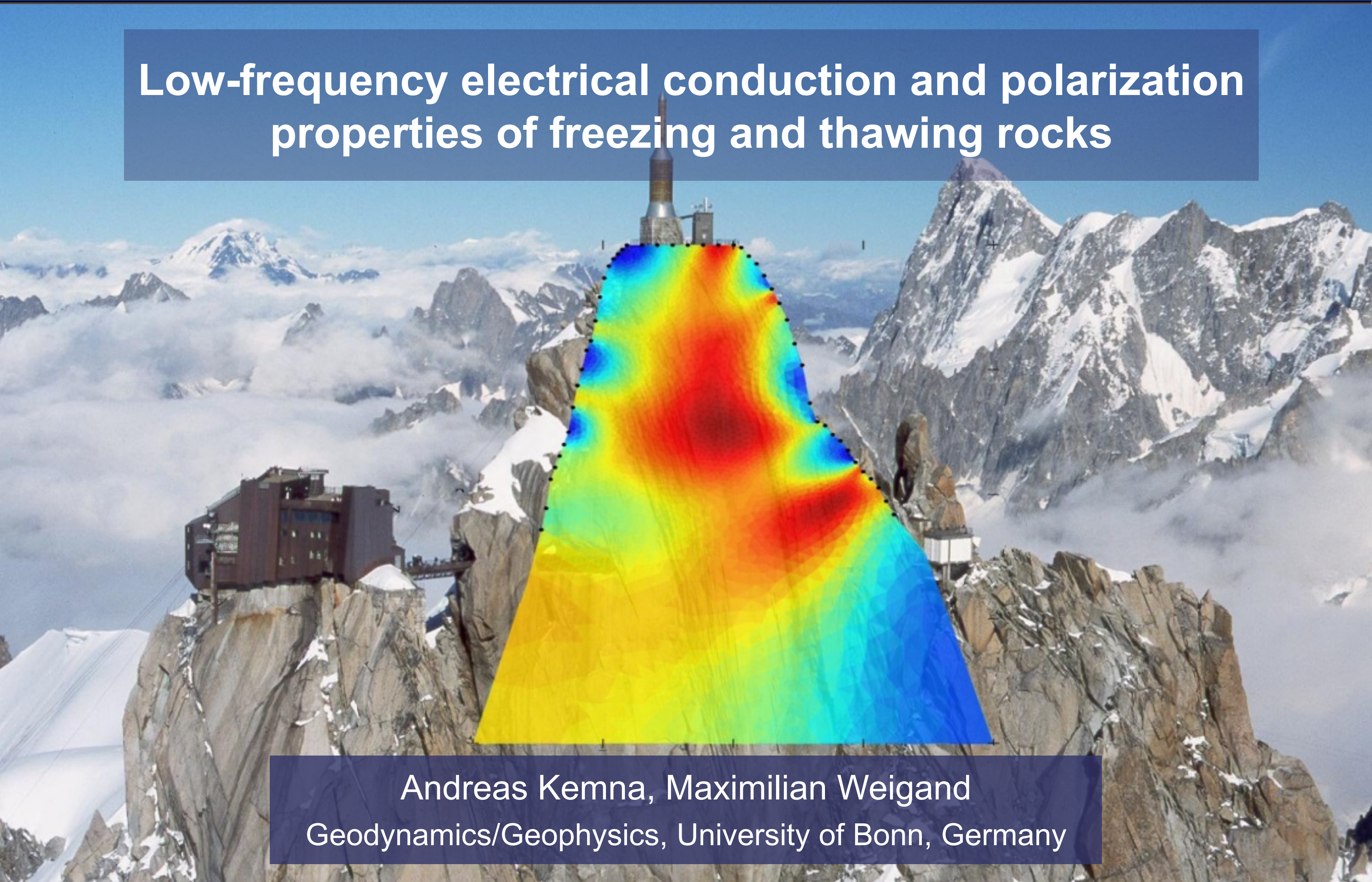
Low-frequency electrical conduction and polarization properties of freezing and thawing rocks



