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# Improved thermal characterization of alpine permafrost sites by broadband SIP measurements

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# INTRODUCTION

# Introduction

- Due to climate change, mountain permafrost is thawing globally. This is associated with an increase in geological risks, like landslides or rock falls (e. g., Ravanel and Deline, 2008).
- Geoelectrical methods are increasingly used for non-invasive characterization and monitoring of permafrost sites, since the electrical properties of the subsoil are sensitive to the phase change of liquid to frozen water.
- In this context, electrical subsurface parameters act as proxies for temperature and ice content.
- However, geoelectric measurements are subject to strong ambiguities. For example, ice and air act as good electrical insulators and electrical resistances show a temperature dependence.
- Since ice has a known polarization signature (e. g., Auty and Cole 1952, Fabbri et al., 2006), the use of Spectral Induced Polarization (SIP) for quantification of ice content and thermal characterization of alpine permafrost sites is investigated by comparative laboratory and field measurements.

**Research questions:**

- Can we quantify ice polarization effects in laboratory SIP measurements on frozen soils or rocks?
- Can we quantify the ice content at alpine permafrost sites from SIP measurement?
- Can we characterize the thermal state of alpine permafrost sites via SIP?

# PART 1: LABORATORY MEASUREMENTS

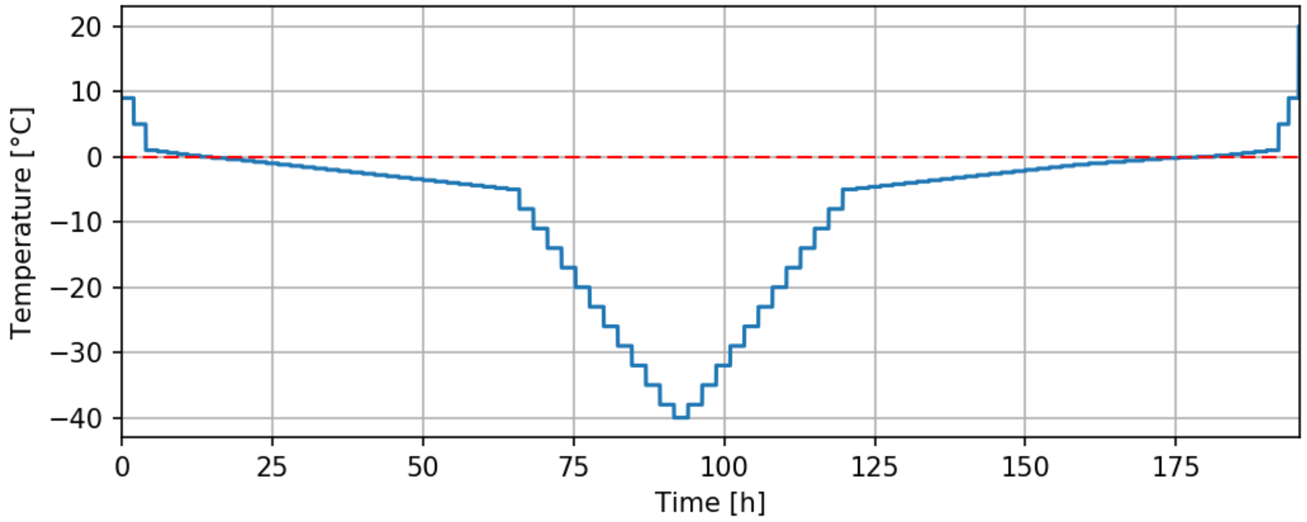
  

# Laboratory measurements: General setup

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

**Temperature setup:**
- Temperature range: from +20°C to -40°C
- Temperature steps: 4°C and 0.2°C (around freezing point)
- Duration of each T step: between 120 and 180 minutes

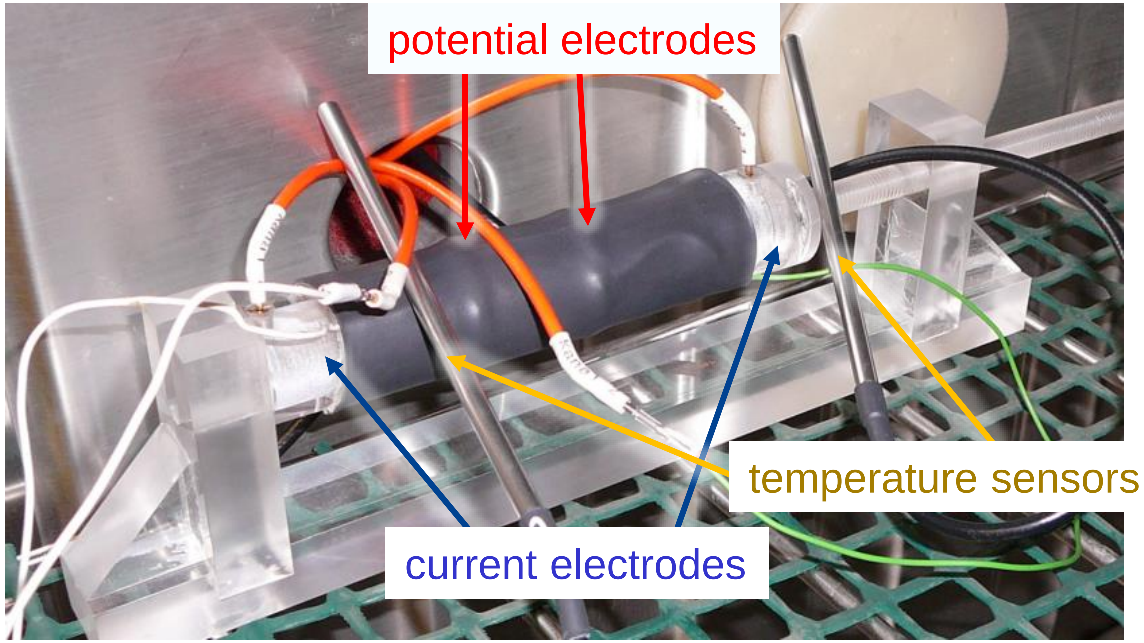
**Samples:**
- Solid rock samples from permafrost sites:
  – Schilthorn: mica schist
  – Zugspitze: limestone
- Loose sediment samples from permafrost site:
  – Schilthorn

