UNIVERSITÄT BONN

EGU21-14273:

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

**Jonas K. Limbrock, Maximilian Weigand, and Andreas Kemna**

University of Bonn, Institute of Geosciences, Geophysics Section, Germany
Contact: limbrock@geo.uni-bonn.de

**EGU General Assembly 2021 - Session EMRP1.15**

**https://doi.org/10.5194/egusphere-egu21-14273**

UNIVERSITÄT BONN

Just click for an easy and direct navigation

## Introduction

- Motivation and expected SIP behavior

## Laboratory setup

## Results

- Temperature dependence of DC-resistivity
- SIP results: unfrozen thermal state
- SIP results: (partially) frozen thermal state
- Summary of laboratory measurement results

## Conclusions and outlook

## Literature

# Motivation

- 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).

- Electrical subsurface properties are sensitive to the phase change of water, from liquid to frozen. Thus, geoelectrical methods are increasingly used for non-invasive characterization and monitoring of permafrost sites.

- In this context, electrical subsurface parameters act as proxies for temperature and ice content.

- However, geoelectrical measurements are subject to strong ambiguities. For example, ice and air act as good electrical insulators and electrical resistances show a distinct temperature dependence.

**Research question**

**Is an improved ice quantification at alpine permafrost sites based on spectral induced polarization (SIP) measurements possible?**

# Expected behavior of SIP signatures during freezing and thawing

**For the unfrozen thermal state: Electrochemical polarization in the liquid pore water in the vicinity of charged interfaces**

- Well known relationship between time scale and length scale of polarization.
- For example, after Schwarz (1962) and Revil et al. (2012) for the polarization around charged spherical mineral grain:

$$r = \sqrt{2\,\tau\,D_{(+)}}.$$

**Parameters**

$r$: pore radius
$\tau$: relaxation time
$D_{(+)}$: diffusion coefficient of the counter-ions in the Stern layer

**For the (partially) frozen thermal state: Polarization in the ice crystal lattice**

- Ice has a characteristic polarization signature with a well known temperature dependence (e. g., Auty and Cole 1952, Fabbri et al., 2006, Stillman et al., 2010).
- The spectral response partially falls into the SIP measurement range (100 Hz to 10 kHz).

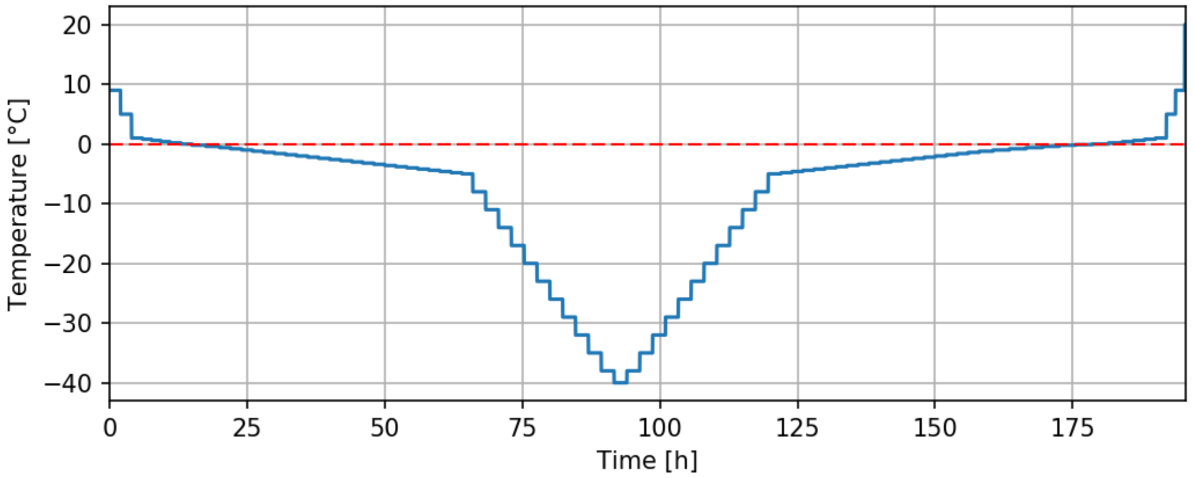
**Research questions**

1. **Can we also observe these effects in laboratory SIP measurements of solid rock samples during controlled freeze-thaw cycles?**
2. **Can the different polarization effects be separated from each other in the measured SIP signatures?**
3. **Can we quantify the ice content (of permafrost) using SIP measurement?**

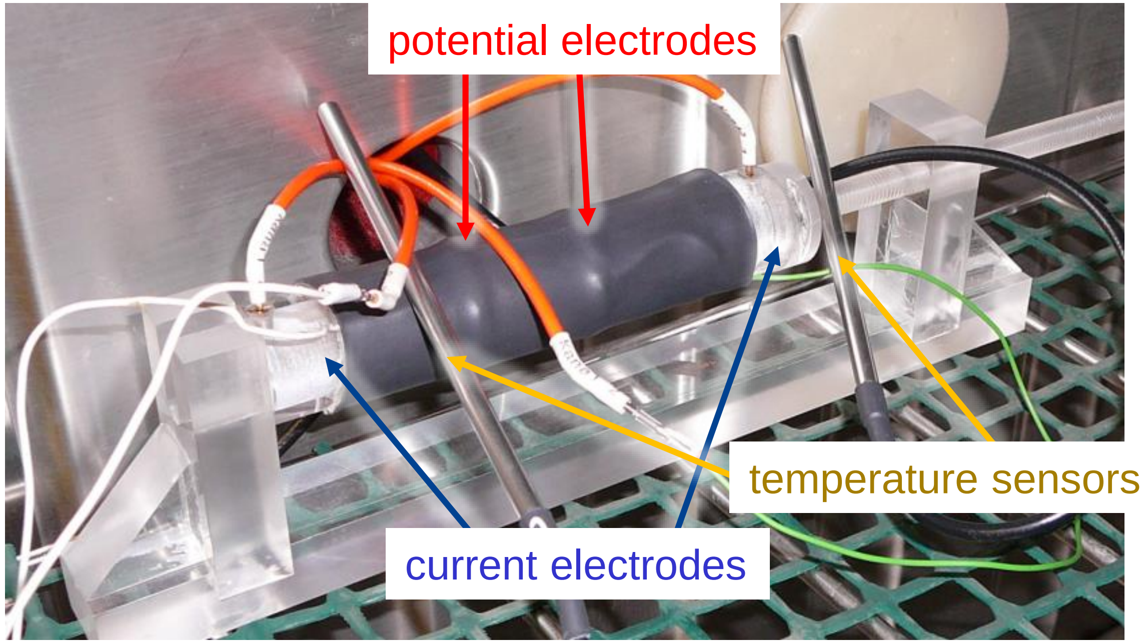
# Laboratory SIP setup

**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 temperature step: between 120 and 180 minutes




**Sample preparation and measurement geometries:**
- Sample cylinders
  - Length: 9 - 10 cm
  - Diameter: 3 cm
  - Potential electrodes: ring electrodes
  - Distance between potential electrodes: 3 cm
  - Current electrodes: plate electrodes
- Saturated with water and sealed in shrinking tube

