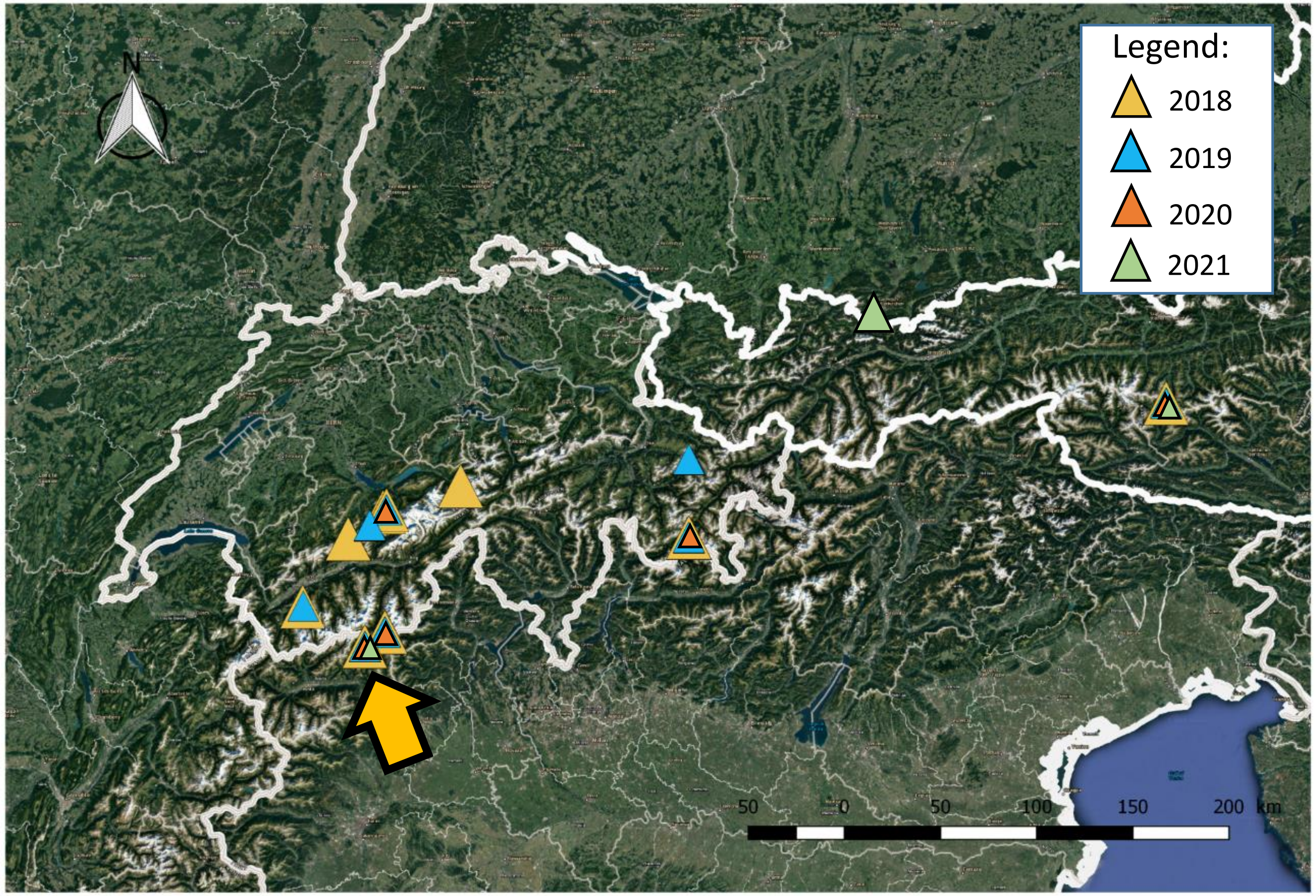
Active layer: seasonally freezing and thawing surface layer

MAGST: Mean annual ground surface temperature at the depth of zero annual amplitude

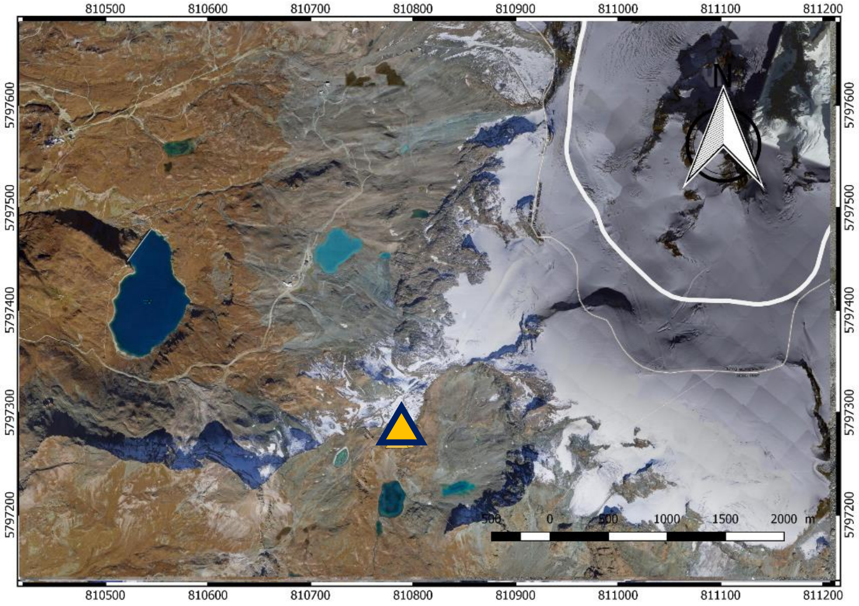
- Permafrost or permanently frozen ground defined as soil or rock that remains beneath 0°C for at least 2 years
- Mountain permafrost typically occurs in high mountain environments in various geomorphological landforms under variable geological climatic and topographic conditions

Permafrost sites

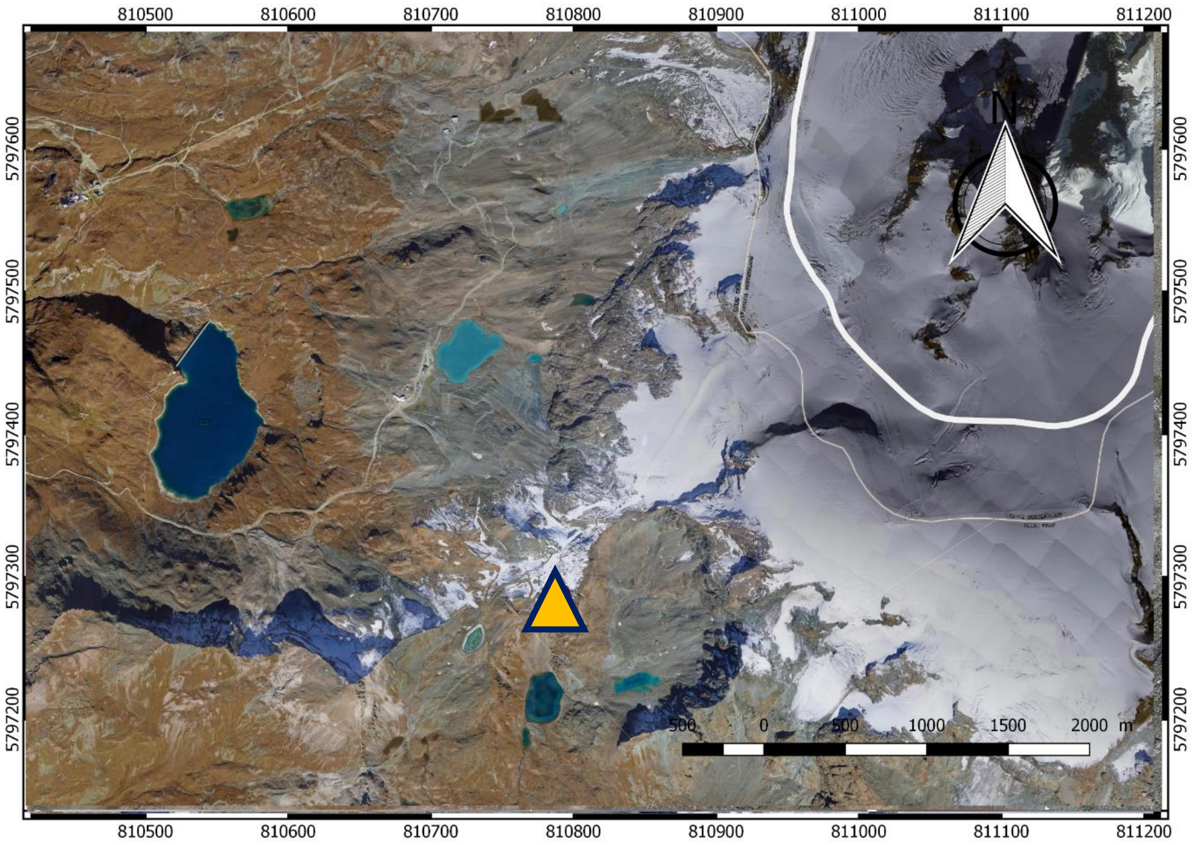
- SIP data were collected at various permafrost sites in the Swiss, Austrian, Italian and German Alps, Cervinia (Italy) – SIP monitoring site