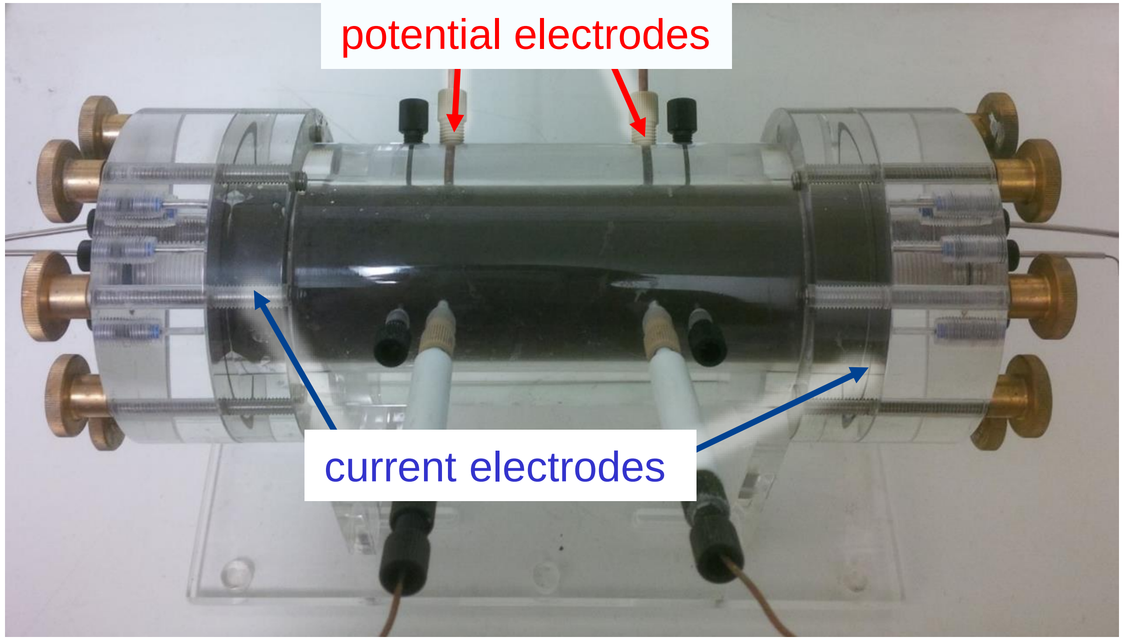


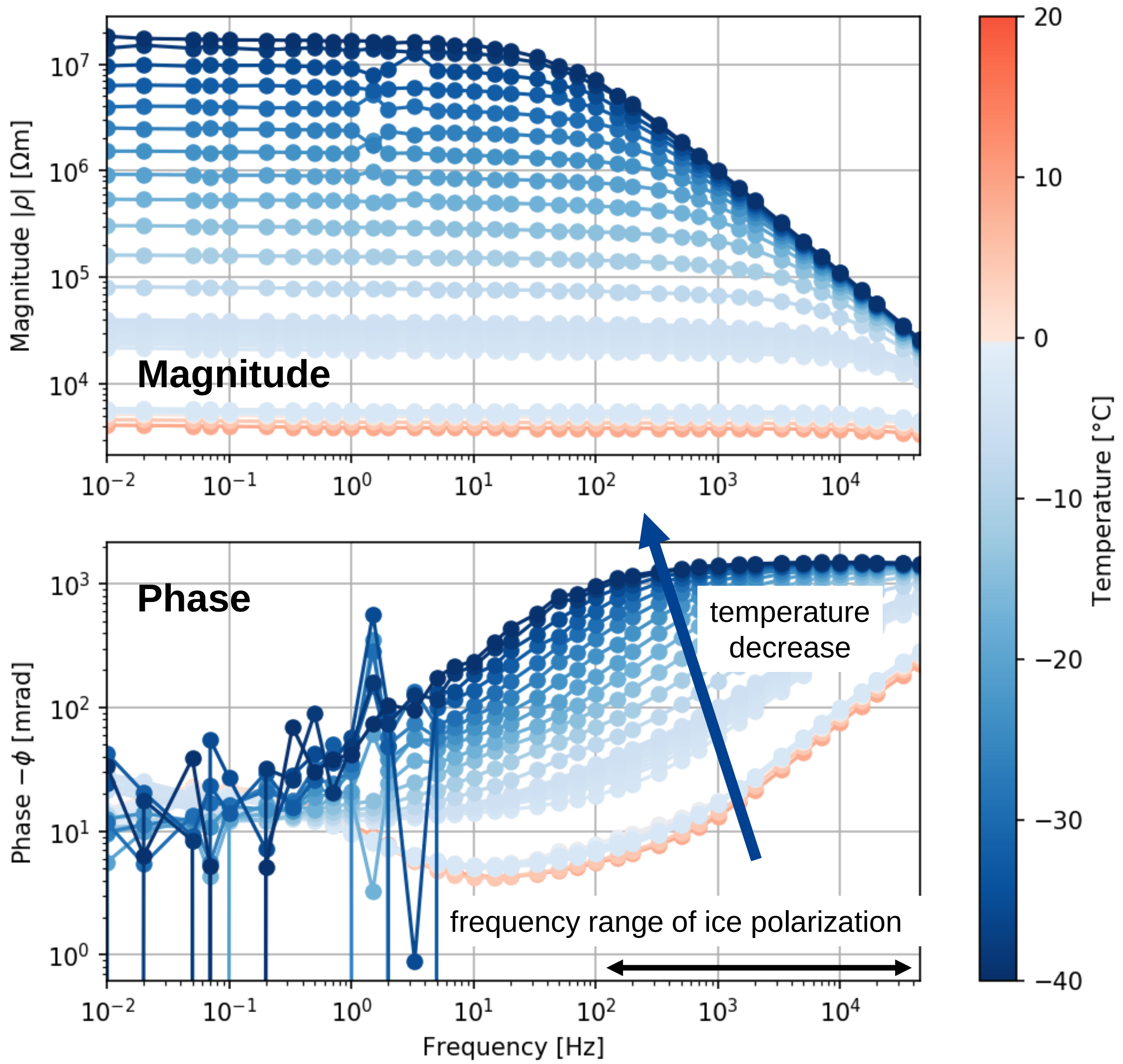
**Solid rock samples:**
- Sample cylinders
  - Length: 9 - 10 cm
  - Diameter: 3 cm
  - Distance between potential electrodes: 3 cm
- Saturated with water
- Sealed in shrinking tube

**Loose sediment sample:**
- Measurement cell
  - Length : 18 cm
  - Diameter: 4 cm
  - Distance between potential electrodes: 6 cm
- Volumetric water content similar to field conditions



# SIP spectra: Zugspitze solid rock sample - freezing




## Resistivity

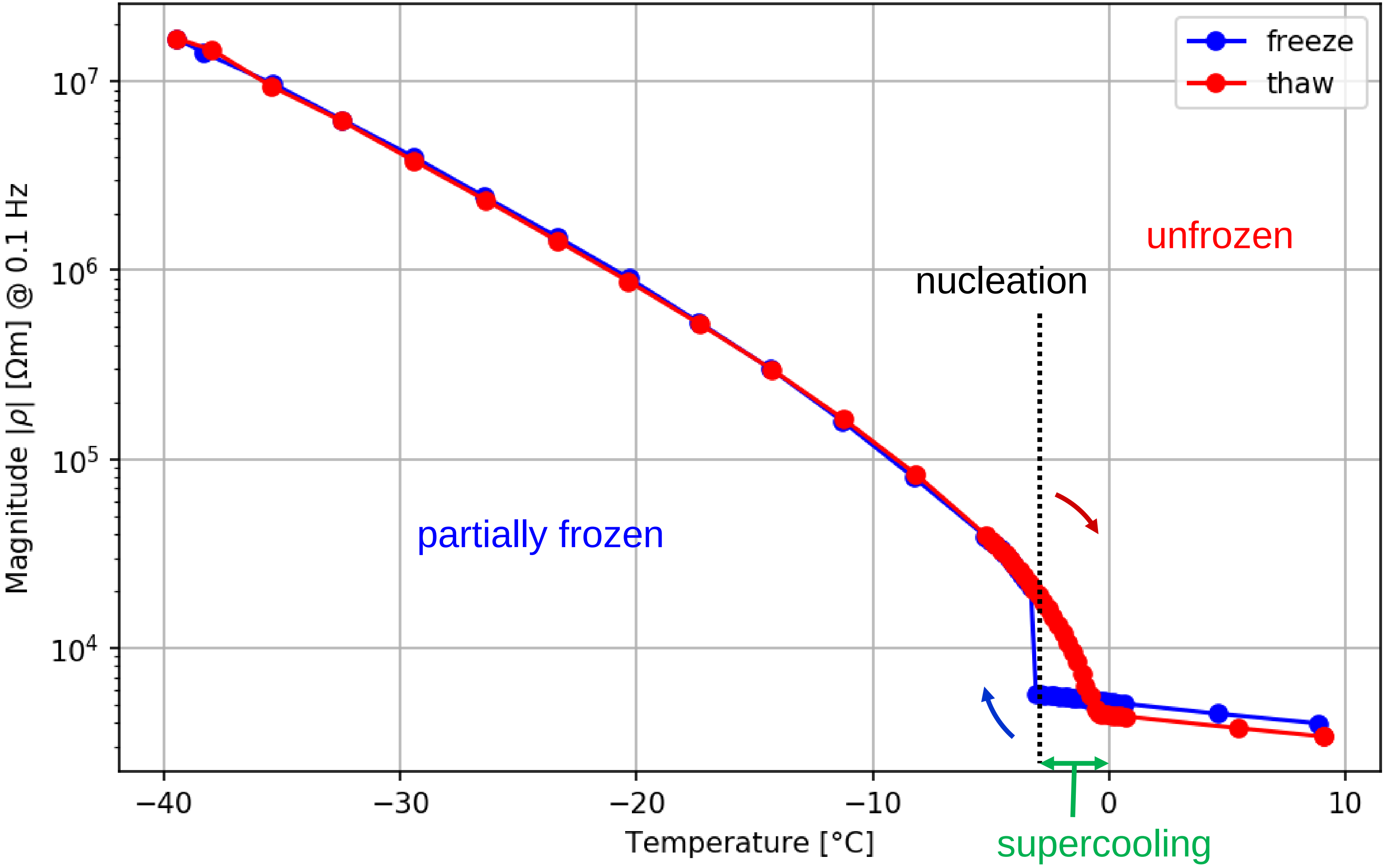
- Resistivity magnitude is temperature dependent.
- Unfrozen and (partially) frozen state can be distinguished in resistivity.