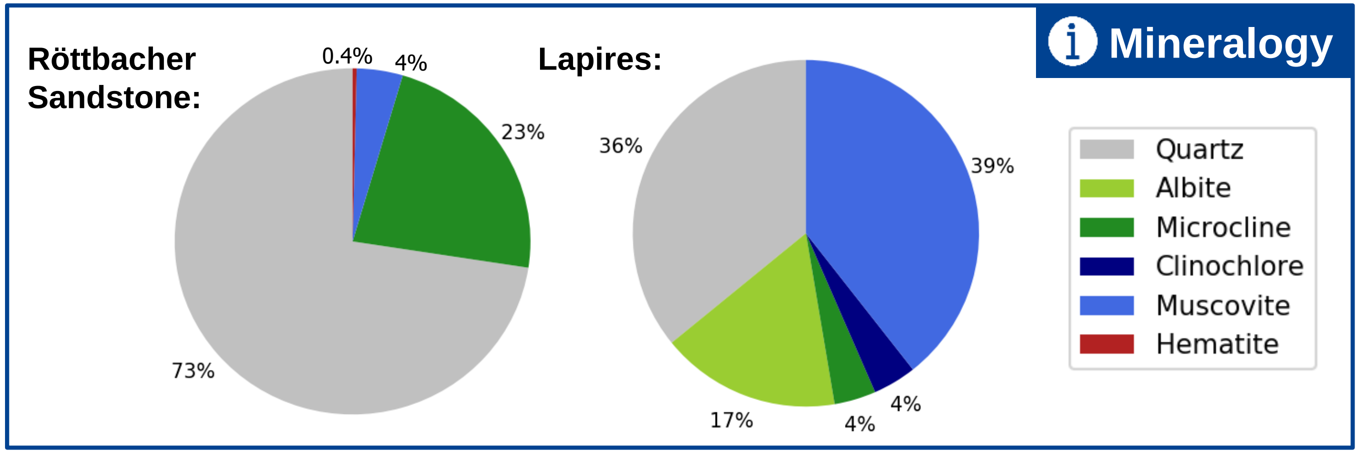


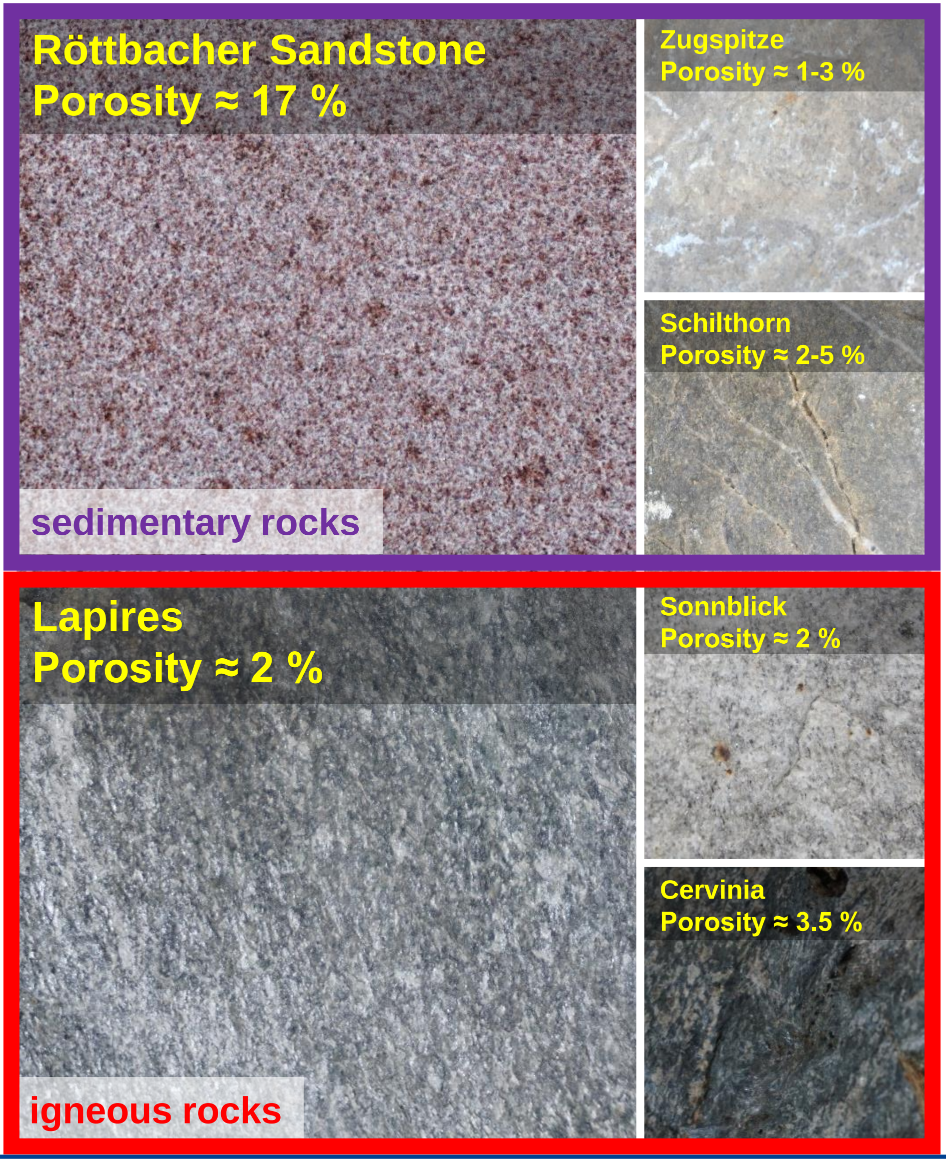
**Samples:**

- Solid rock samples from five alpine permafrost sites plus one additional sandstone in total.
- Here, we present the results of two samples:
  - Röttbacher Sandstone
  - Granite from alpine permafrost site Lapires

**Additional petrological and petrophysical characterization:**

- Hg-porosimetry: Porosity and pore size distribution (PSD)
- Electrophoresis: Zeta potential
- X-ray diffraction(XRD): Mineralogy