Cervinia, Cime Bianche



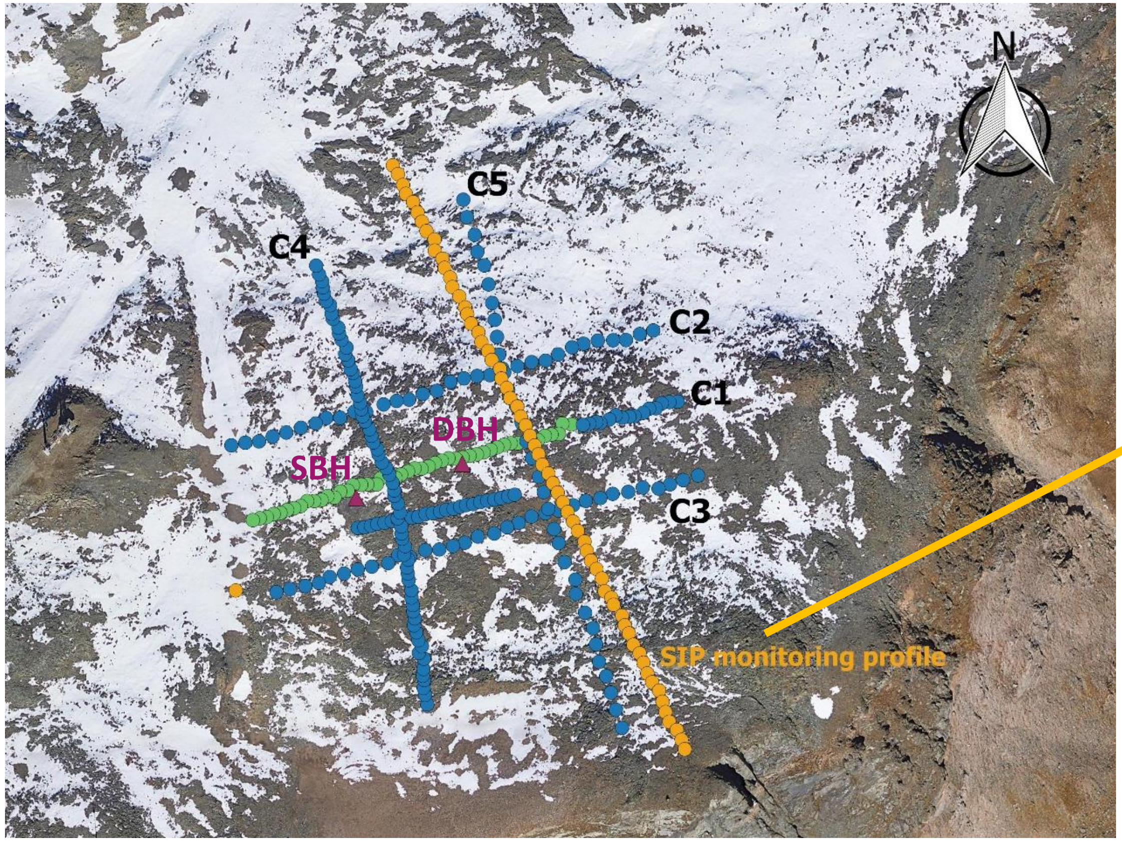
Permafrost site characteristics

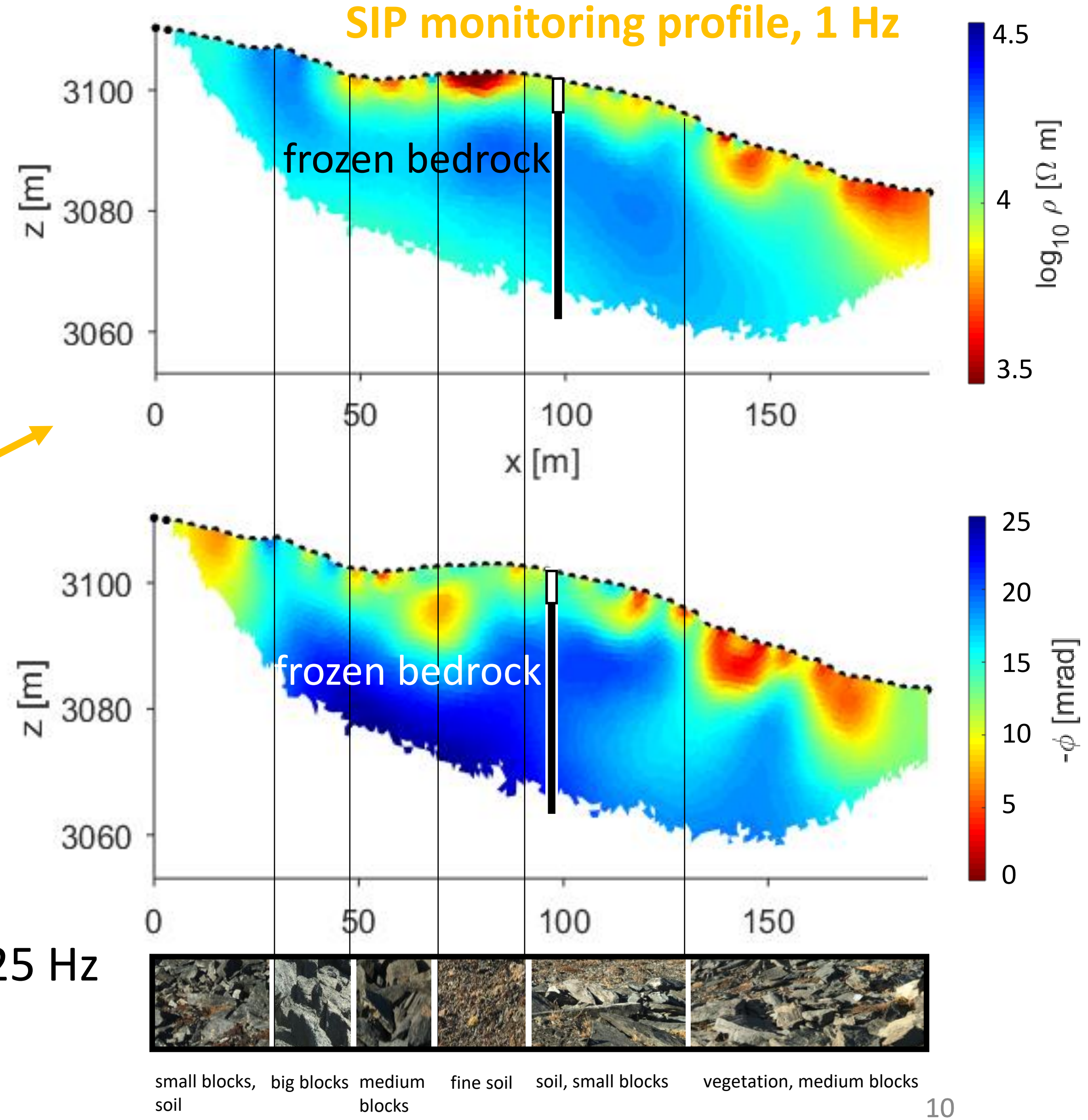


→ We chose this site as our SIP monitoring site

- Cime Bianche monitoring site
- Located in the Western Alps
- Altitude: 3100 ma.s.l.
- Homogeneous bedrock lithology (micaschists and calcschists)
- Cover of coarse-debris deposits (few centimeters to a couple of meters)
- ALT of about 5m

Measurement setup & data-error





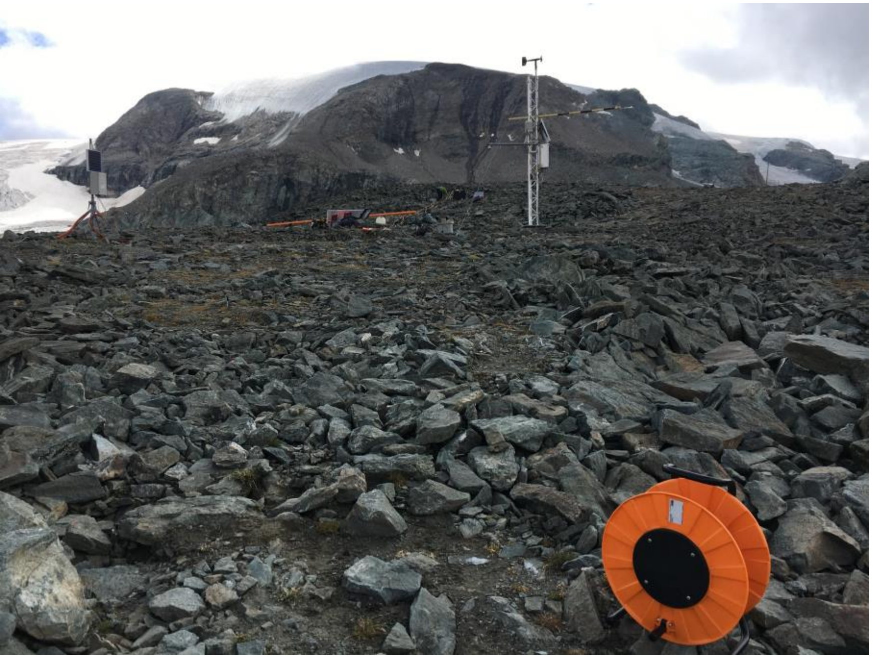
SIP monitoring setting:

- measurement device: DAS-1, frequency range: 0.1-225 Hz
- 64 electrodes, 3m spacing, coaxial cables
- Dipole Dipole (normal reciprocal), Multiple Gradient

Measurement setup & data-error

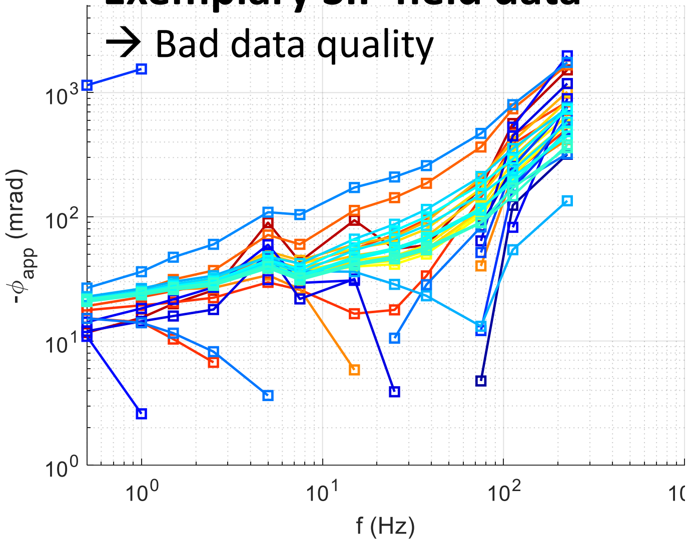
Challenges of collecting reliable SIP data at higher frequencies

- Challenges SIP: polarization of the electrodes, anthropogenic structures (high metal content), electromagnetic coupling (cross-talking with the cables, induction effects in the ground)