## Phase

- Unfrozen and (partially) frozen state can be distinguished in phase.
- Resistivity phase shows an increase of high-frequency polarization (probably ice polarization response) and a decrease of low-frequency polarization (probably membrane polarization response) with decreasing temperature.
- Relaxation time of ice polarization is temperature dependent.

# Temperature dependence of resistivity – Zugspitze solid rock sample



# Temperature dependence of ice polarization: Debye decomposition

## Is the high-frequency polarization caused by ice?

- Debye decomposition after Nordsiek and Weller (2008), Weigand and Kemna (2016):

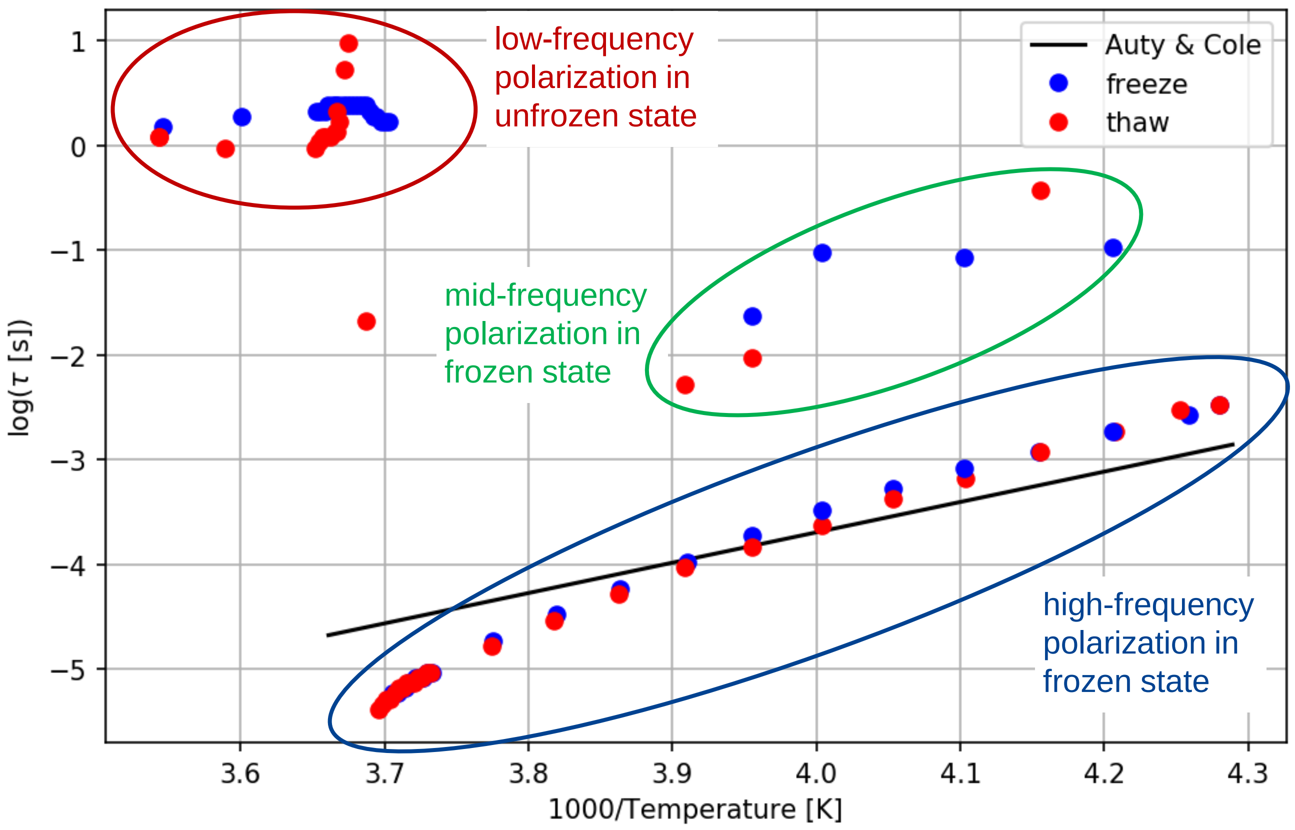
$$\hat{\rho}(\omega) = \rho_0 \left(1 - \sum_{k=1}^{N_\tau} m_k \left[1 - \frac{1}{1 + j\omega\tau_k}\right]\right)$$

Mit:

- $\hat{\rho}(\omega)$: complex resistivity
- $\rho_0$: DC resistivity
- $m_k$: chargeability
- $\tau_k$: relaxation time

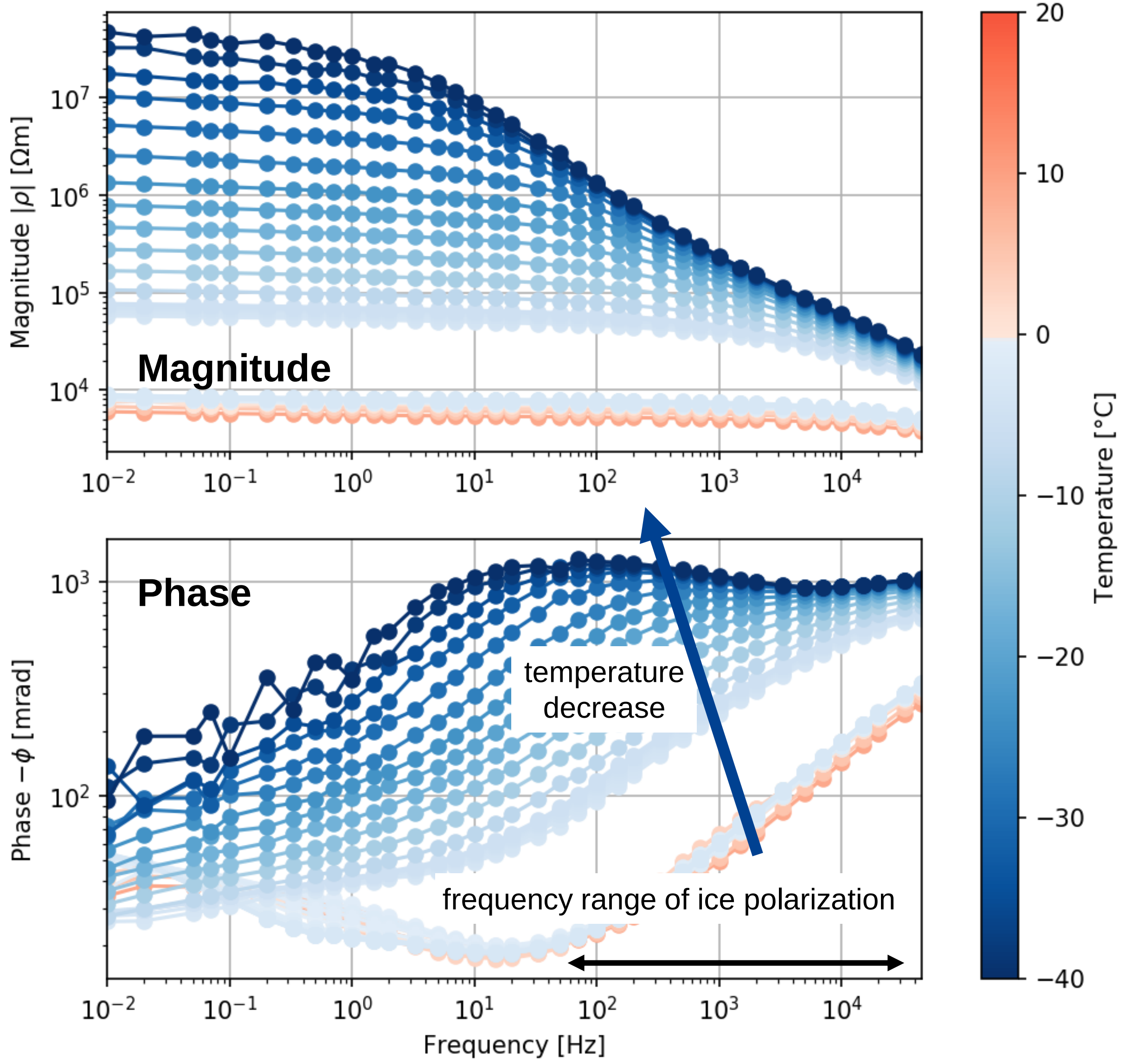
- $m_{tot} = \sum_{k=1}^{N_\tau} m_k$: total chargeability
- $\tau_{mean} = \exp\left(\sum_{k=1}^{N_\tau} m_k \log(\tau_k) \,/\, \sum_{k=1}^{N_\tau} m_k\right)$: mean chargeability
- $\tau_{peak}$: local maximum of RTD