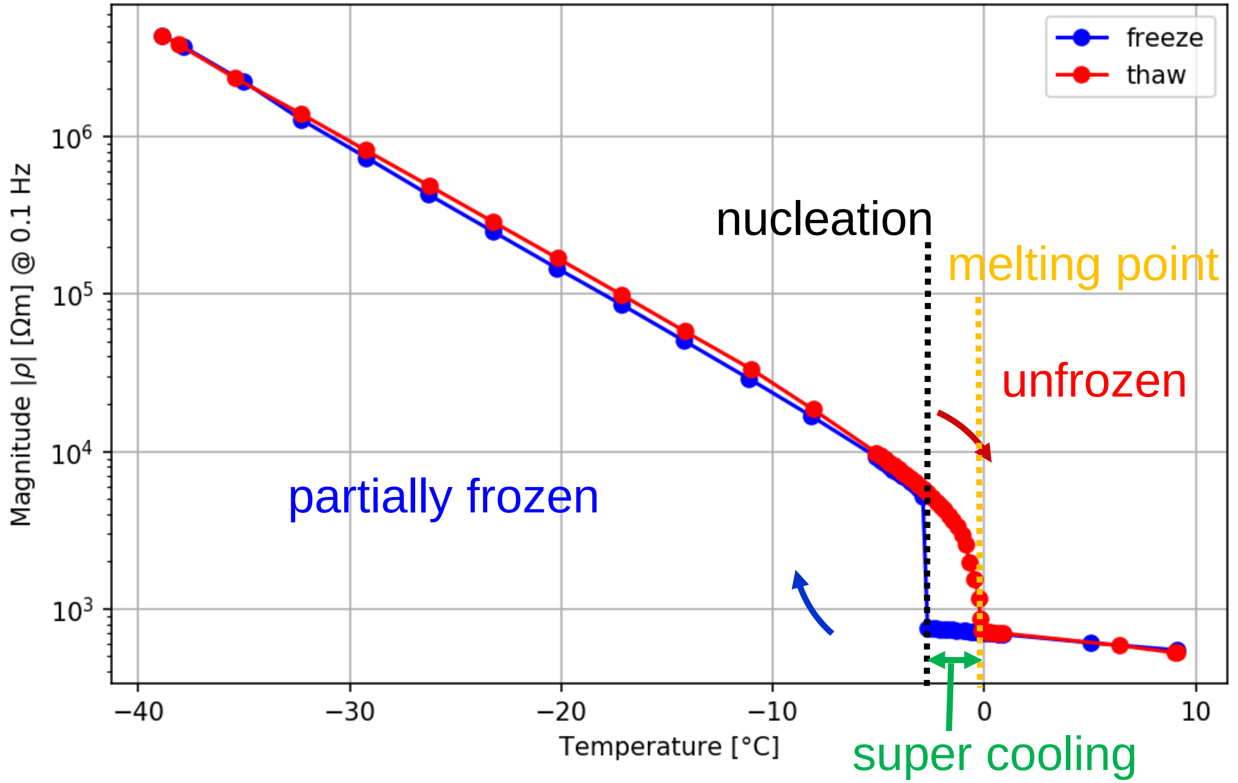


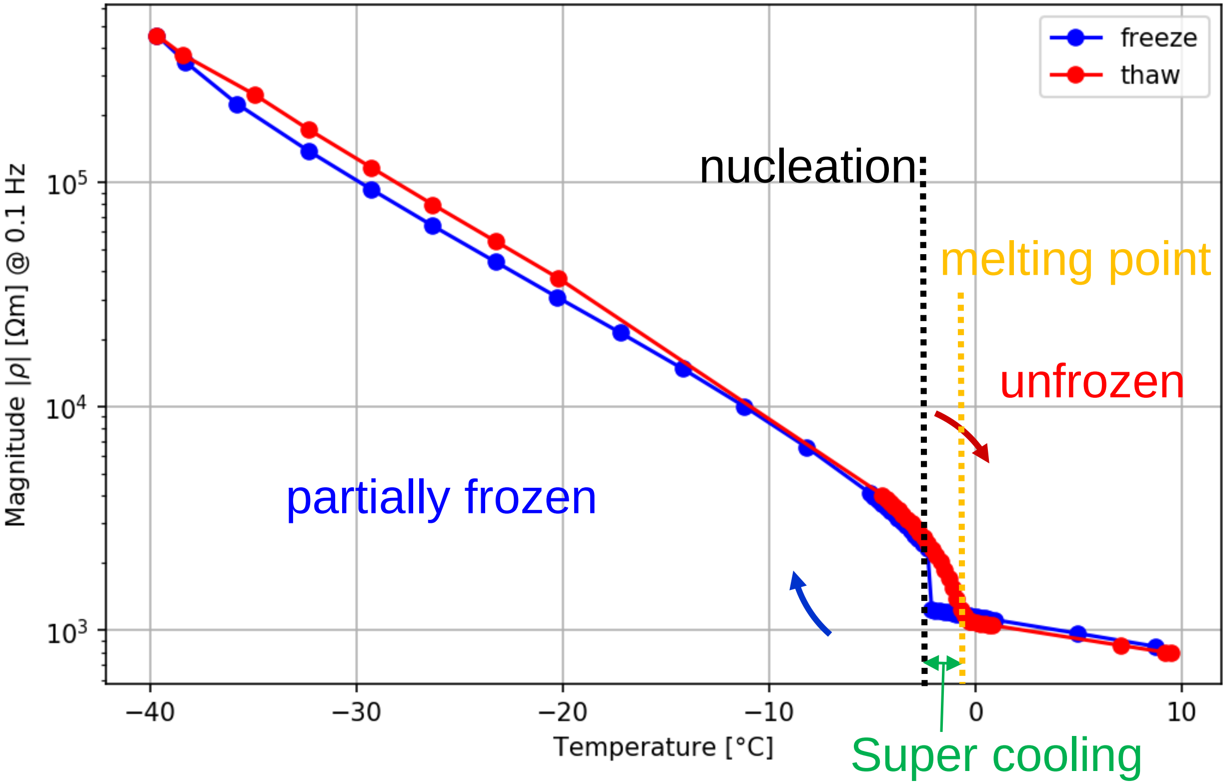
# Temperature dependence of DC-resistivity

UNIVERSITÄT BONN

## Röttbacher Sandstone




## Lapires granite



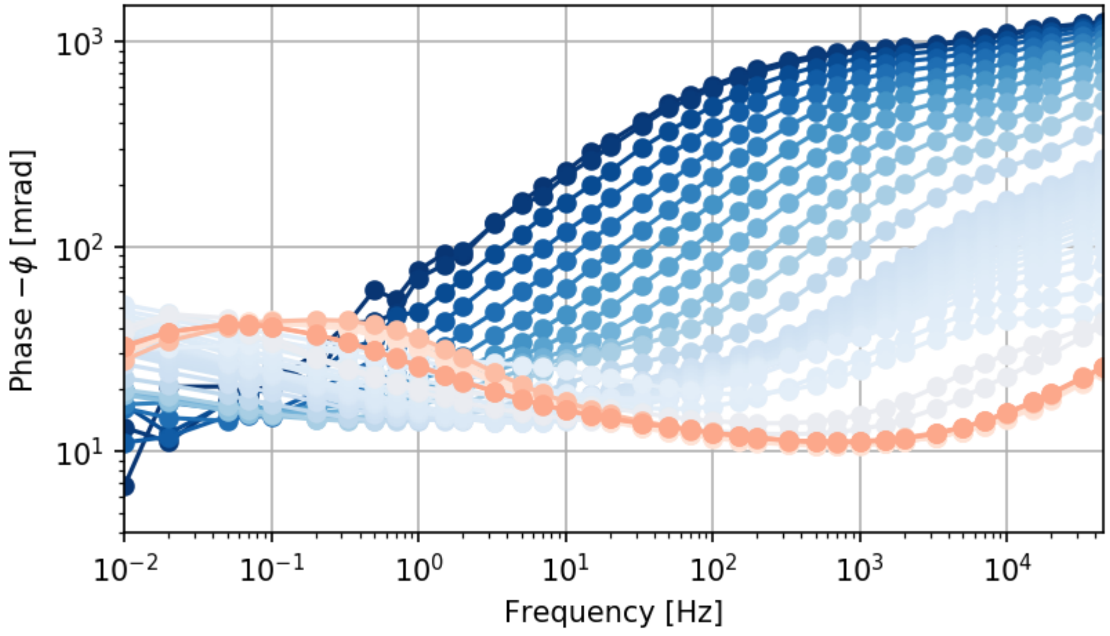

**Observations for both samples**

- Well-known temperature dependence for frozen and (partially) frozen state
- Super cooling and nucleation observed during freezing
- Melting point depression observed during thawing