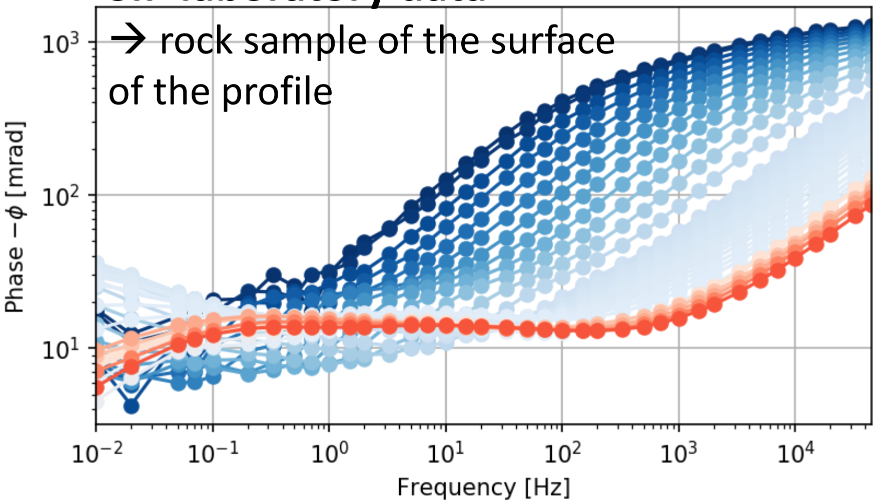
Exemplary SIP field data

→ Bad data quality



SIP laboratory data

→ rock sample of the surface of the profile



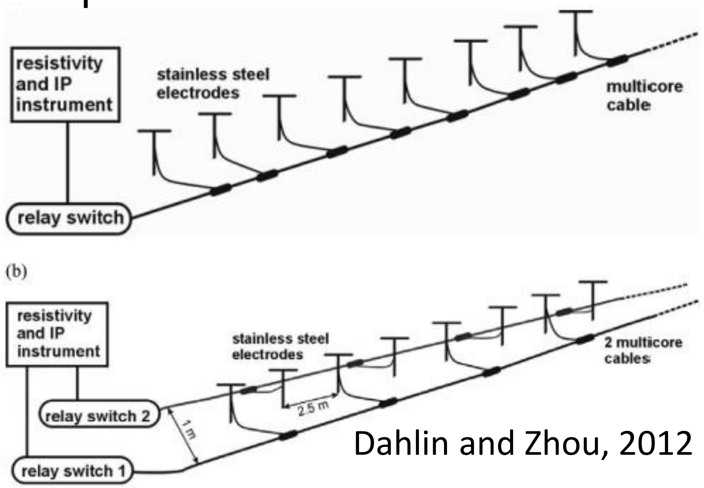
→ We need better data quality at higher frequencies

- Tests of different measurement protocols and cable layouts
- Identification and quantification of errors in the data