- Comparison of temperature dependent $\tau_{peak}$ for Zugspitze solid rock sample with well-known temperature dependent relaxation time of ice (Auty and Cole, 1952):




➔ **High-frequency polarization response likely caused by ice.**

# SIP spectra: Schilthorn solid rock sample - freezing

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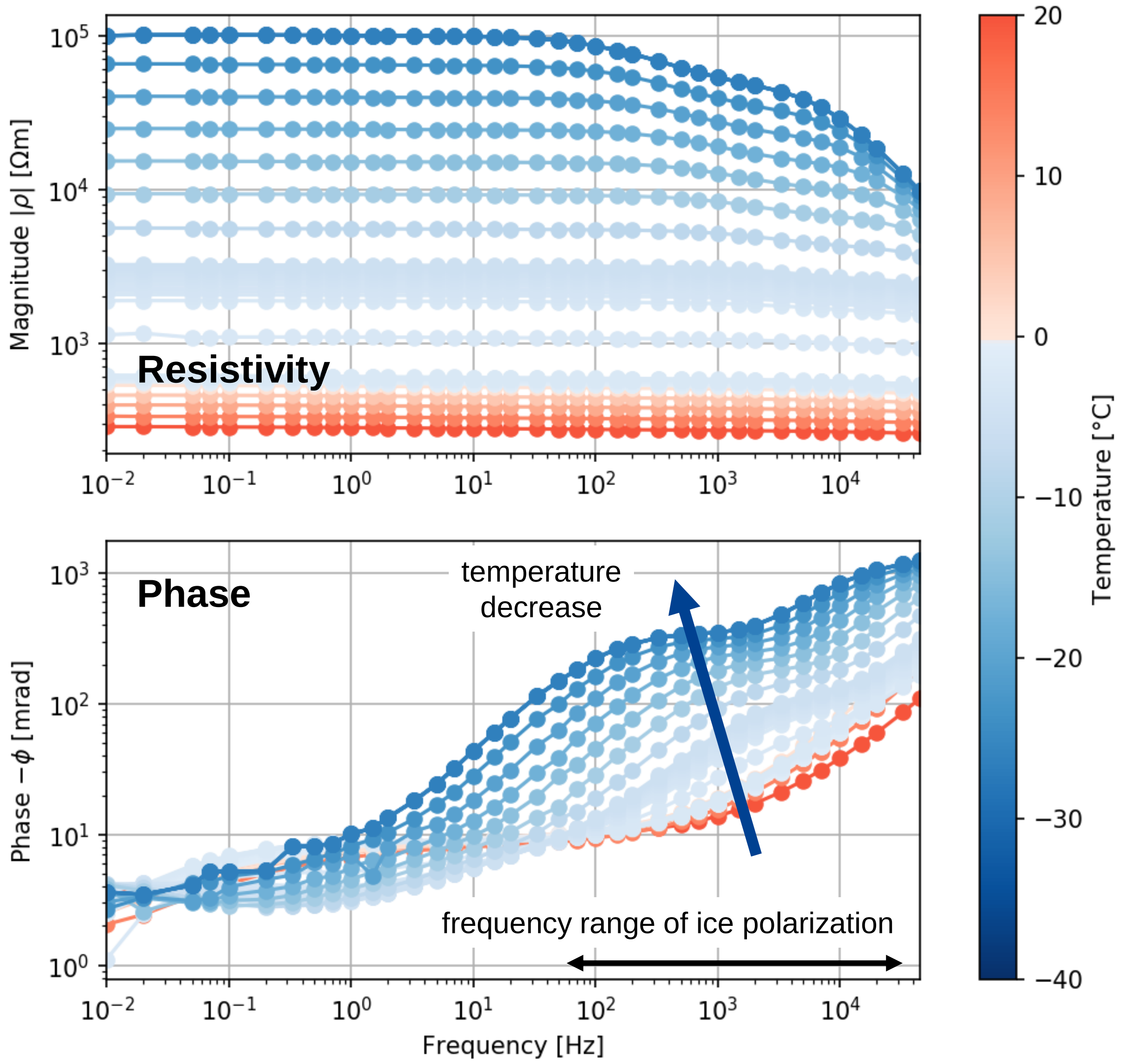
# SIP spectra: Schilthorn loose sediment sample - freezing




### Resistivity

- Resistivity magnitude is temperature dependent.
- Unfrozen and (partially) frozen state can be distinguished in resistivity.

### Phase

- Unfrozen and (partially) frozen state can be distinguished in phase.
- Resistivity phase shows an increase of high-frequency polarization (probably ice polarization response) and a decrease of low-frequency polarization (probably membrane polarization response) with decreasing temperature.
- Relaxation time of ice polarization is temperature dependent.

# Summary laboratory measurements

- SIP response of the ice is **suited to characterize the thermal state of a sample**
  - Clear distinction between frozen and unfrozen states possible.
  - Qualitative detection of ice possible.
  - High-frequency measurements (> 100 Hz) necessary.
  - High data quality also necessary for field measurements

- General SIP behavior is **independent of lithology**
  - Resistivity magnitude: Same temperature dependence, but different absolute values for different lithologies
  - Resistivity phase: Same temperature dependence and similar ice polarization response for different lithologies

- **Independent information** required for signature understanding and calibration