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Electrical imaging in permafrost studies

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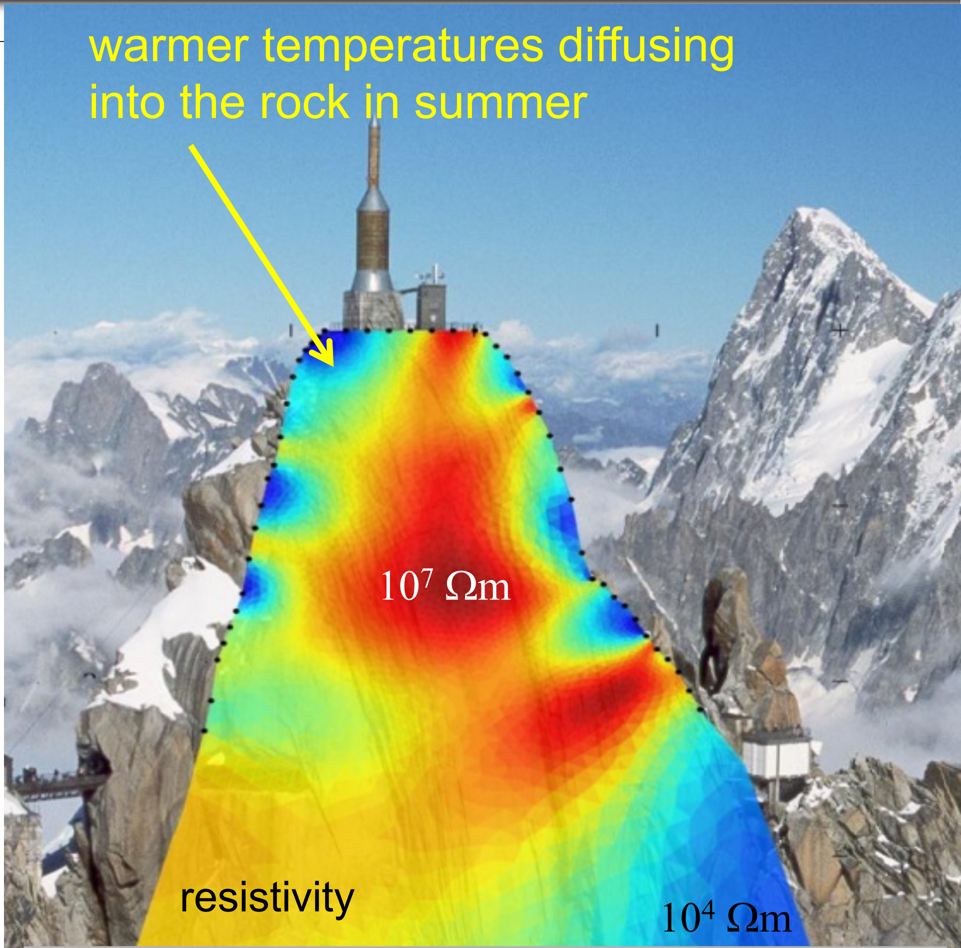
- Electrical resistivity of soils/rocks strongly dependent on water and ice content, and temperature
- Electrical Resistivity Tomography (ERT) increasingly used with a view to:
  - thermal state characterization and monitoring
  - quantification of water/ice content