Measurement setup & data-error

Different cable setups

- Separated cables

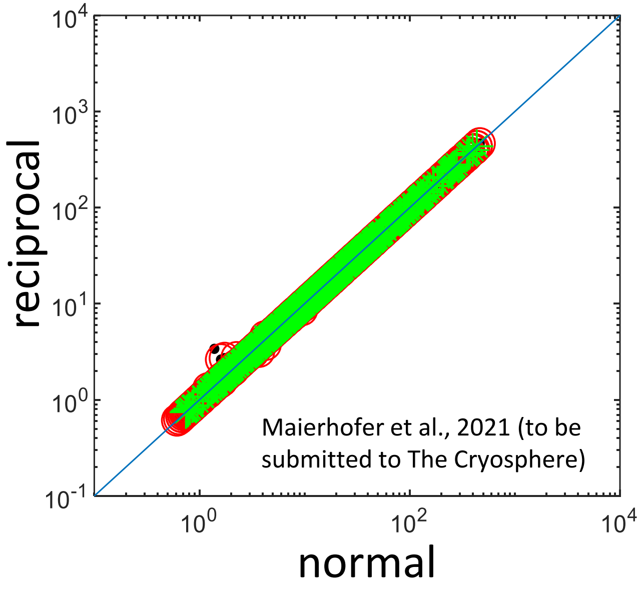


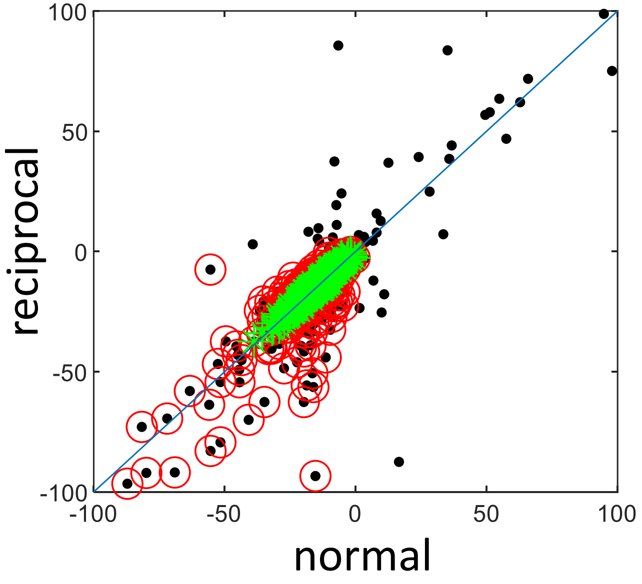
Dahlin and Zhou, 2012

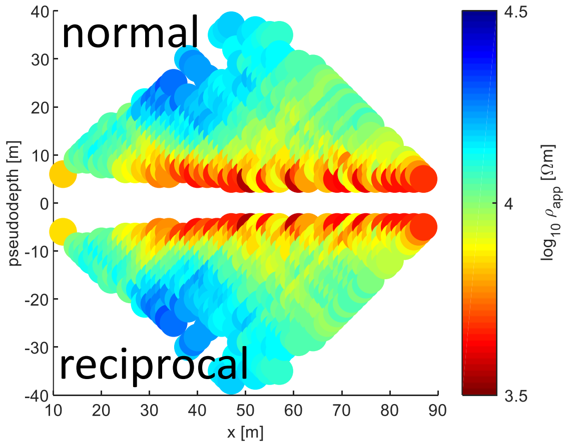
- Coaxial cables

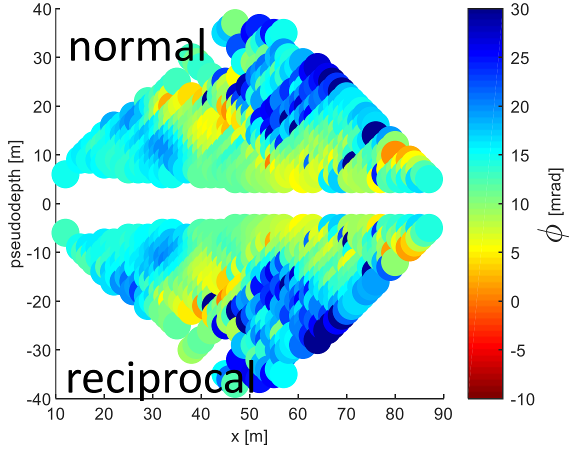
Flores Orozco et al., 2021

Quantification of data error → Normal/reciprocal misfit



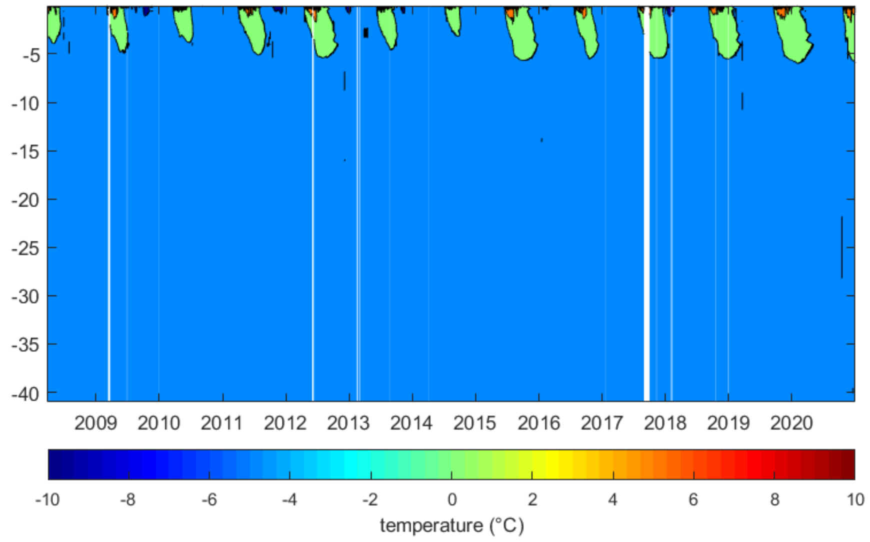




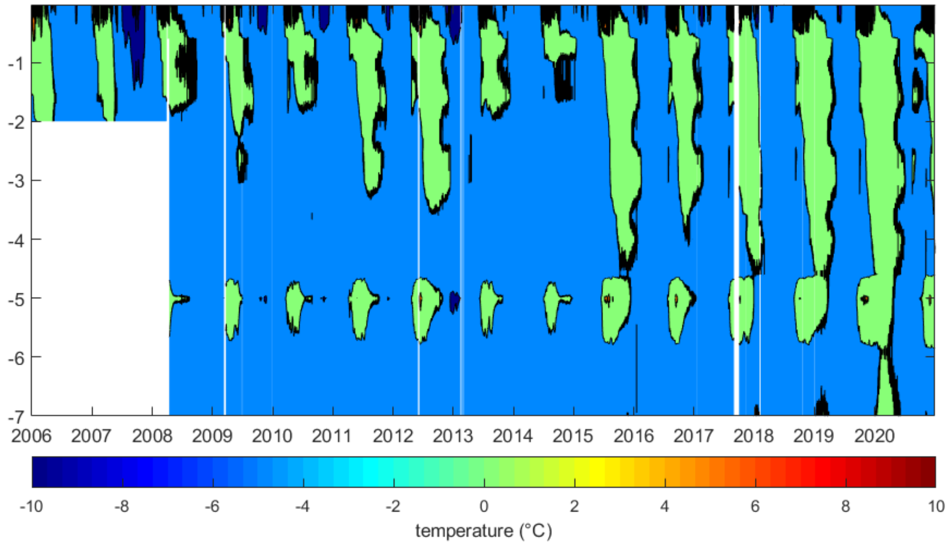


Validation: borehole temperatures

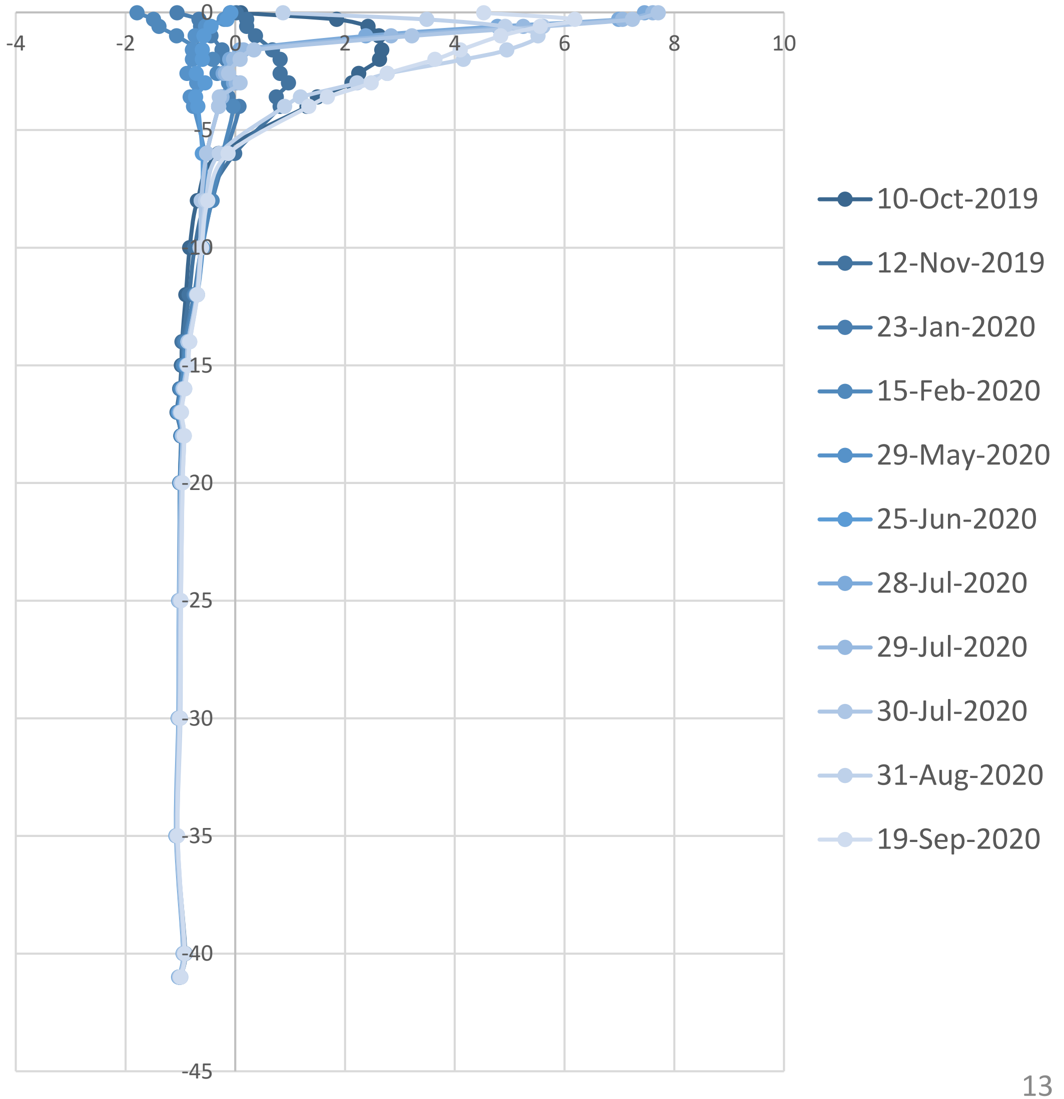
Deep borehole



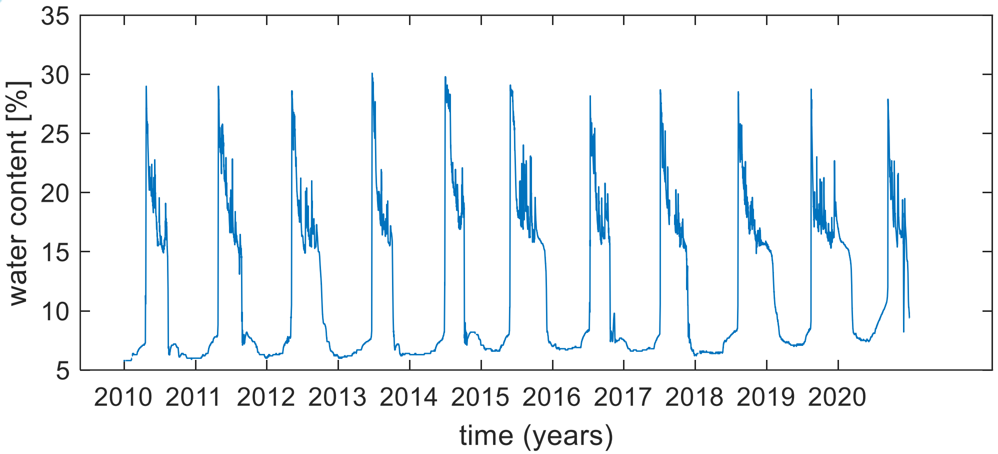
Shallow borehole



Borehole temperature data at measurement date

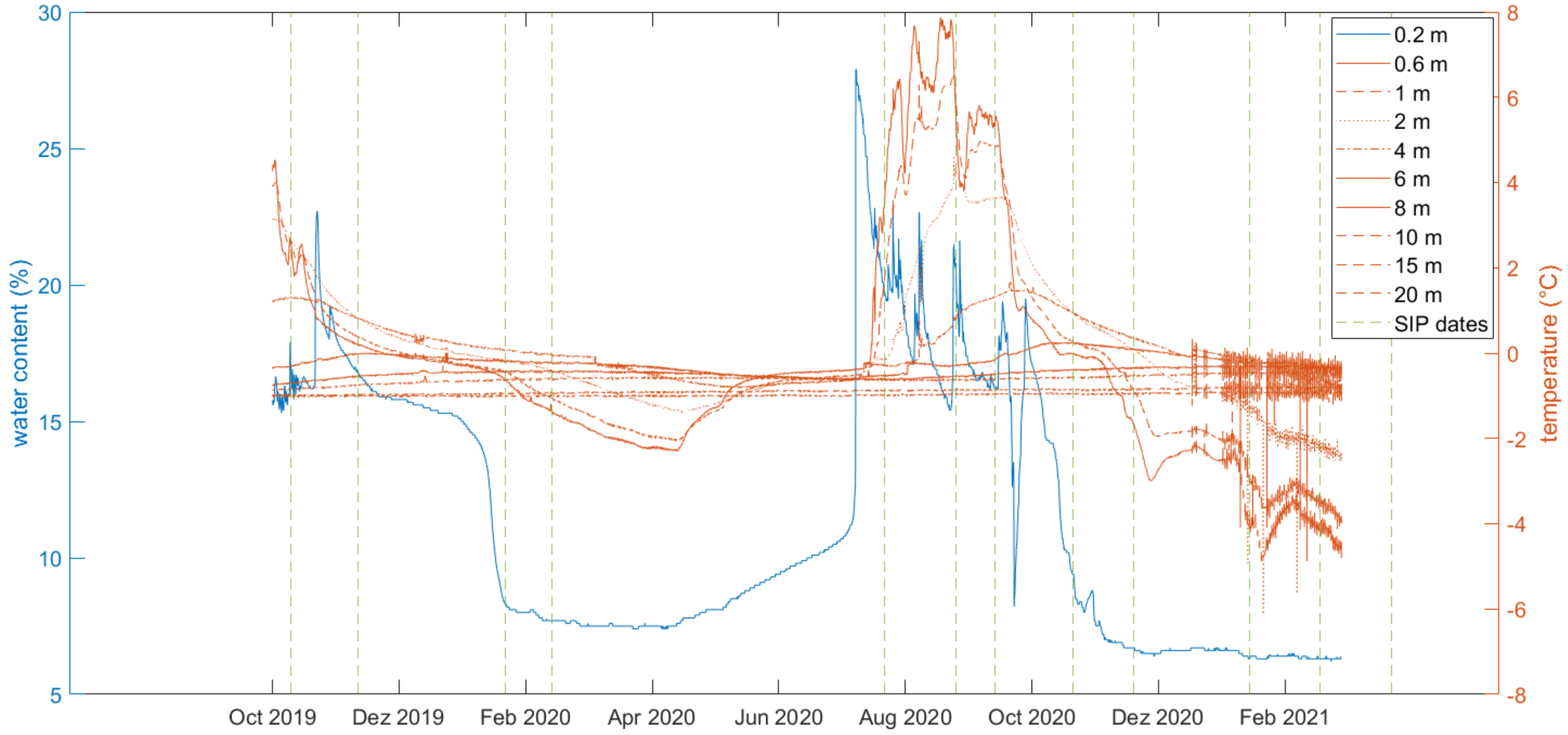


Validation: water content



Water content measurements close to the deep borehole at 20 cm depth collected in the last 10 years