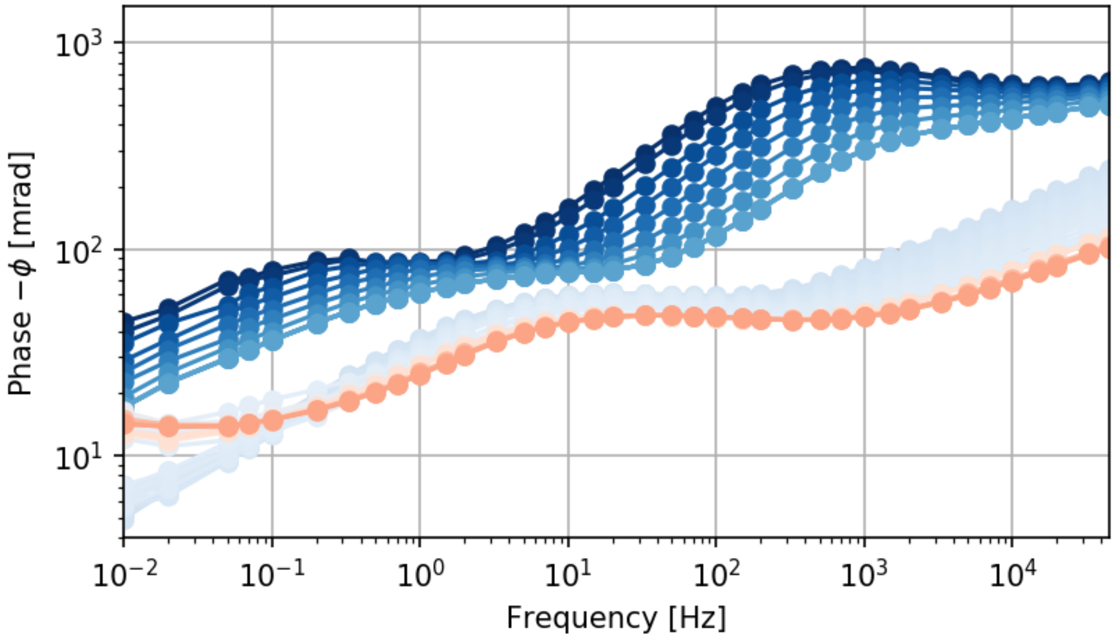
**DC-resistivity $\rho_{DC}$ depends on**

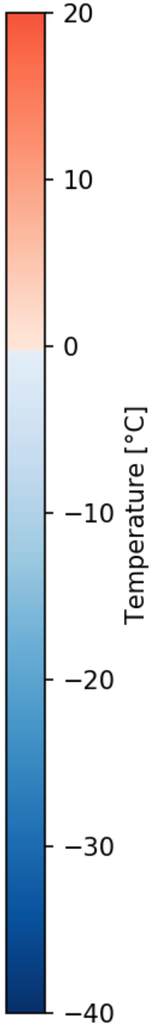
- Porosity, PSD and (residual) water content
- Pore fluid conductivity
- Temperature

### Röttbacher Sandstone




### Lapires granite




**Resistivity phase of unfrozen SIP signatures**

- Significant different phase spectra for both samples.
- Relaxation behavior is only slightly temperature-dependent.
- Unfrozen and (partially) frozen state can be distinguished in the phase values.

# Spectral analysis for unfrozen thermal state: Debye decomposition

UNIVERSITÄT BONN

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

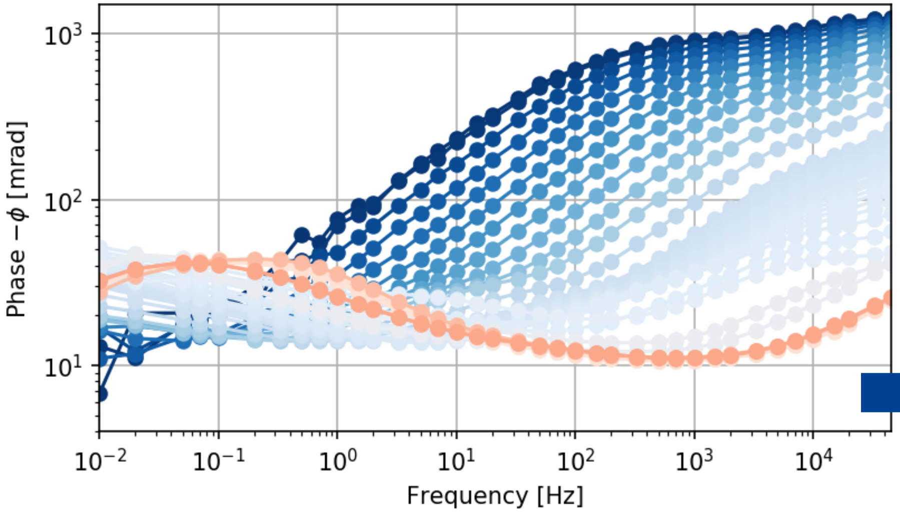
$$\hat{\rho}(\omega) = \rho_0 \left(1 - \sum_{k=1}^{N_\tau} m_k \left[1 - \frac{1}{1 + j\omega\tau_k}\right]\right)$$

results on relaxation time distribution (RTD) $m(\tau)$ of each spectrum with the following characteristic parameters:
$m_{\mathrm{tot}}$, $\tau_{\mathrm{peak}}$ and $\tau_{\mathrm{mean}}$.

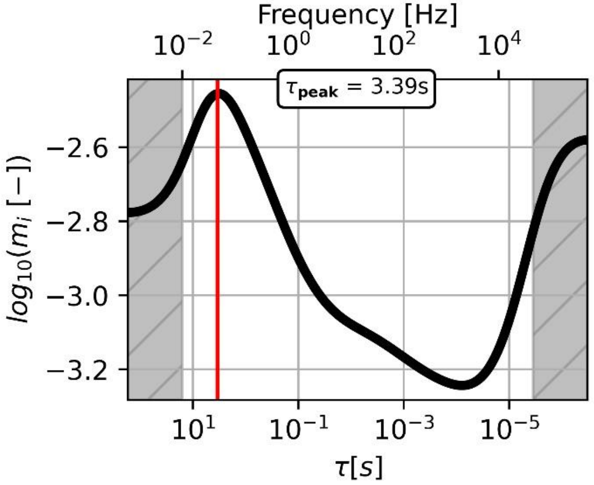
**Parameters**

$\hat{\rho}(\omega)$: complex resistivity
$\rho_0$: DC resistivity
$m_k(\tau_k)$: chargeability
$\tau_k$: relaxation time
$m_{\mathrm{tot}} = \sum_{k=1}^{N_\tau} m_k$: total chargeability
$\tau_{\mathrm{peak}}$: local maximum of RTD
$\tau_{\mathrm{mean}} = \exp\left(\sum_{k=1}^{N_\tau} m_k \log(\tau_k) \,/\, \sum_{k=1}^{N_\tau} m_k\right)$: mean relaxation time