# PART 2: FIELD MEASUREMENTS AND COMPARISON TO LABORATORY MEASUREMENTS

# Location of field sites

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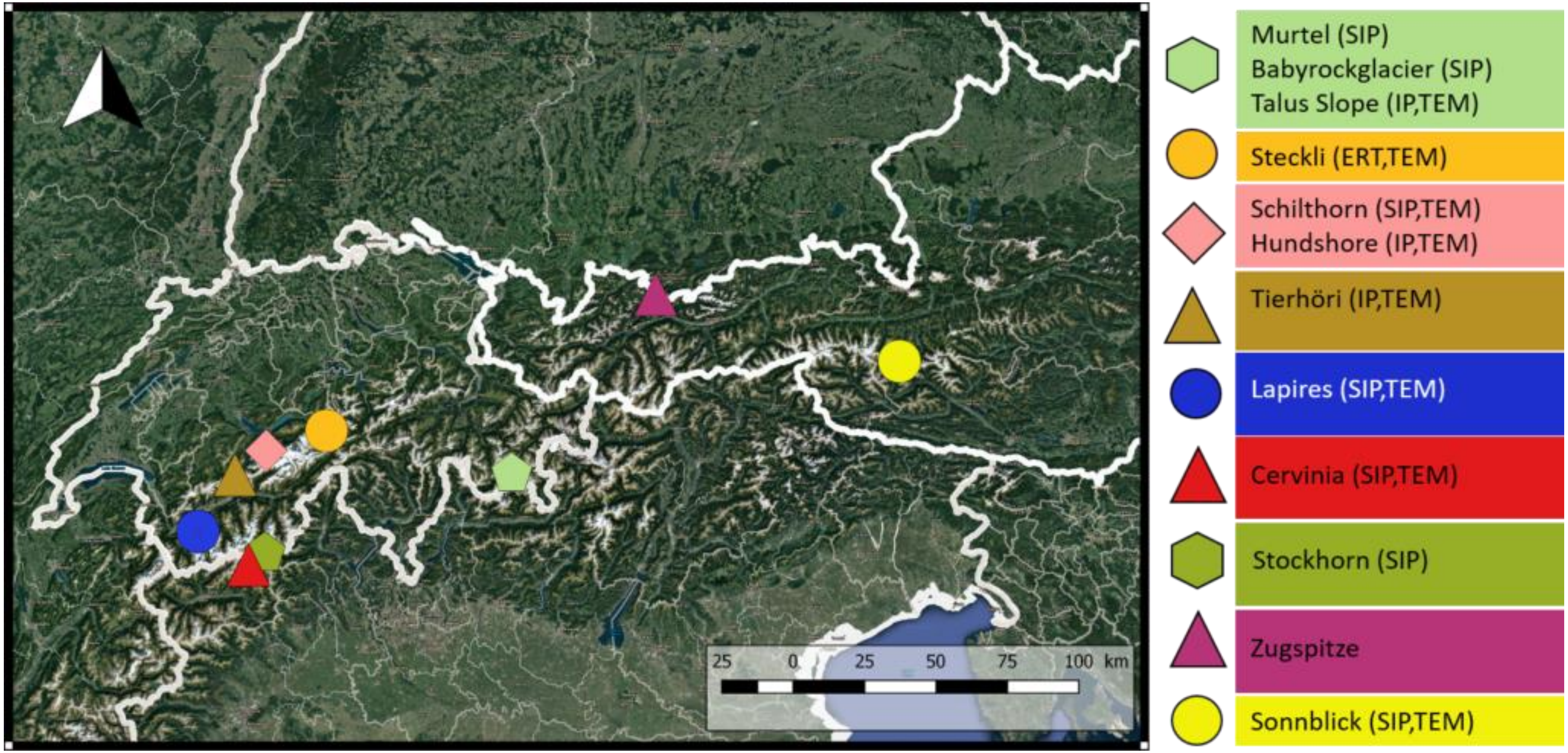
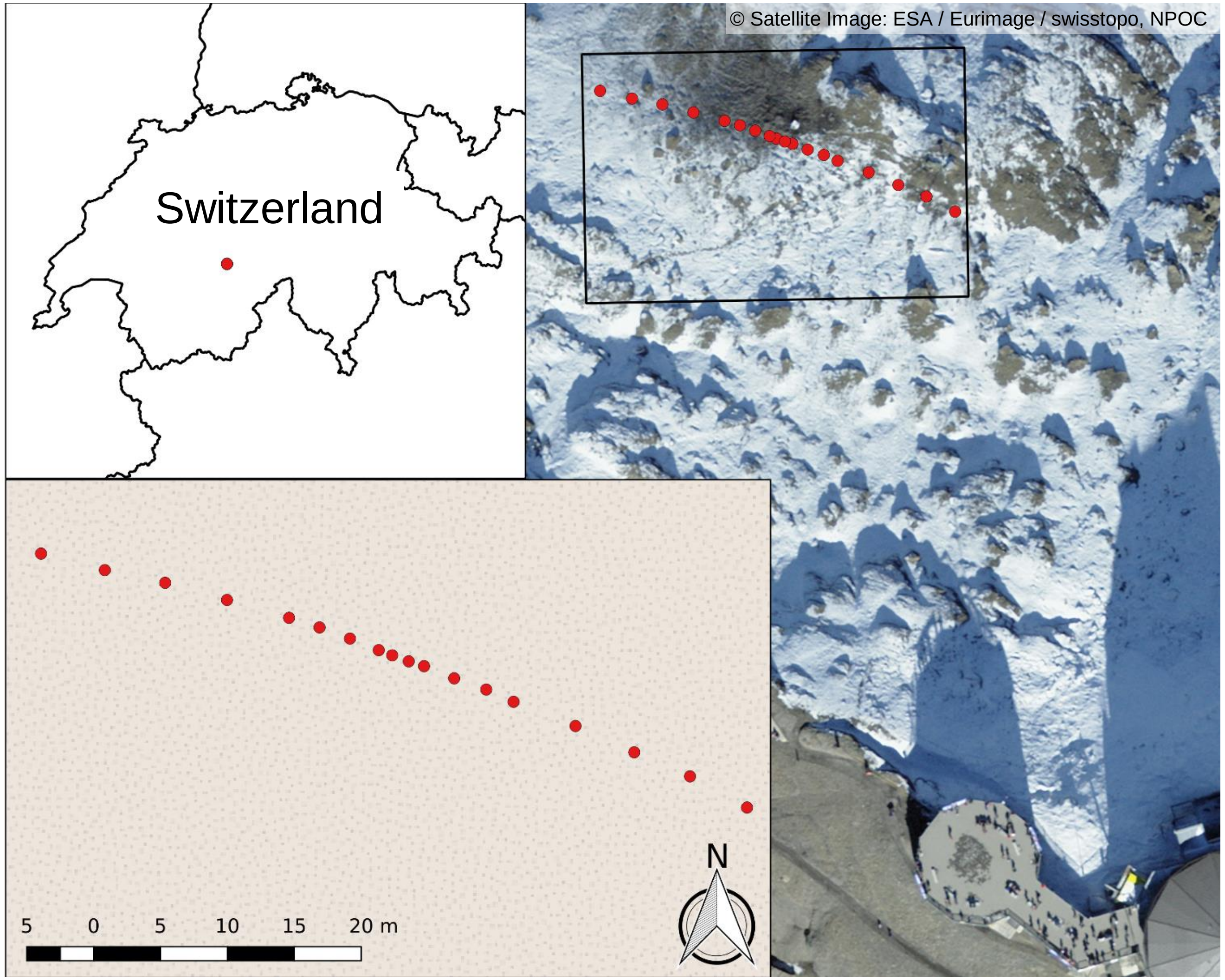