Sensor: Campbell CS61630 Water Content Reflectometer

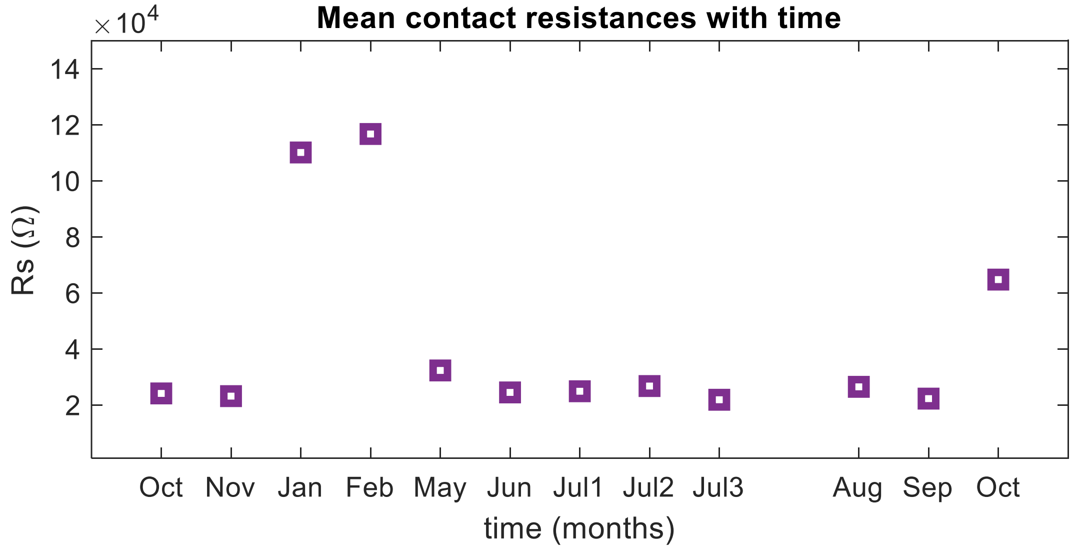


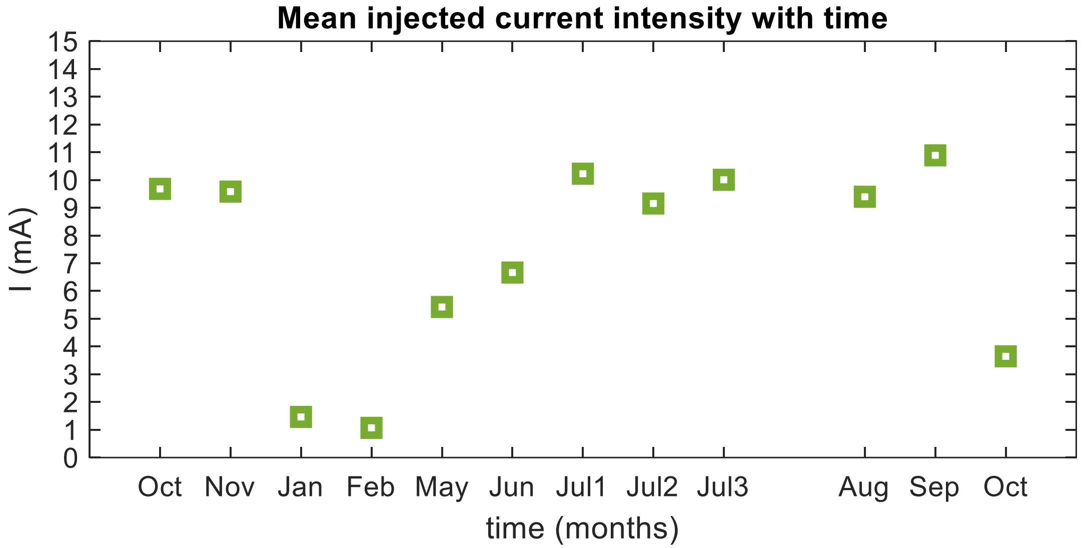
SIP measurement dates

- 2019-10-10
- 2019-11-12
- 2020-01-23
- 2020-02-15
- 2020-05-29
- 2020-06-25
- 2020-07-27
- 2020-07-28
- 2020-07-29
- 2020-07-30
- 2020-08-31
- 2020-09-19
- 2020-10-27
- 2020-11-26
- 2021-01-21
- 2021-02-25
- 2020-04-01

Data processing

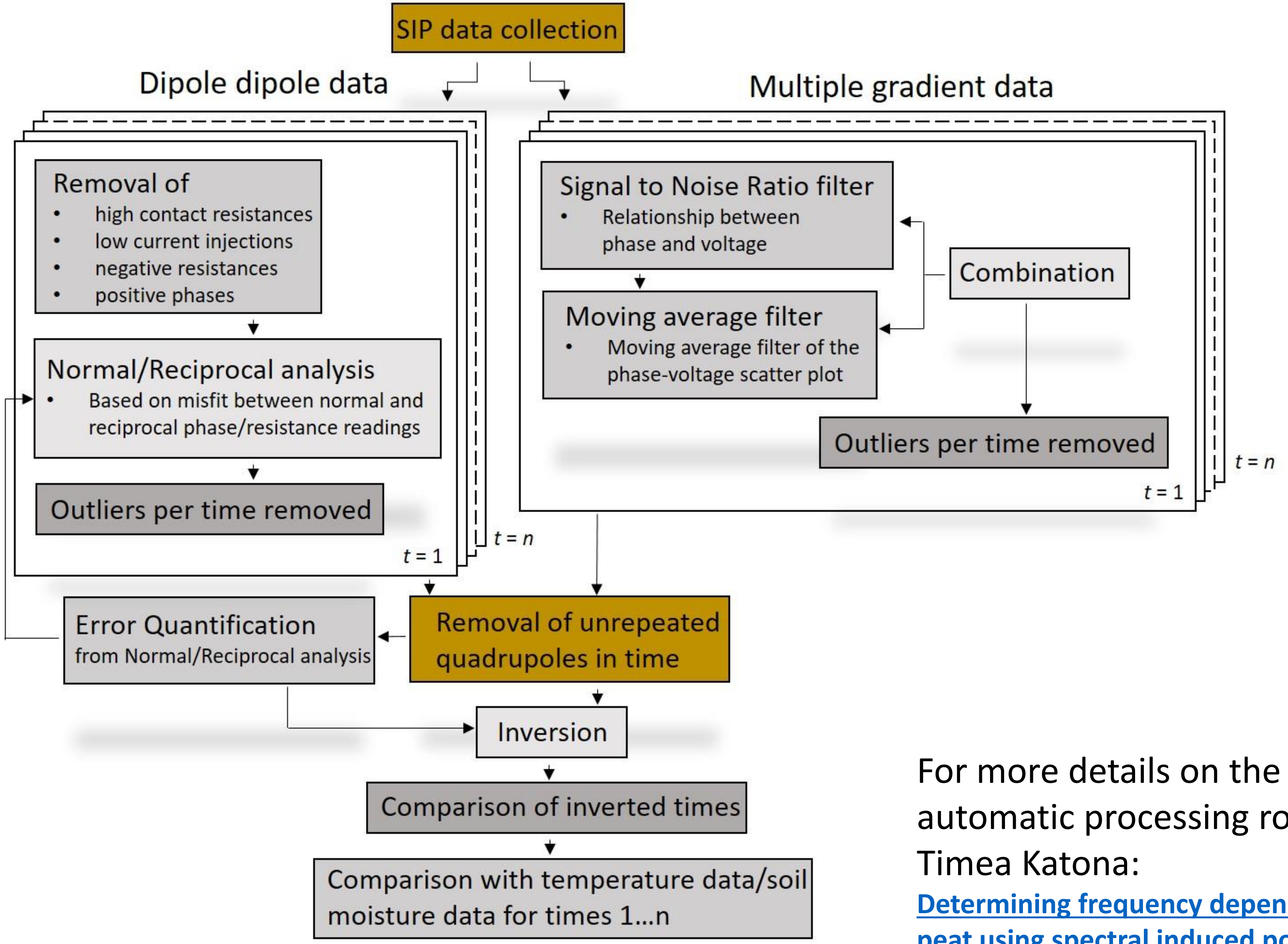
First inspection of the IP data - challenges





- High contact resistances in winter leading to low current injections
- Need for electrode configurations with high signal strength relative to noise
  → Multiple Gradient configuration

Data processing



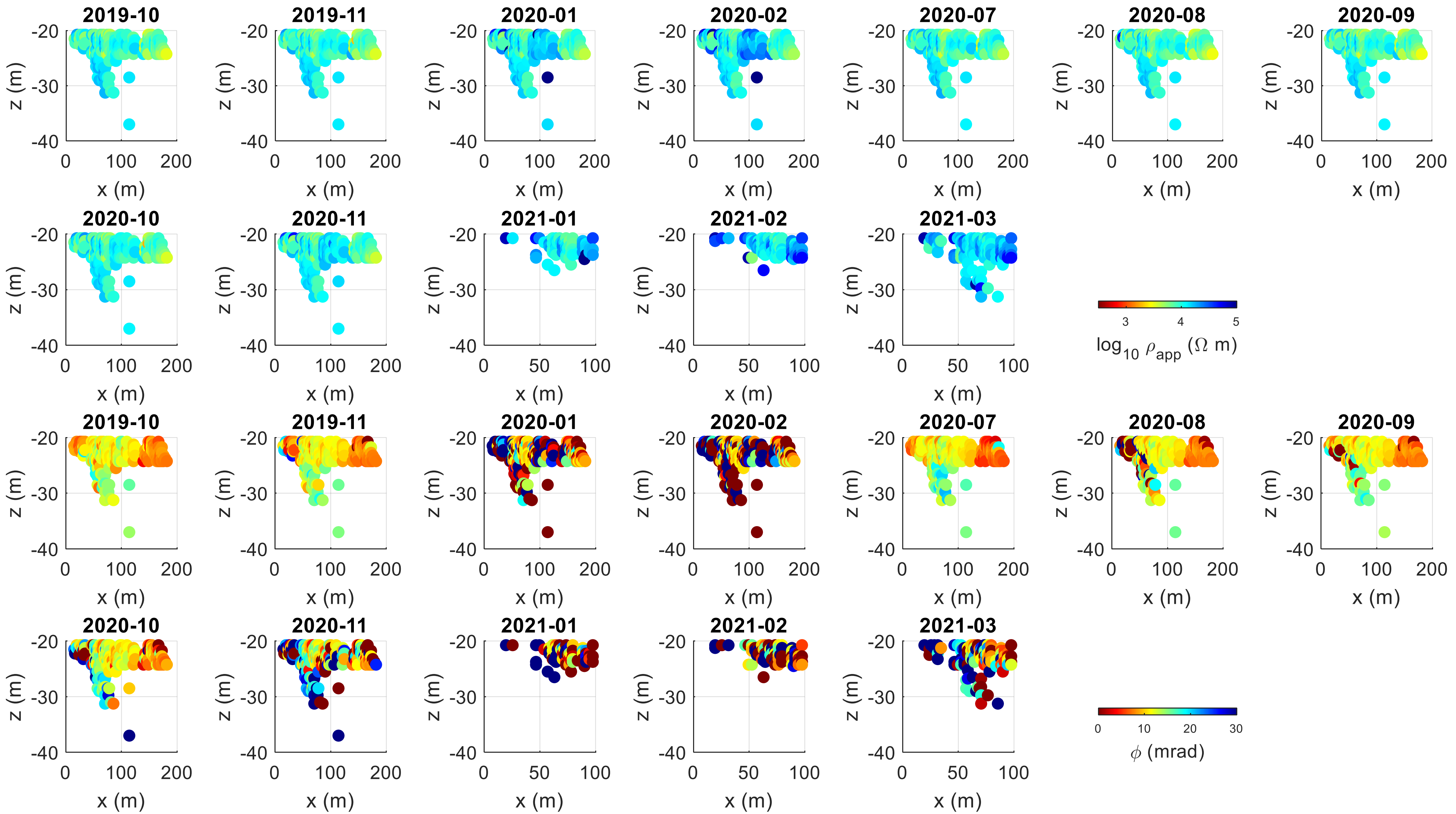
For more details on the newly developed automatic processing routine see the talk of Timea Katona:

Determining frequency dependence of carbon turnover in peat using spectral induced polarization