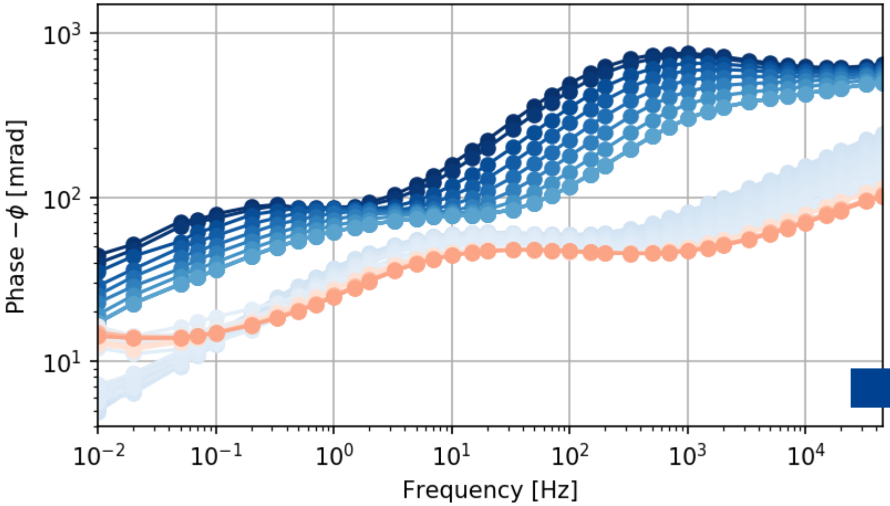
**Röttbacher**

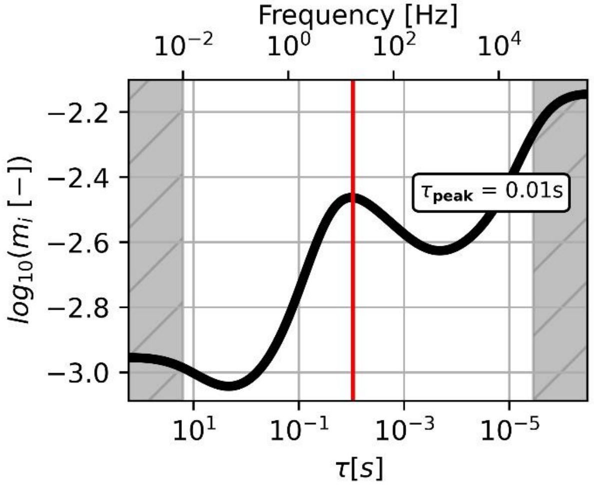



**Relaxation time distributions:**




**Lapires**

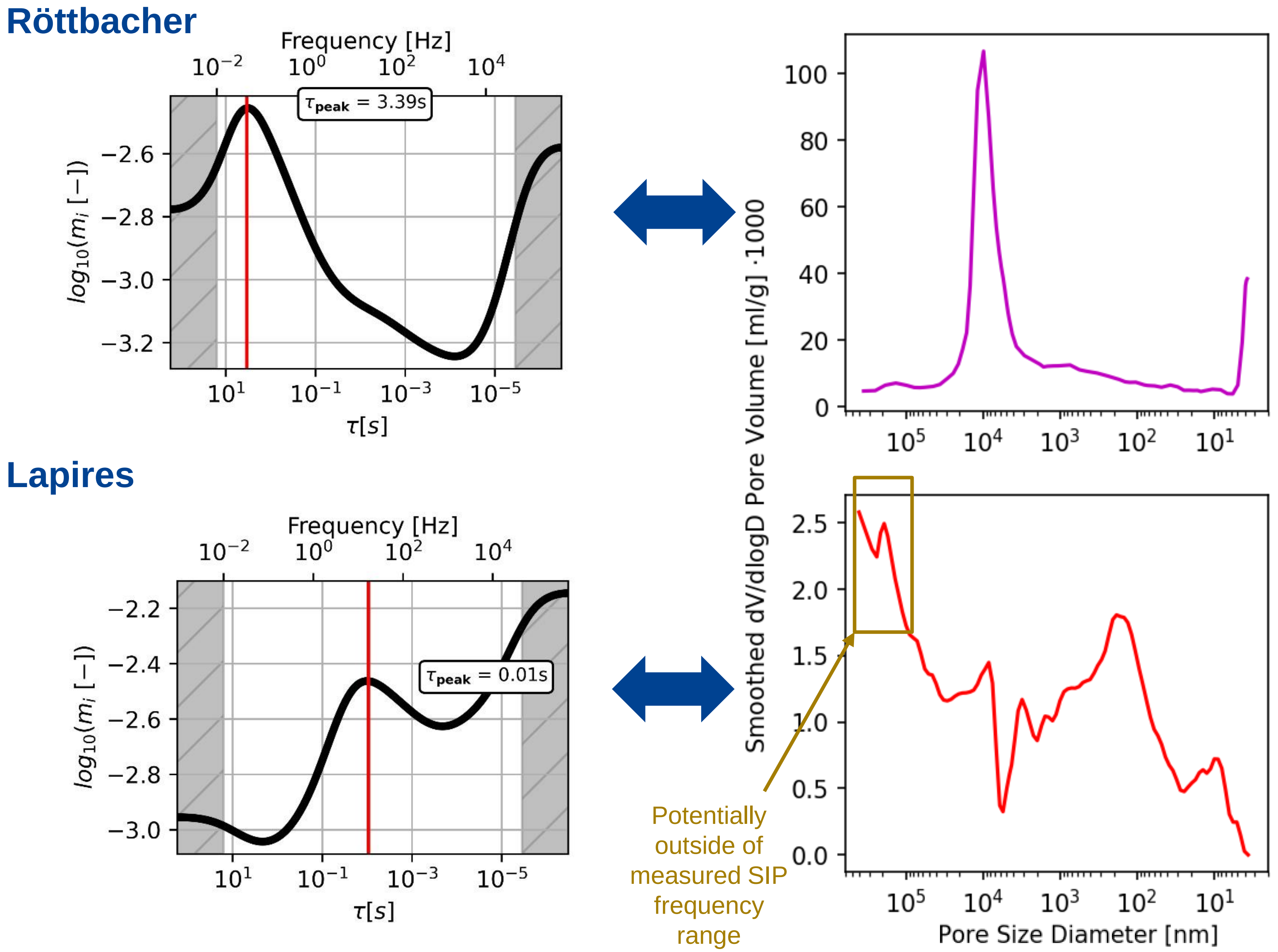


# Comparison of relaxation time distributions and pore size distributions

**Relaxation time distributions:**

**Pore size distributions:**

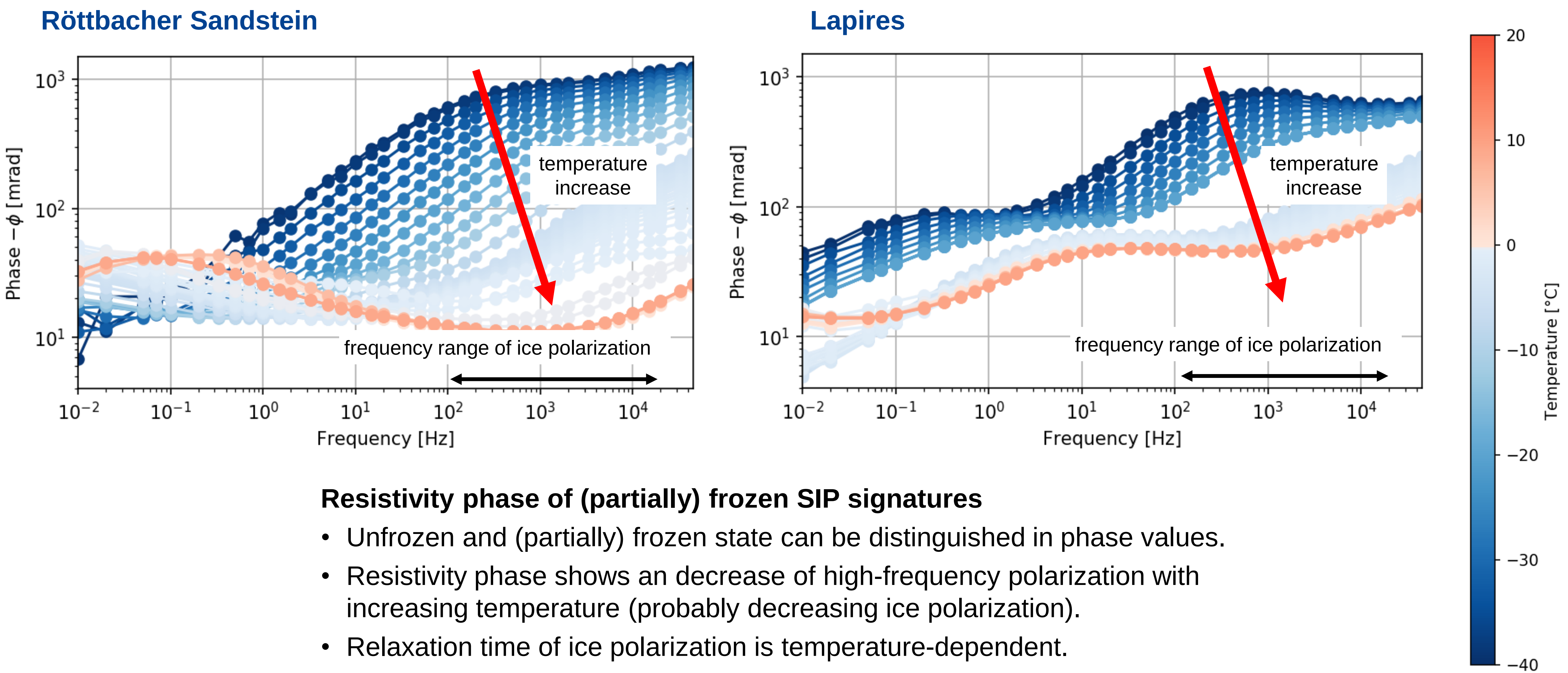



**Qualitative comparison:**

- Röttbacher Sandstone:
  - Distinct single peak, both in RTD and PSD
- Lapires:
  - Wider PSD and wider RTD
  - One dominating relaxation time $\tau_{\text{peak}}$ and one dominating pore size (peak at around $10^2\ nm$
  - These two dominant peaks are shifted by approx. two decades, compared to the Röttbacher Sandstone

➔ **RTD and PSD show similar patterns**

# SIP phase spectra (thawing) – (partially) frozen thermal state




**Resistivity phase of (partially) frozen SIP signatures**

- Unfrozen and (partially) frozen state can be distinguished in phase values.