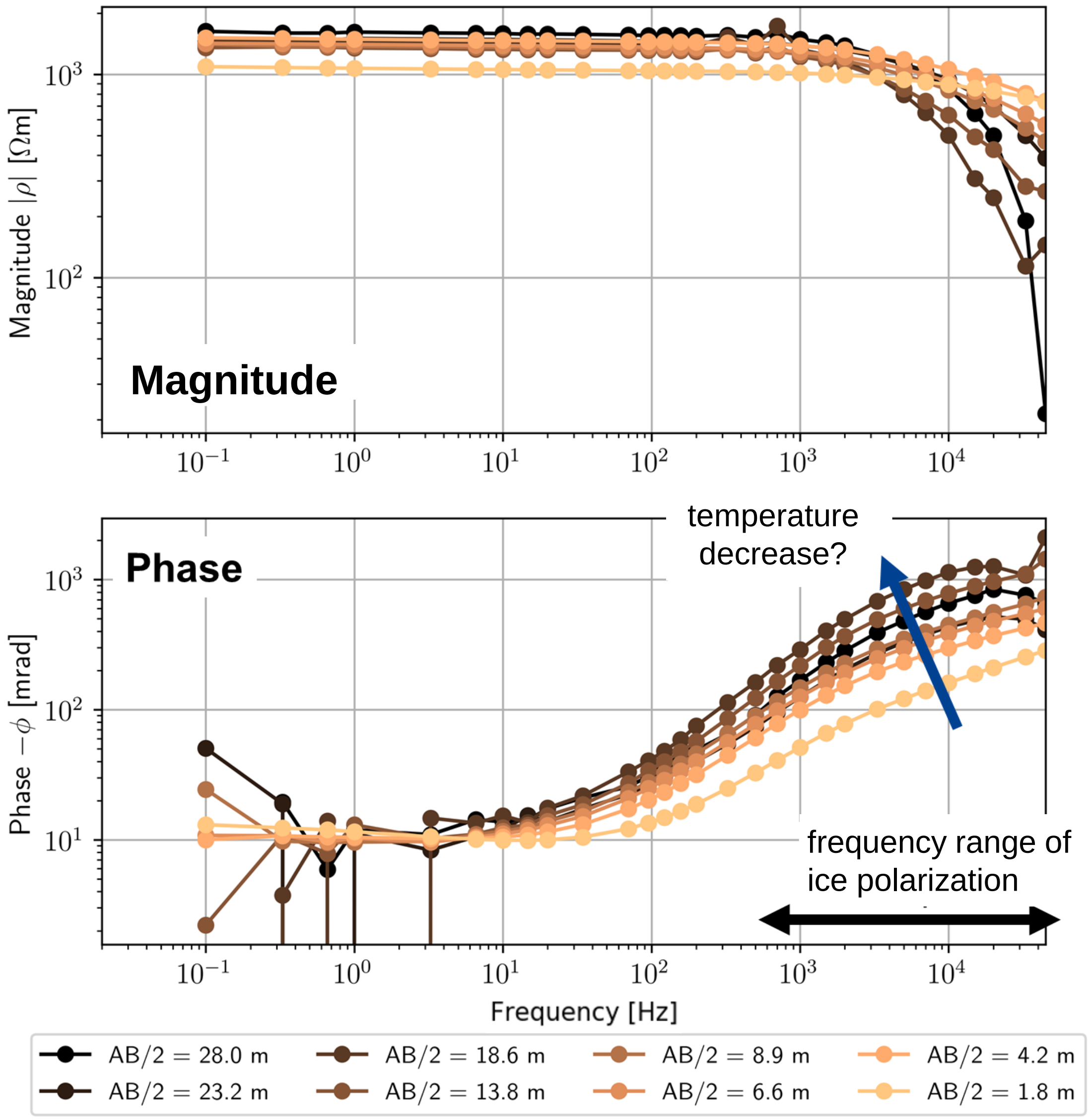

  

# SIP sounding measurements – Schilthorn, July 2019

- sEIT device: EIT40 (Zimmermann et al., 2008b)
- Frequencies: from 100 mHz to 45 kHz
- Schlumberger sounding with eight differentcurrent dipoles:
  - Minimal distance: 3.6 m (light spectra)
  - Maximal distance: 56 m (dark spectra)
- Distance of potential electrodes: 1.2 m
- Borehole temperatures during SIP measurements (PERMOS, unpublished data):
  - Active layer thickness of about 4 m
  - Slightly frozen below depth of 4m (about -1°C)



# Results of Schlumberger sounding at Schilthorn field site




## Resistivity

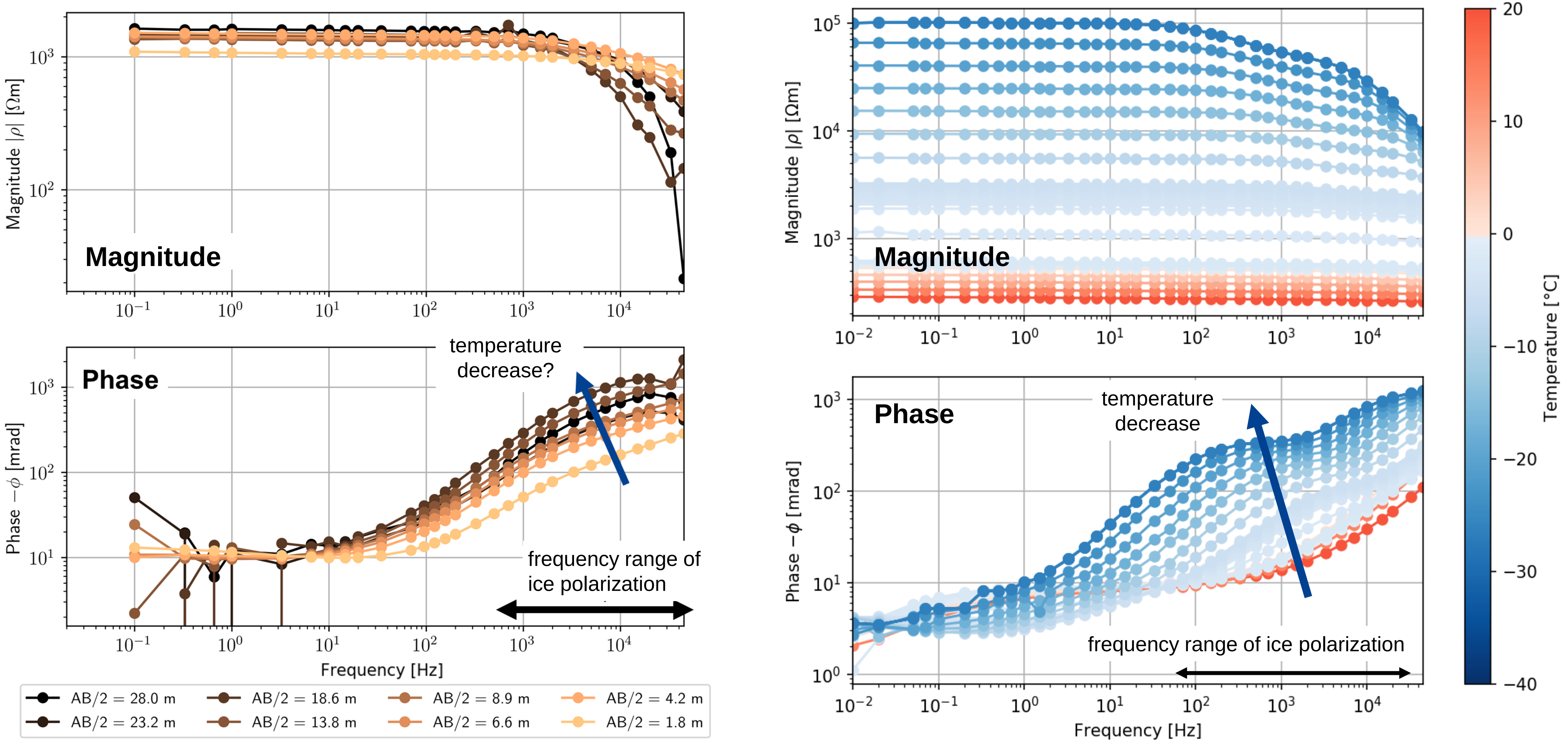
- Only small variations in resistivity magnitude with depth of investigation

## Phase

- Higher variations in resistivity phases with depth of investigation
- Increasing ice polarization for increasing depths of investigation