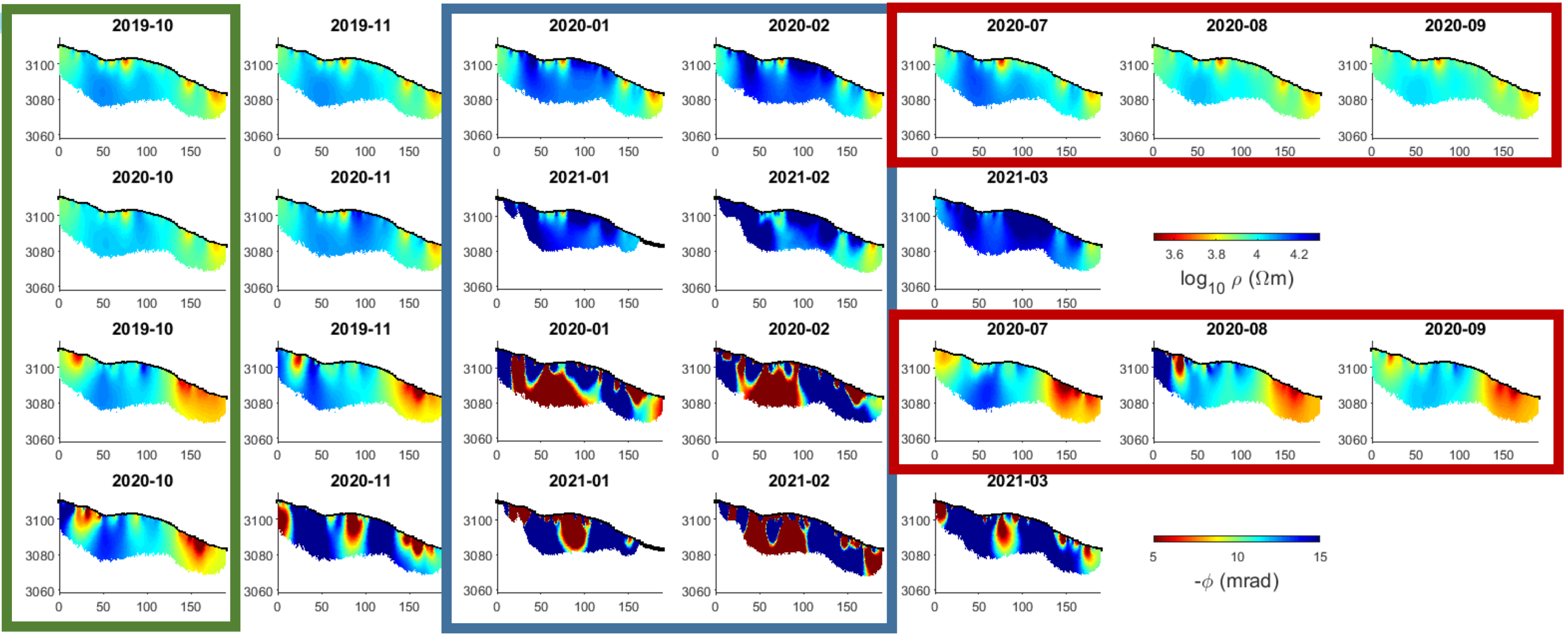
[Session HS8.1.10]

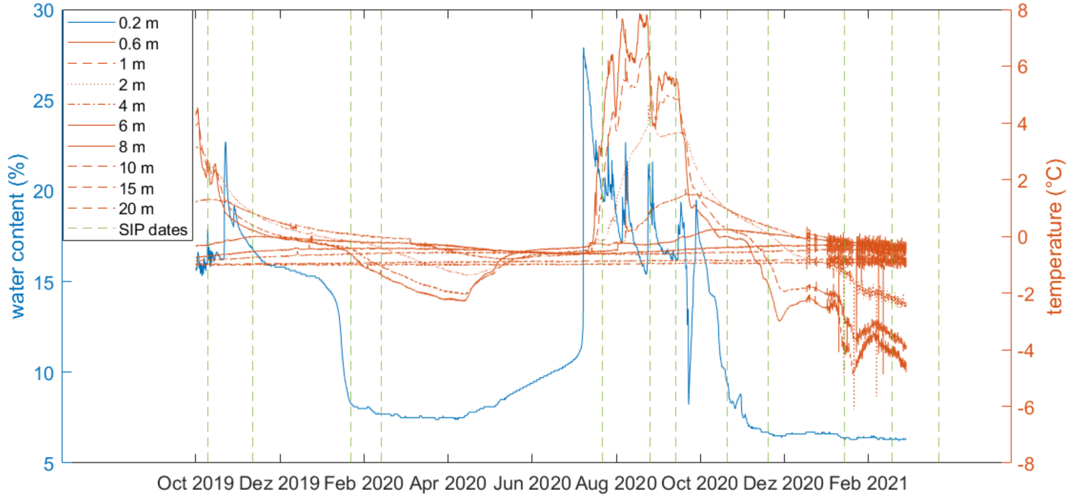
Data processing

Data sets after filtering of the data



IP imaging results – 1.5 years

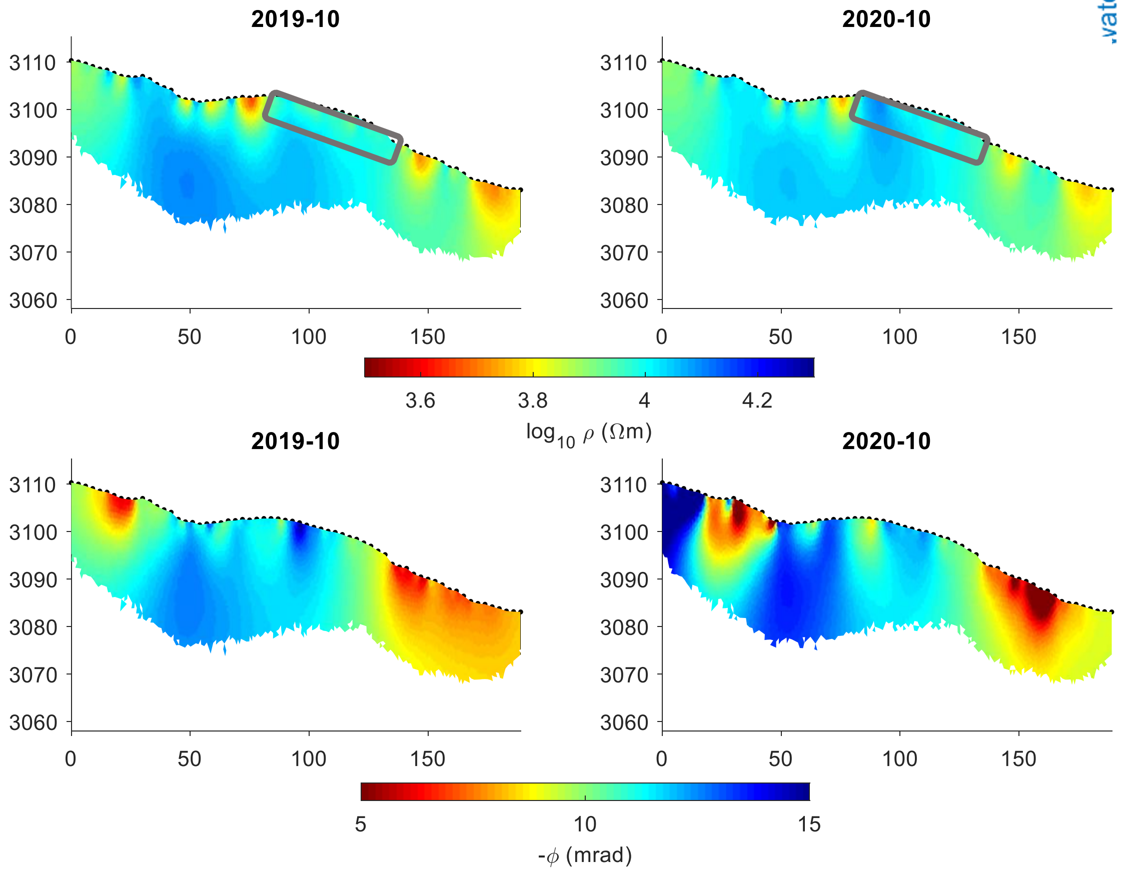


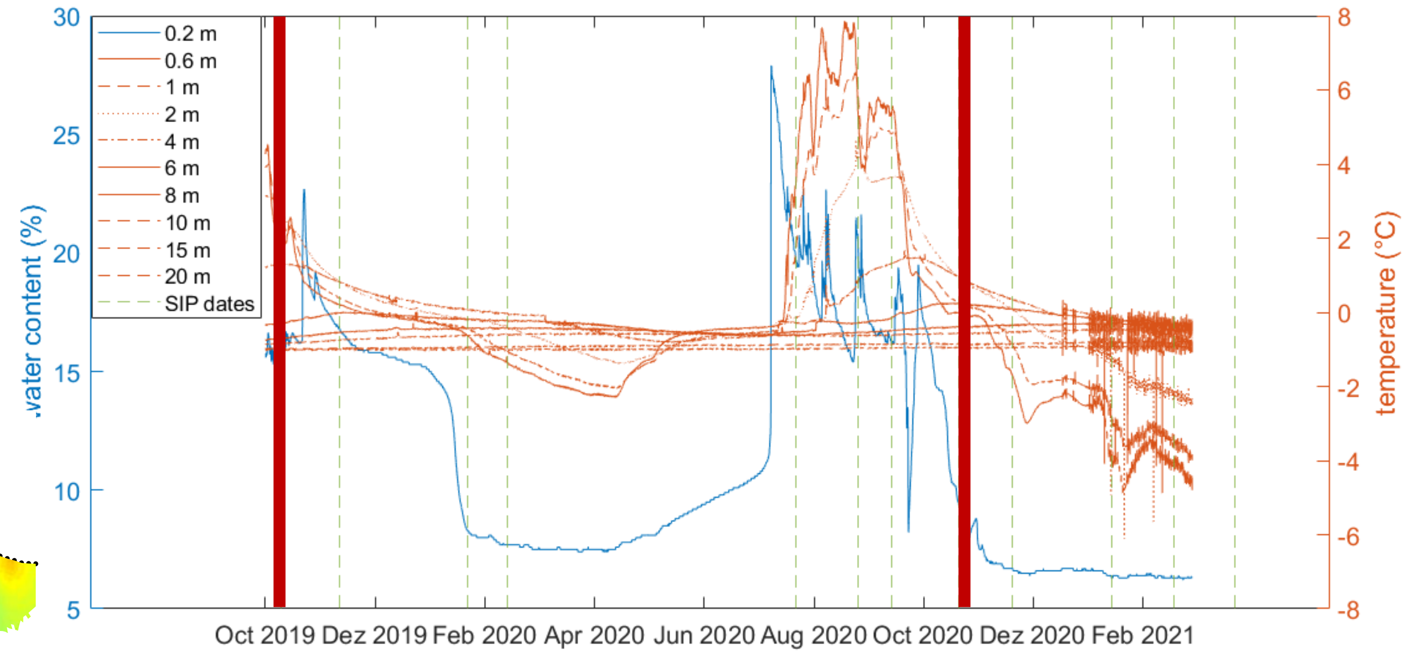


- Higher phase values at depth than at the surface in summer (active layer/permafrost)
- Highest resistivity and polarization for winter months (Jan, Feb) than for summer months
- Active layer deepening from July 2020 to September 2020, the phase shows higher values at depth for July than for September
- Higher phase values for Oct 2020 compared to Oct 2019, water content and borehole temperatures lower in Oct 2020 than in Oct 2019