- Resistivity phase shows an decrease of high-frequency polarization with increasing temperature (probably decreasing ice polarization).
- Relaxation time of ice polarization is temperature-dependent.
- Same patterns for both samples.

# Spectral analysis for (partially) frozen samples: Cole-Cole model fits

Multi term Cole-Cole model for permittivity $\varepsilon^*$ after Stillman et al. (2010):

$$\varepsilon^* = \varepsilon_\infty + \sum_k \frac{\Delta\varepsilon_k}{1 + (i\omega\tau_k)^{c_k}} - \frac{i\,\sigma_{DC}}{\varepsilon_v \omega}.$$

For electrical conductivity $\sigma^* = i\,\omega\,\varepsilon_v\,\varepsilon^*$, this model can be formulated for electrical conductivity as:

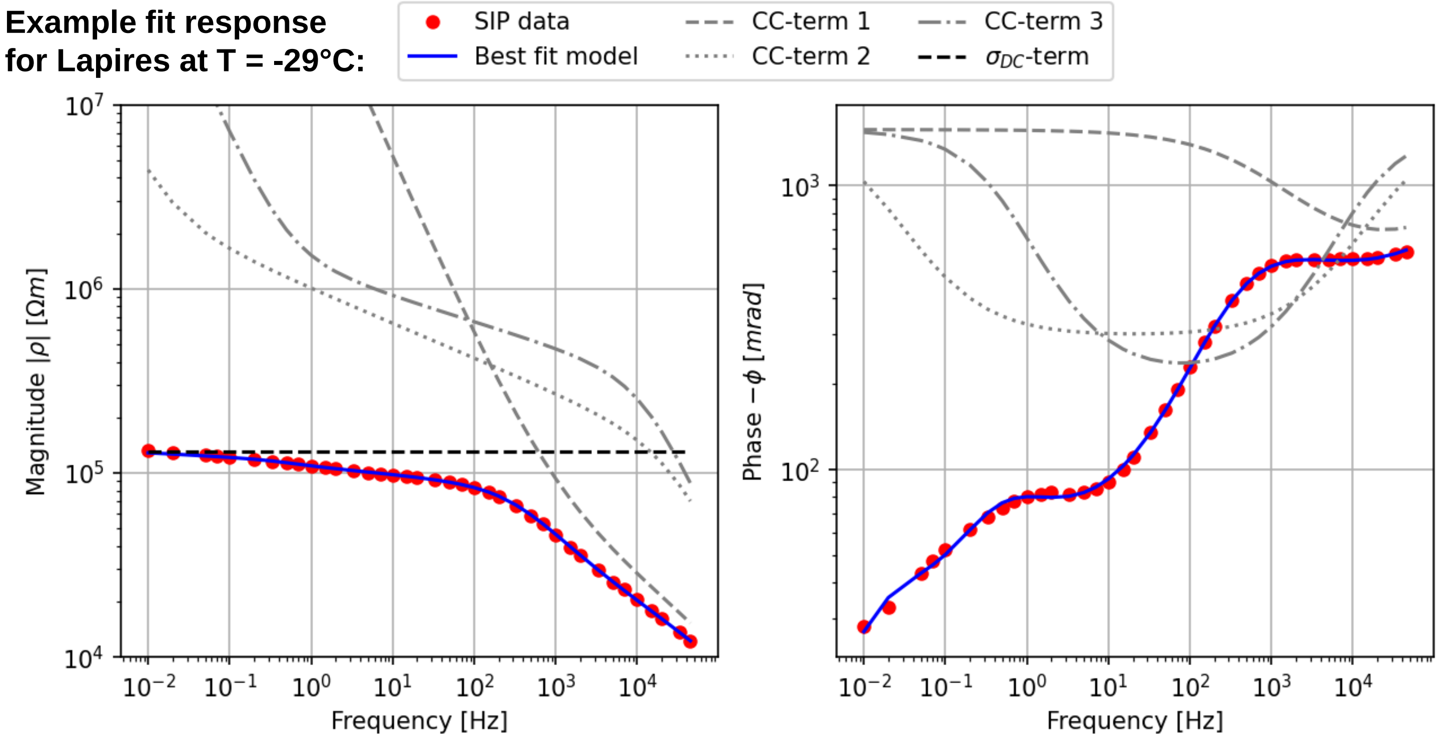
$$\sigma^* = \sigma_{DC} + i\,\omega\,\varepsilon_v \left[\sum_k \frac{\Delta\varepsilon_k}{1 + (i\omega\tau_k)^{c_k}} + \varepsilon_\infty\right].$$