# Comparison of Schlumberger sounding and laboratory measurements



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**Frozen vs. non frozen:**

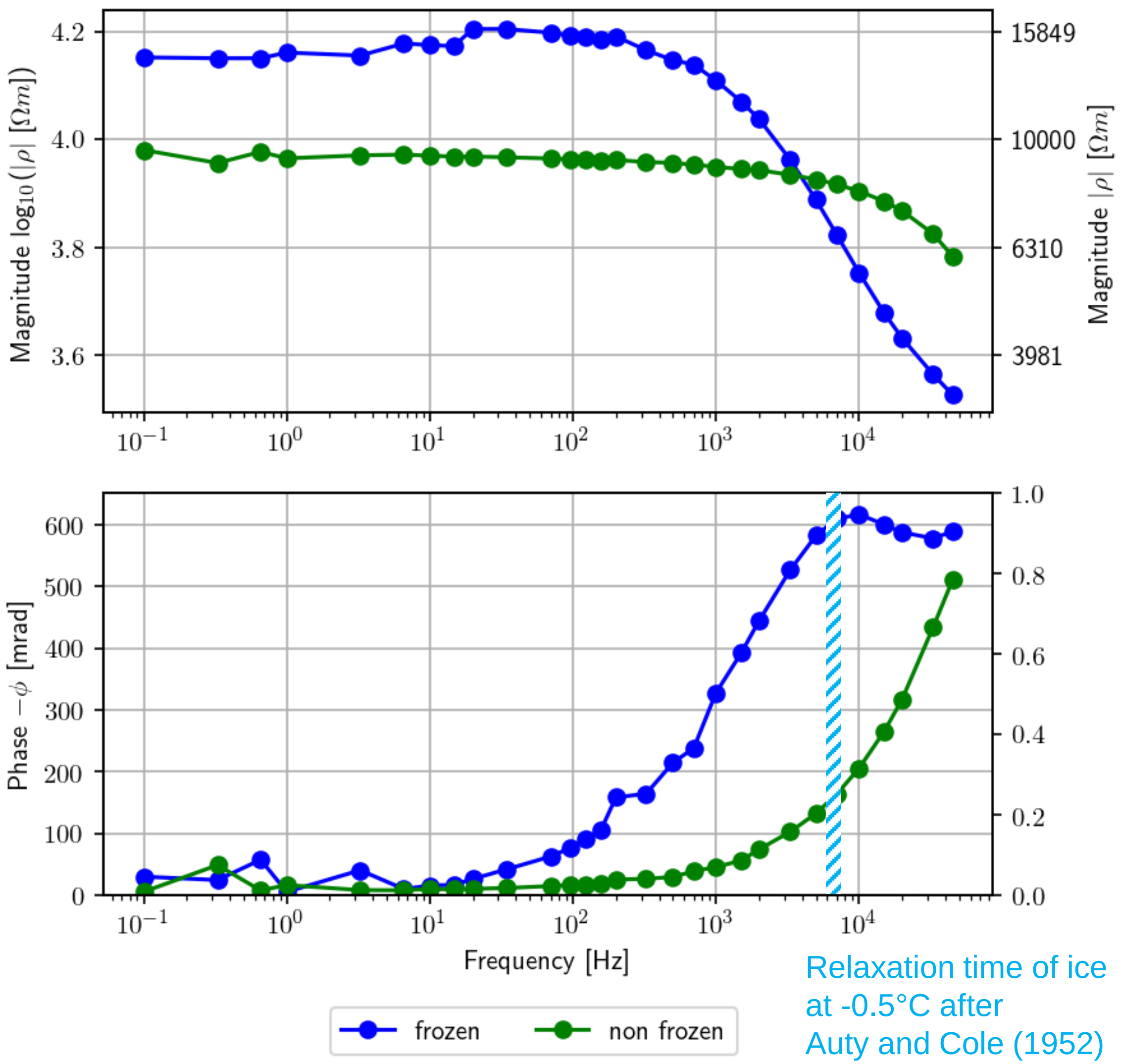
- 4-point measurements (Wenner).
- Non frozen and frozen (ice rich) parts in Kammstollen at Zugspitze.

**Resistivity**:

- Higher values in resistivity magnitude for frozen part.
- Lower values in resistivity magnitude for non frozen part.
- Values in good agreement to ERT monitoring data (e. g., Krautblatter et al. 2010) and to laboratory data.

**Phase**:

- Low frequency: More or less same values for both parts.
- High frequency: Additional polarization response for frozen (ice rich) part.
- Relaxation time of potential ice polarization response in good agreement with relaxation time of ice (Auty and Cole 1952).



**Wenner transect from frozen to non frozen:**

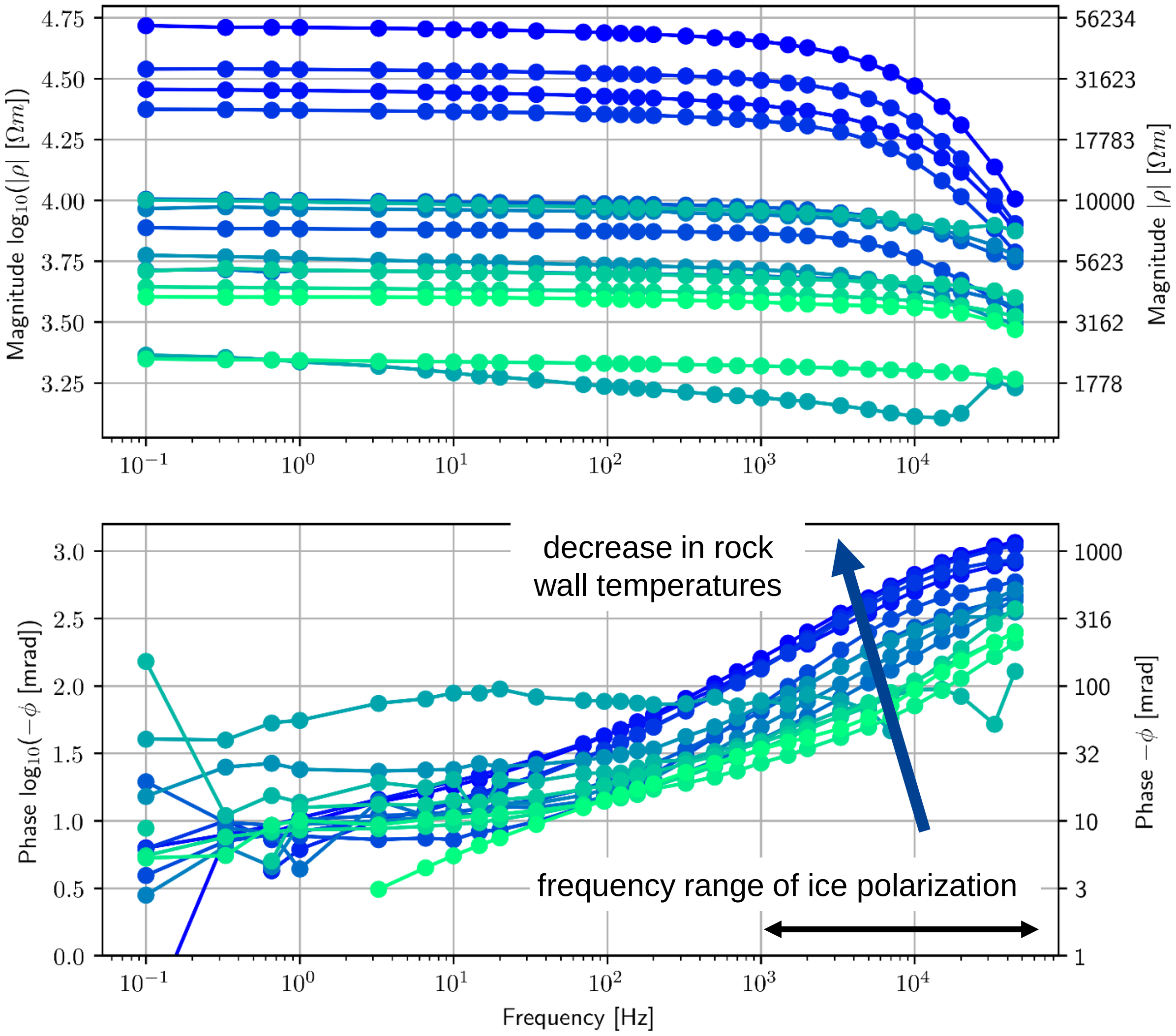
- Wenner measurements with constant geometry (a = 1.5 m).
- Moving from non frozen part (green spectra) to and frozen (blu
  Zugspitze.
- Total length of transect: 25.5 m.

**Resistivity**:

- Higher values in resistivity magnitude for frozen part.
- Lower values in resistivity magnitude for non frozen part.
- Values in good agreement to ERT monitoring data (e. g., Krau

**Phase**:

- Low frequency: no clear trend visible.
- High frequency: Increase in polarization with decrease in (expe