IP imaging results – 1 year comparison

→ Comparison SIP imaging results at 1 Hz for October 2019 and October 2020

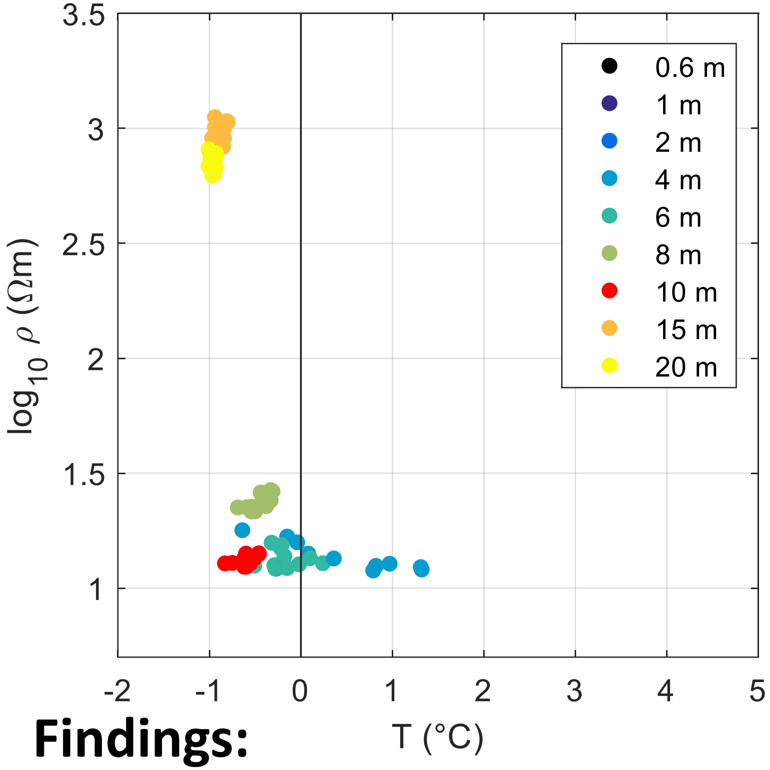


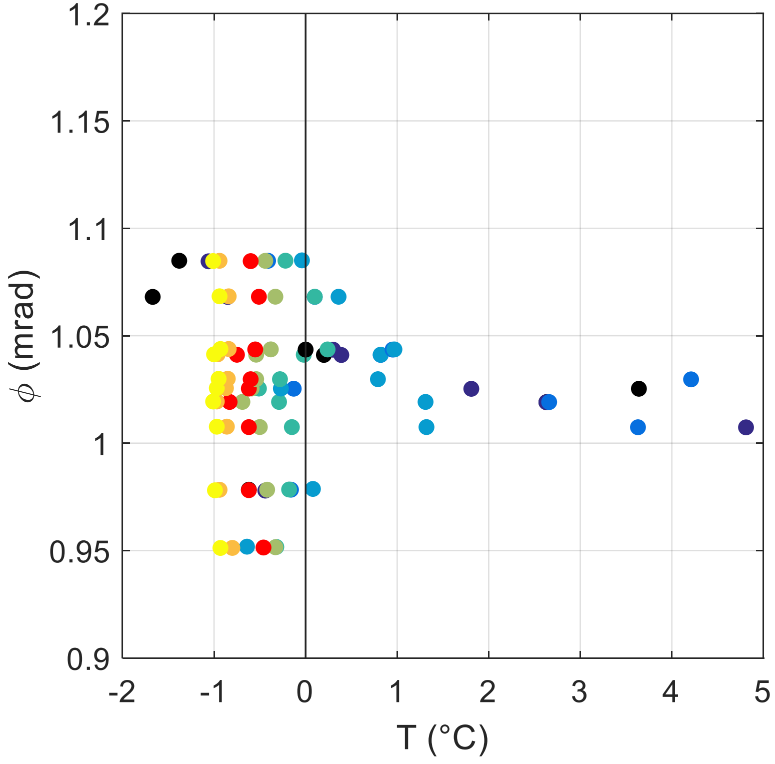


- Higher phase values in Oct 2020 compared to Oct 2019
- Higher resistivity values in the active layer in Oct 2020 compared to Oct 2019
- Water content and borehole temperatures lower in Oct 2020 than in Oct 2019

IP imaging results – 1.5 years

IP/temperature relations





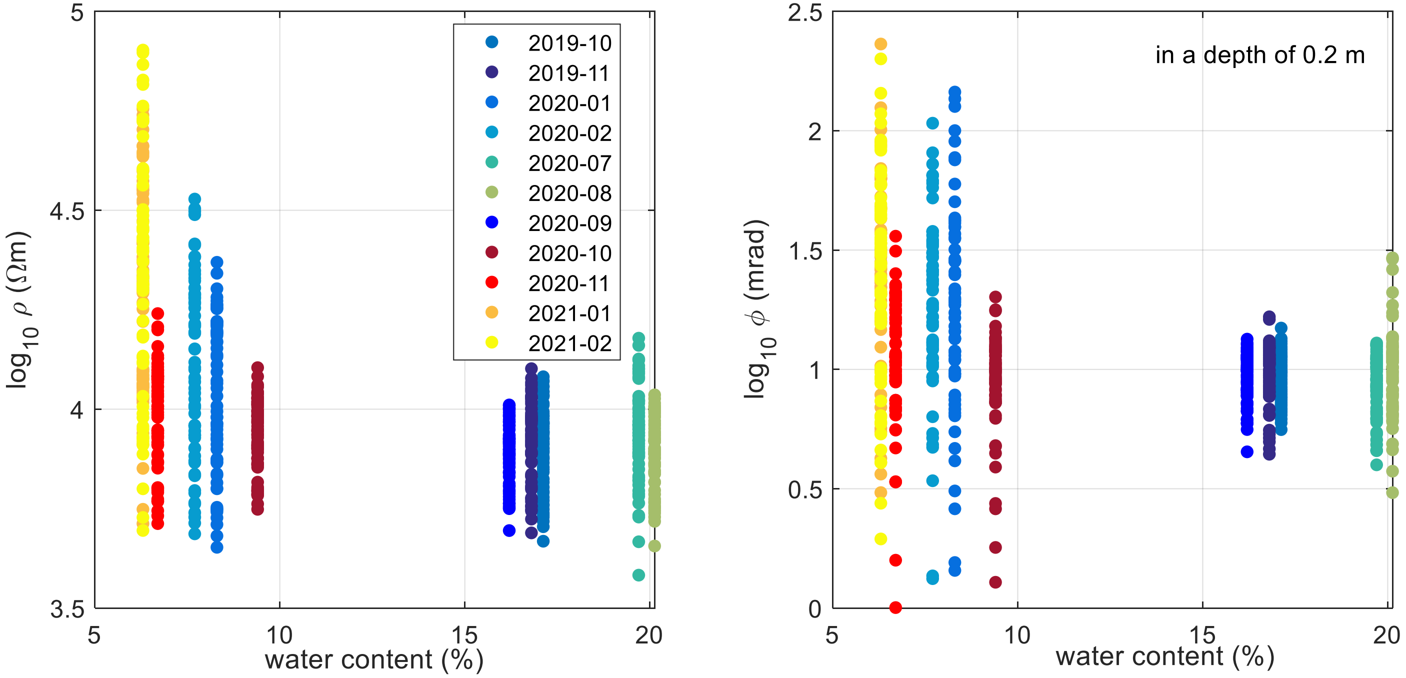
Examplary resistivity/phase – temperature relations for 1 Hz at different depths extracted from SIP inversion results at close proximity to the borehole for all measurement dates

Findings:

- At freezing temperatures (below 0° C), the resistivity and phase values are higher with a wider range observed for the phase values compared to phase values at positive temperatures
- The phase is more dependent on the different compositions at depth, we observe slight changes with time at each depth, so it is sensitive to T/ice, T-rho relation clearer than T-phase relation .

IP imaging results – 1.5 years

IP/water content relations



Relation between resistivity/phase and water content for 1 Hz in a depth of 0.2 meter for the whole profile during a monitoring period of 1.5 years

Findings

- At freezing temperatures (below 0° C), the resistivity and phase values are higher with a wider range observed for the phase values compared to phase values at positive temperatures
- A combination of low water content (6%) and low temperatures (-4°C) exhibits the highest resistivity and phase values

SIP laboratory setup

SIP laboratory setup:

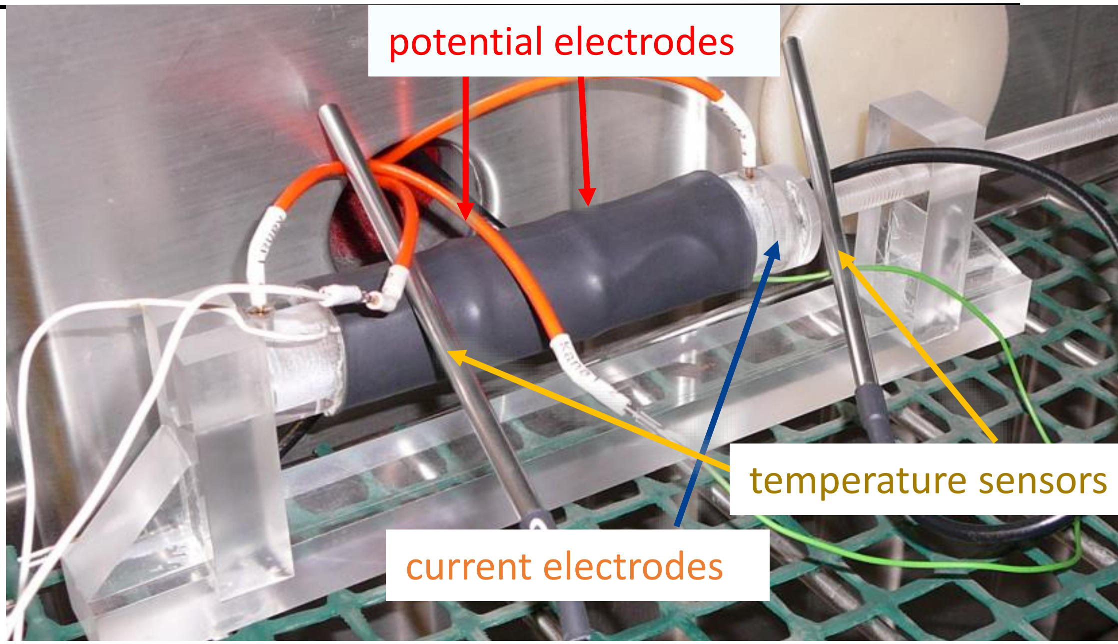
- SIP device: SIP04 (Zimmermann et al., 2008)
- Frequency range: from 10 mHz to 45 kHz
- 4-point measurements