And for electrical resistivity $\rho^* = \frac{1}{\sigma^*} = \frac{1}{i\,\omega\,\varepsilon_v\,\varepsilon^*}$, the resulting Cole-Cole model can be formulated as:

$$\rho^* = \left(\sigma_{DC} + i\,\omega\,\varepsilon_v \left[\sum_k \frac{\Delta\varepsilon_k}{1 + (i\omega\tau_k)^{c_k}} + \varepsilon_\infty\right]\right)^{-1}.$$

A fitting routine for this last formulation was implemented using the non-linear least squares solver of the SciPy Python package.

**Example fit response for Lapires at T = -29°C:**




$\varepsilon_\infty$: high-frequency asymptote of permittivity
$\Delta\varepsilon = \varepsilon_0 - \varepsilon_\infty$
$\varepsilon_0$: low-frequency asymptote of permittivity
$\tau$: relaxation time
$\varepsilon_v$: permittivity of vacuum
$c$: Cole-Cole exponent
$\sigma_{DC}$: DC conductivity

**Parameters**

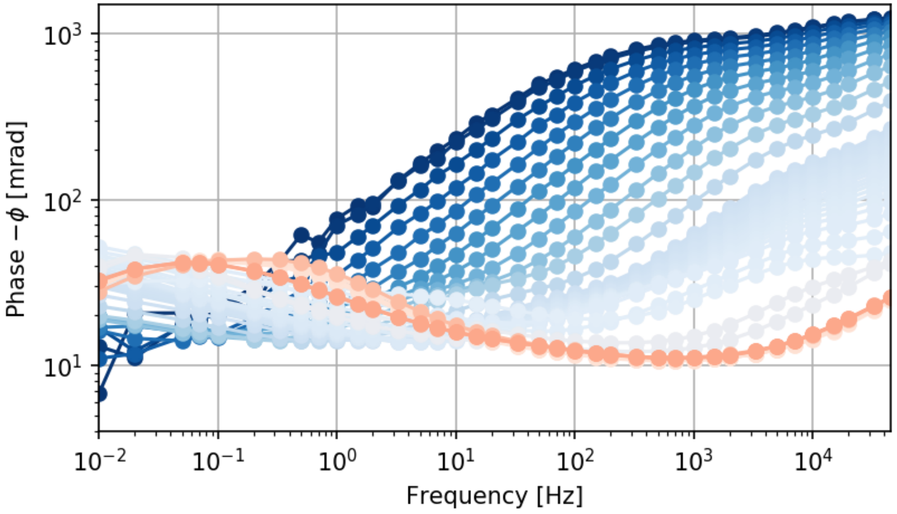
## Results of Cole-Cole fit

SIP-data from (partially) frozen state can be fitted by a Cole-Cole model with three terms: One high-frequency term and two low-frequency terms.

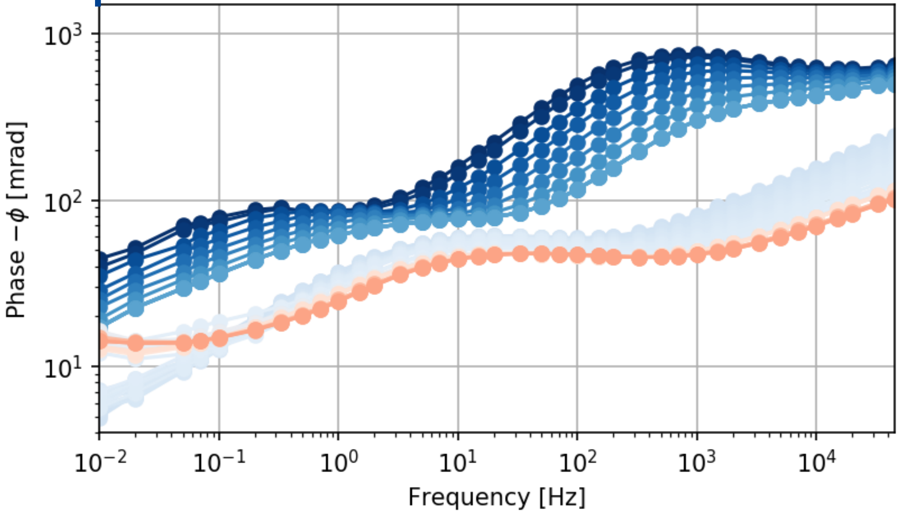
**Is the high-frequency polarization caused by ice?**