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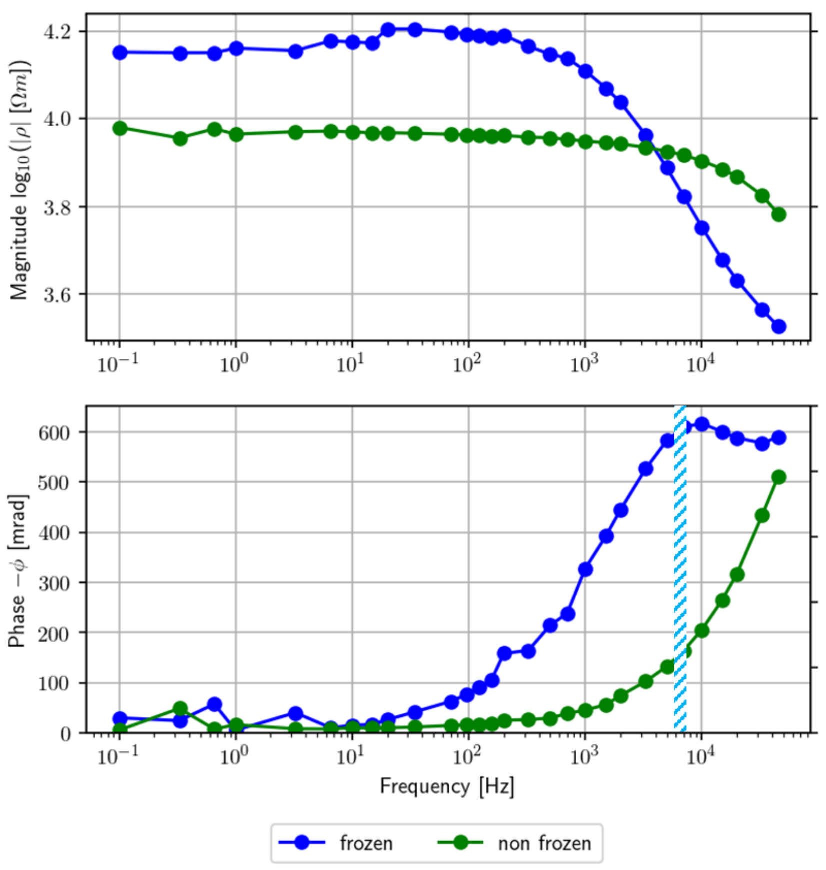
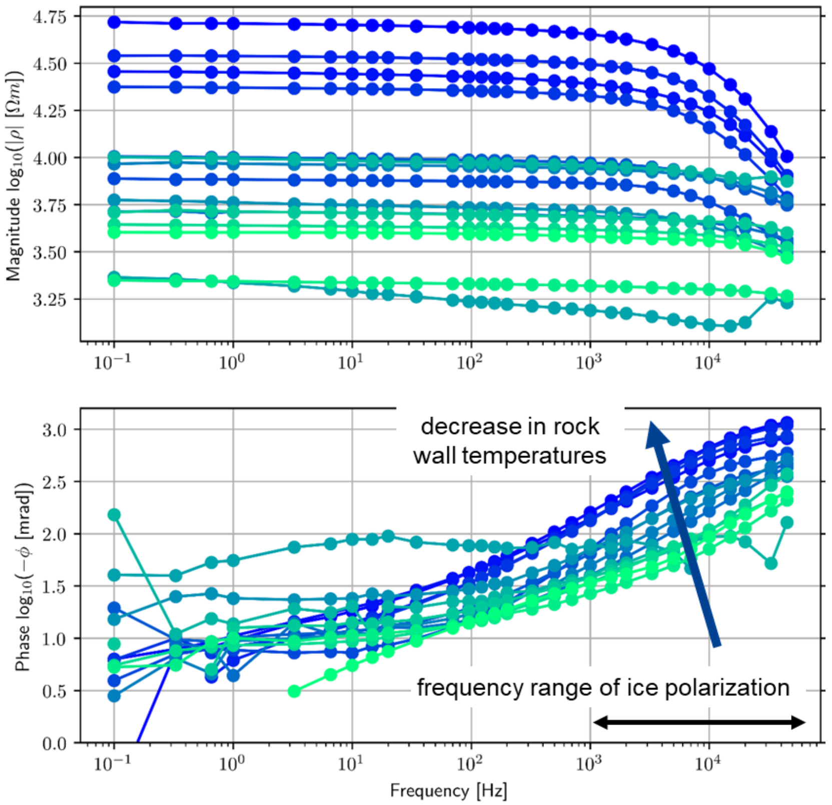
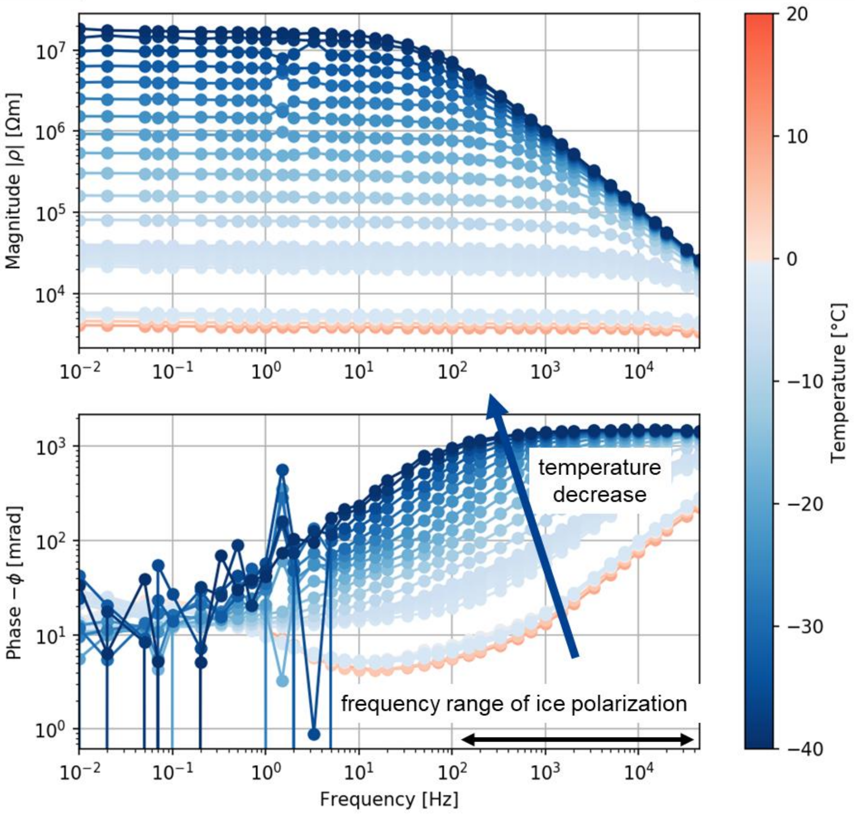
## Frozen vs. non frozen:




## Wenner transect:




## Laboratory data:



# Summary field measurements

**Schlumberger Sounding at Schilthorn:**

- SIP laboratory and field measurements show a similar temperature-dependent behavior.
- An increasing ice polarization with lower temperatures or greater depths of investigation can be observed.
- Using the independently measured temperature data, a systematic comparison of the SIP laboratory and field measurements indicates the possibility of a thermal characterization of the alpine permafrost site Schilthorn, using SIP.

**SIP measurements at Zugspitze:**

- SIP measurements show clear differences between frozen and non-frozen (ice rich) areas.
- In ice rich parts of the site, a clear ice polarization peak is observed.
- SIP laboratory and field measurements show a similar temperature-dependent behavior.
- Measurements in good agreement with ERT field measurements (e. g., Krautblatter et al. 2010)
- By comparing systematic SIP-laboratory and field measurements, a thermal characterization of the alpine permafrost site Zugspitze is possible.

# CONCLUSION AND OUTLOOK

# Conclusion and outlook

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**Conclusion:**

- For field and laboratory measurements, the resistivity magnitude shows a similar temperature dependence, with increasing resistivity magnitude for decreasing temperatures.
- For each sample, the resistivity phase spectra exhibit the well-known temperature-dependent relaxation behavior of ice at higher frequencies (1 kHz - 45 kHz), with an increasing polarization magnitude for lower temperatures or larger depths of investigation, respectively.
- At lower frequencies (1 Hz - 1 kHz), a polarization with a low frequency dependence is observed in the unfrozen state of the samples. We interpret this response as membrane polarization, considering that it decreases in magnitude with decreasing temperature (i.e., with ongoing freezing).
- By comparing systematic SIP laboratory and field measurements, a thermal characterization of alpine permafrost sites is possible.

**Outlook:**

- Quantification of the ice content using spectral polarization data.
- Tomographic measurements (sEIT) for thermal characterization in 2D.
- Application to other permafrost field sites (see also: Maierhofer et al. 2020 - CR2.1/HS1.1.6/SM4.16)

  

The presented work is part of the project:

**„Improved ice quantification at alpine permafrost sites based on electrical and electromagnetic measurements of spectral induced polarization "**

Further information on the project is available at: **www.sip-in-ice.eu**

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