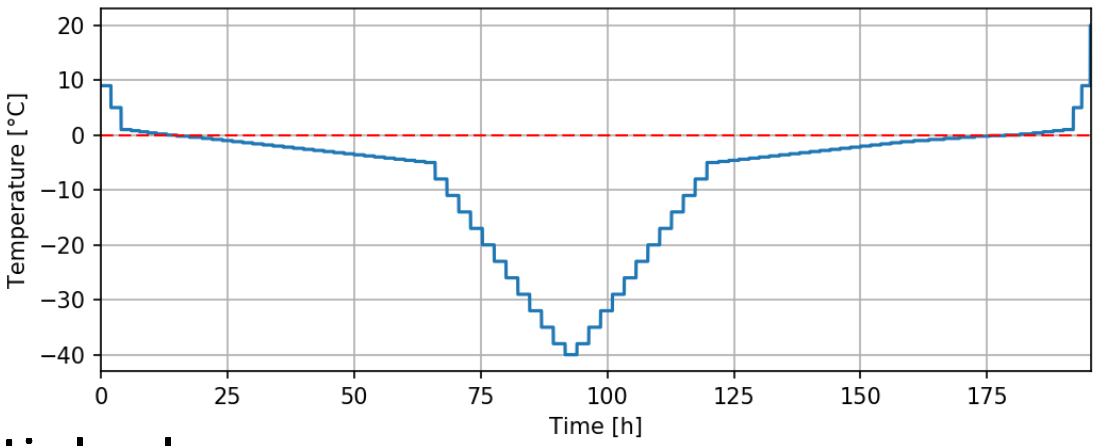
Samples from Cervinia:

- Solid rock samples from surface (saturated with water)
- Not shown: loose sediment samples collected from surface, measured on cylindrical plug (9cm length, 3cm diameter) (volumetric water content similar to field conditions)

Temperature setup:

- Temperature range: from +20°C to -40°C

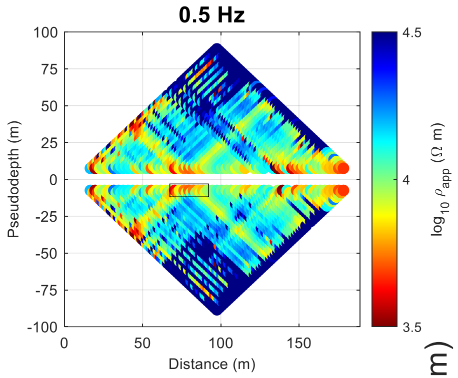




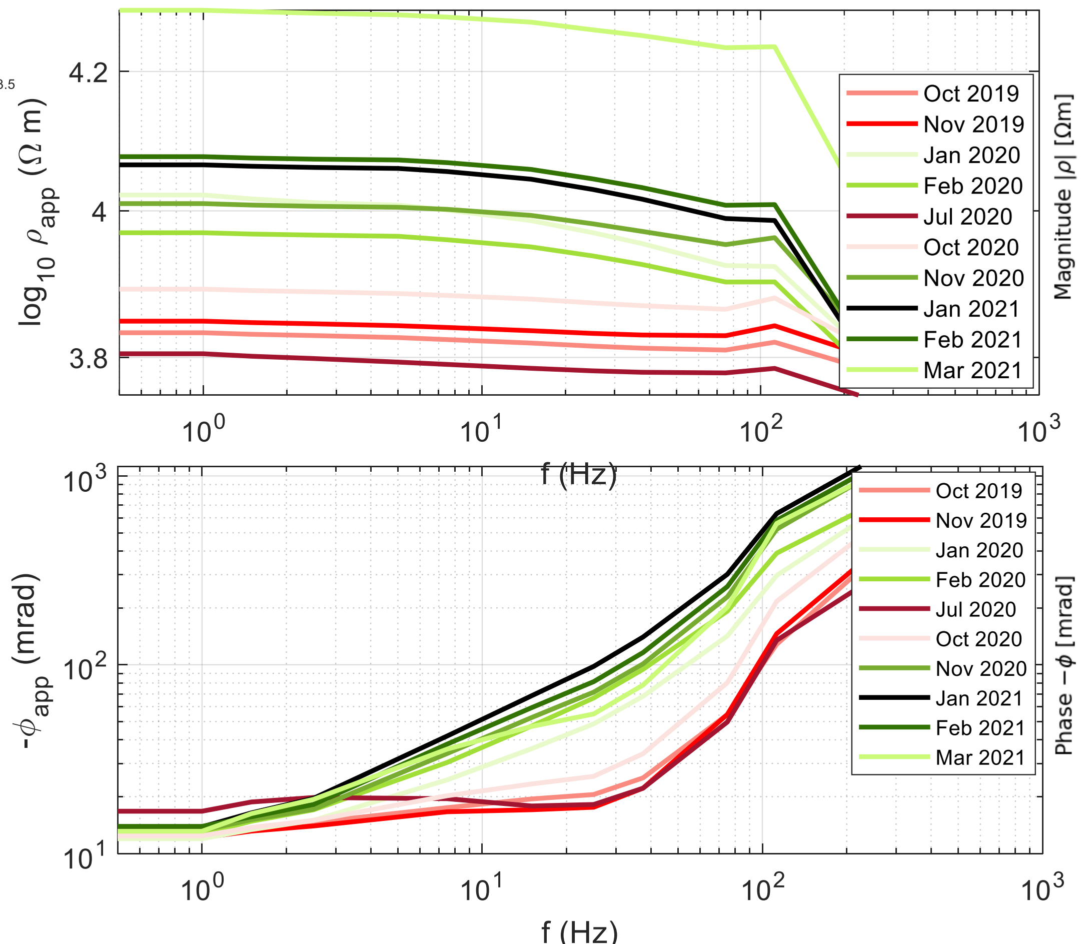
For further details on the laboratory anaylsis, see the talk of Jonas Limbrock:

[Textural and mineralogical controls on temperature dependent SIP behavior during freezing and thawing]

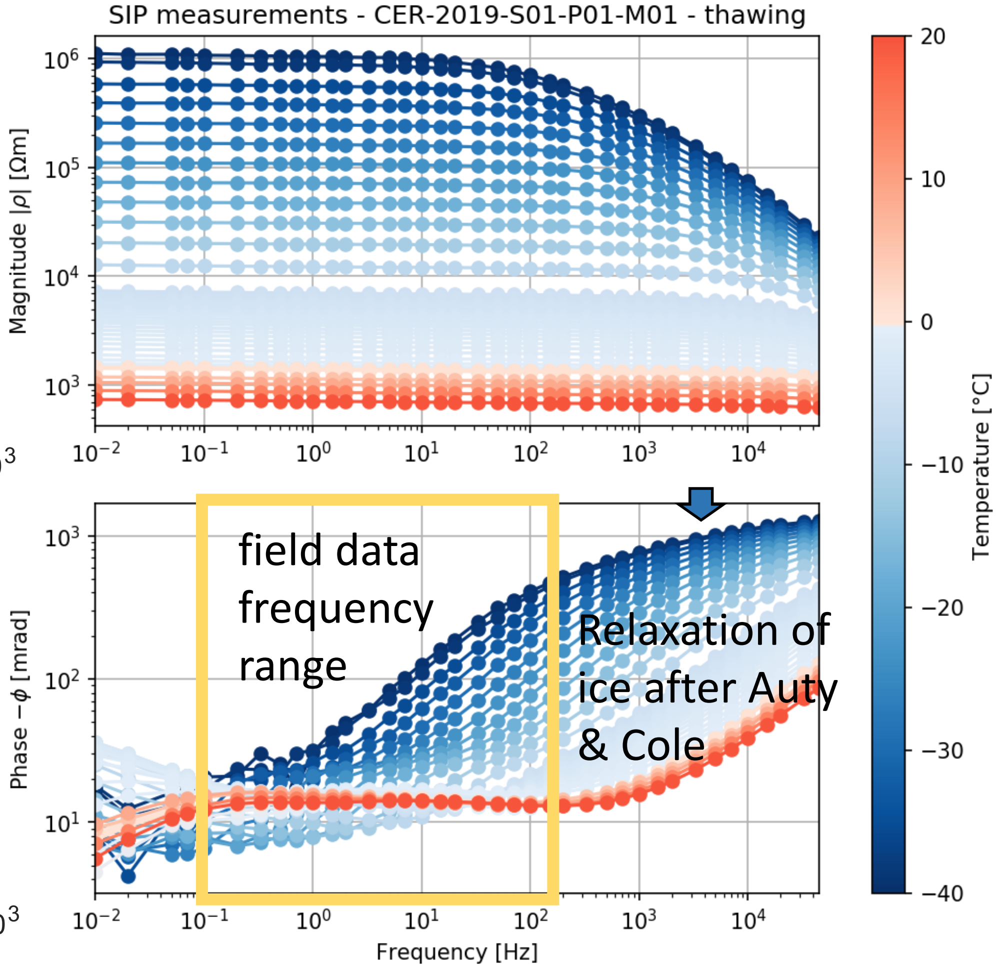
Comparison field/laboratory



Field data



Laboratory data (rock sample)



Conclusion and Outlook

Conclusion

- We observe clear seasonal changes in IP imaging data with an increase in the phase in winter and a decrease in summer, which relate to the seasonal freezing and thawing of the ground reported by borehole temperature data
- The laboratory analysis of the impedance phase spectra exhibit the well-known relaxation behaviour of ice at higher frequencies (1 kHz – 45 kHz). When comparing laboratory and field data, we observe a similar temperature-dependent behaviour in the shape and amplitude of the spectra of the resistance (impedance magnitude) and the impedance phase (polarization) with increasing amplitudes for decreasing temperatures.
- We observe an active layer deepening from July 2020 to September 2020 and highest resistivity and polarization for winter months (January, February, March) than for summer months (July, September, October)
- A clear temperature/phase relation is found for different seasons and depths of the SIP monitoring profile, at freezing temperatures (below 0° C), the resistivity and phase values are higher with a wider range observed for the phase values compared to phase values at positive temperatures
- A combination of low water content (6%) and low temperatures (-4°C) exhibits the highest resistivity and phase values

Outlook

- Quantification of the ice content using SIP field and laboratory data
- SIP monitoring will continue through 2021 → thawing period

References

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