# Temperature dependence of ice polarization

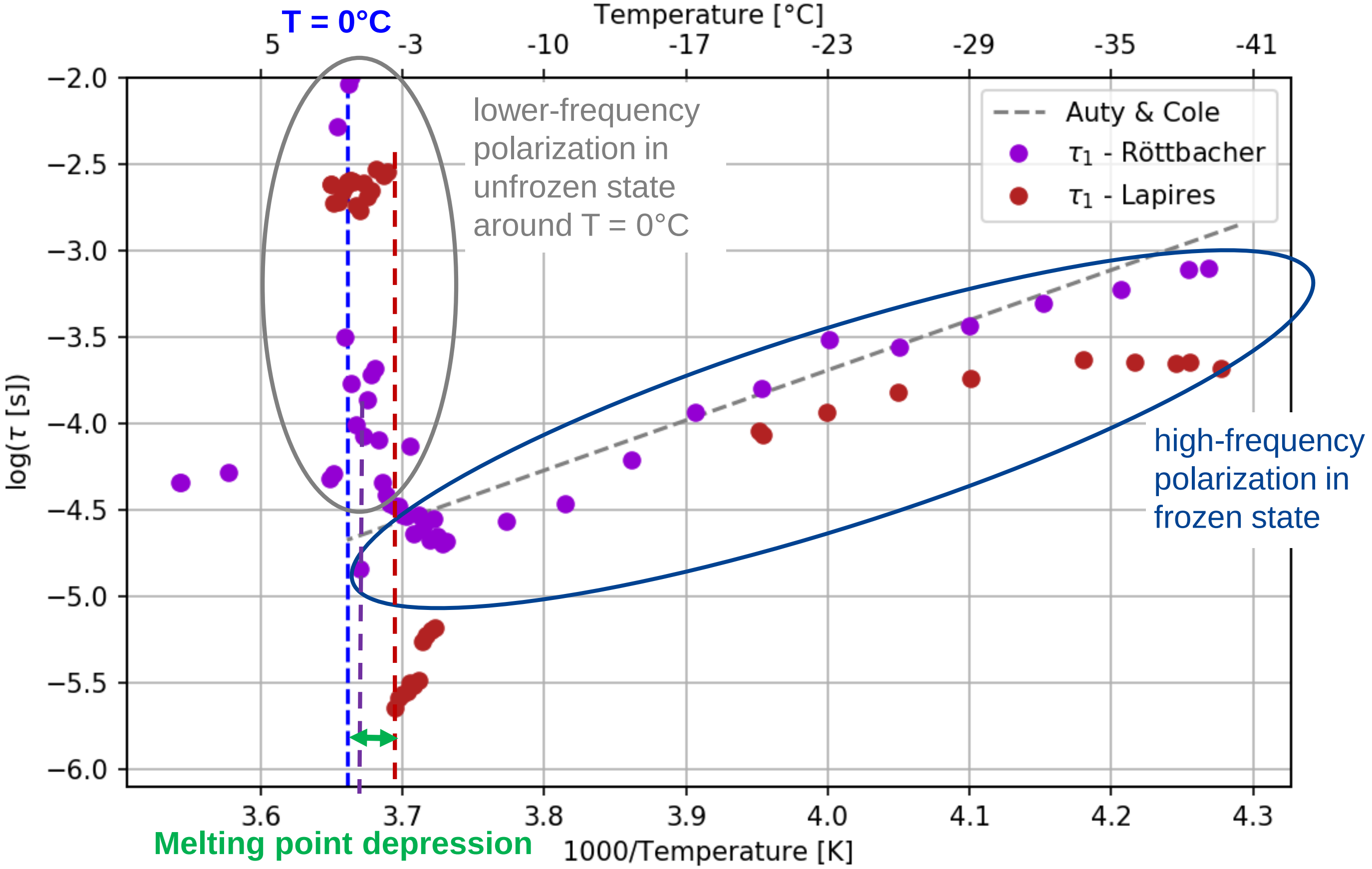
## Röttbacher




## Lapires




Comparison of temperature dependent $\tau_1$ for both solid rock sample with well-known temperature dependent relaxation time of ice (Auty and Cole, 1952):




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

# Summary of laboratory measurement results

UNIVERSITÄT BONN

**General SIP behavior**

- DC-Resistivity:
  - Generally, both samples show the same temperature-dependent behavior.
  - Differences in absolute values and curvature around freezing point for different lithologies observed.
- Resistivity phase:
  - Similar temperature dependence and similar ice polarization response for different lithologies observed.
  - Clear distinction between frozen and unfrozen states is possible.

**SIP spectra in the unfrozen thermal state**

- Relaxation time distribution significantly controlled by pore radius distribution.
- This matches our expectation and shows the plausibility of our SIP measurement results.

**SIP spectra in the (partially) frozen thermal state**

- Qualitative detection of ice possible.
- High-frequency measurements (> 100 Hz) necessary.
- Relaxation behavior of the ice independent of mineralogy and texture

**Conclusions:**

- The temperature-dependent SIP behavior of the **unfrozen thermal state** is also **dependent of lithology**.
- The temperature-dependent SIP behavior of the **(partially) frozen thermal state** is **independent of lithology**.

- SIP response of the ice is **suited for thermal state characterization** and a qualitative **detection of ice.**
- **Independent information** is required for detailed signature understanding and calibration.
- By comparing systematic SIP laboratory and field measurements, a thermal characterization of alpine permafrost sites is possible.

**Outlook:**

- Cryo-NMR measurements for validation.
- Modeling of the presented temperature-dependent SIP measurements.
- Quantitative estimation of ice content from SIP measurements.
- Application to field data for thermal characterization and ice content estimation of alpine permafrost sites.

**Further reading**

Laboratory measurements from additional samples:

- Cervinia: Maierhofer et al. (2021) - EGU21-14598, Session CR6.1
- Schilthorn and Zugspitze: Limbrock et al. (EGU 2020)

Application to permafrost field sites:

- Cervinia: Maierhofer et al. (2021) - EGU21-14598, Session CR6.1
- Schilthorn and Zugspitze: Limbrock et al. (EGU 2020)

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**

Contact: **limbrock@geo.uni-bonn.de**

**Acknowledgments:**

For support in laboratory: Georg Nover and Johanna Braun

**The presented work is funded by:**

DFG Deutsche Forschungsgemeinschaft

gefördert durch Cusanuswerk Bischöfliche Studienförderung

## Introduction

- Motivation and expected SIP behavior

## Laboratory setup

## Results

- Temperature dependence of DC-resistivity
- SIP results: unfrozen thermal state
- SIP results: (partially) frozen thermal state
- Summary of laboratory measurement results

## Conclusions and outlook

## Literature

# Literature


Auty, R. P.; Cole, R. H., 1952. Dielectric Properties of Ice and Solid D2O. J. Chem. Phys. 20, 1309-1314, DOI:10.1063/1.1700726.

Fabbri, A., Fen-Chong, T., Coussy, O., 2006. Dielectric capacity, liquid water content, and pore structure of thawing-freezing materials, Cold Reg. Sci. Technol., 44, pp. 52-66, DOI:10.1016/j.coldregions.2005.07.001

Nordsiek, S., Weller, A., 2008. A new approach to fitting induced-polarization spectra. Geophysics 73 (6), F235–F245, DOI:10.1190/1.2987412.

Ravanel, L., Deline, P., 2008. The West Face of Les Drus (Mont-Blanc massif): slope instability in a high-Alpine steep rock wall since the end of the Little Ice Age. Géomorphologie 4:261–272.

Revil, A., Koch, K., and Holliger, K, 2012.: Is it the grain size or the characteristic pore size that controls the induced polarization relaxation time of clean sands and sandstones?, Water Resour. Res., 48, W05602, DOI:10.1029/2011WR011561.

Schwarz, G., 1962: A theory of the low-frequency dielectric dispersion of colloidal particles in electrolyte solution, J. Phys. Chem., 66, 2636–2642, DOI:10.1021/j100818a067.

Stillman, D. E., Grimm, R. E., & Dec, S. F., 2010. Low-Frequency Electrical Properties of Ice-Silicate Mixtures. The Journal of Physical Chemistry B, 114(18), 6065-6073, DOI:10.1021/jp9070778.

Weigand, M. & Kemna, A., 2016. Debye decomposition of time-lapse spectral induced polarisation data, Comput. Geosci., 86, 34-45, DOI:10.1016/j.cageo.2015.09.021.

Zimmermann, E., Kemna, A., Berwix, J., Glaas, W., Münch, H.M., Huisman, J.A., 2008a. A high-accuracy impedance spectrometer for measuring sediments with low polarizability. Measurement Science and Technology 19, 105603-105603, DOI:10.1088/0957-0233/19/10/105603.