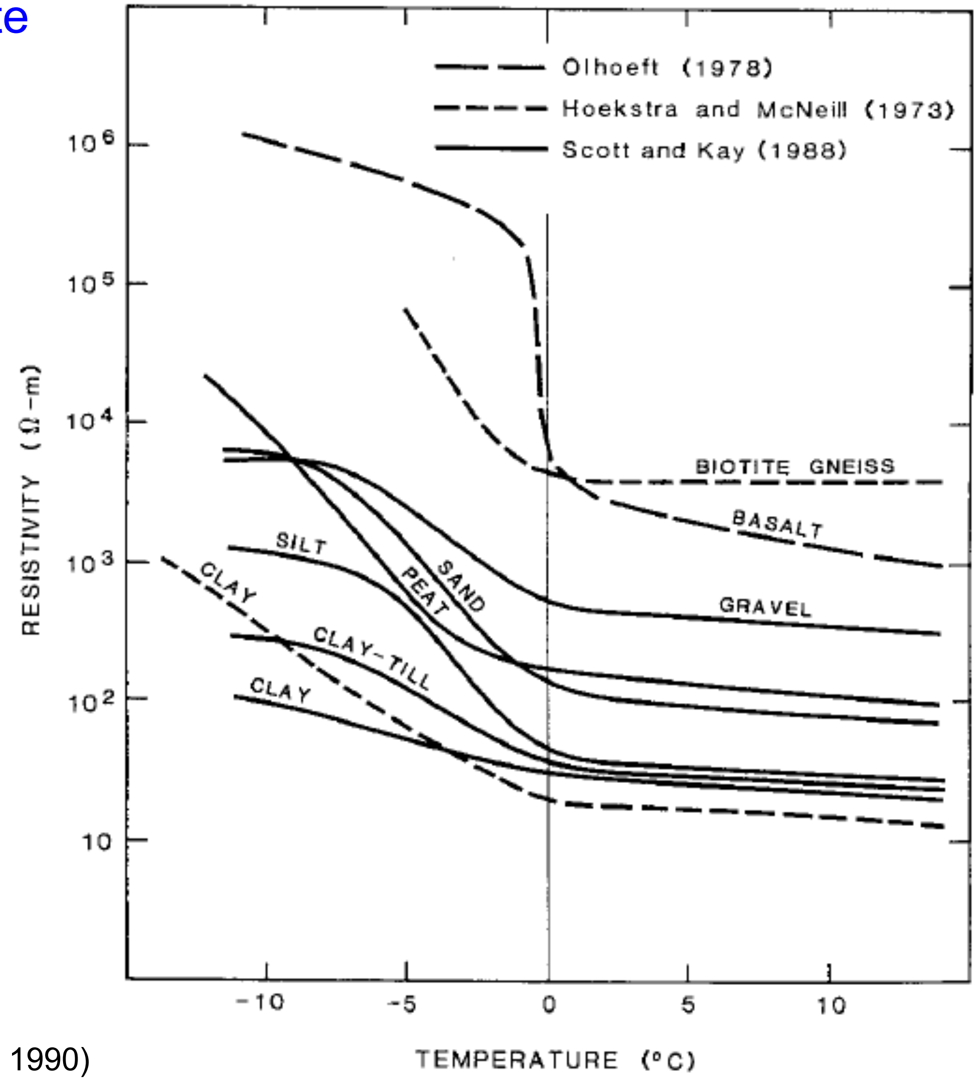
See, e.g.:
Krautblatter et al. (S16, P31)
Magnin et al. (S7-1, 9:30)
Hauck (Plenary Lecture 3)



- ERT data collected at Aiguille du Midi, France (3842 m a.s.l.) in Oct. 2010 in collaboration with P. Deline, L. Ravanel (Savoie Univ., Chambéry) and M. Krautblatter (TU Munich)
- Data inverted with CRTomo (Kemna, 2000)

Resistivity of frozen and unfrozen soils/rocks

- Characterization of thermal state (frozen vs. unfrozen) based on resistivity difficult



(Scott et al., 1990)

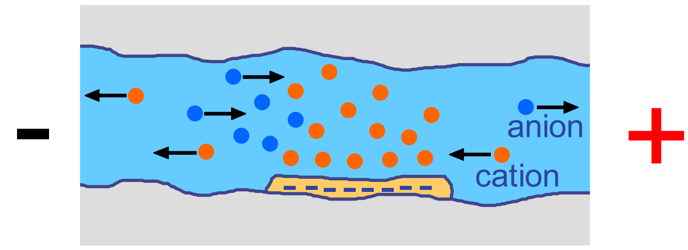
Frequency-dependent electrical rock properties

- Electrical conduction and polarization properties
- Measured as magnitude and phase (or real and imaginary components) of an effective complex conductivity (resistivity) or, alternatively, permittivity

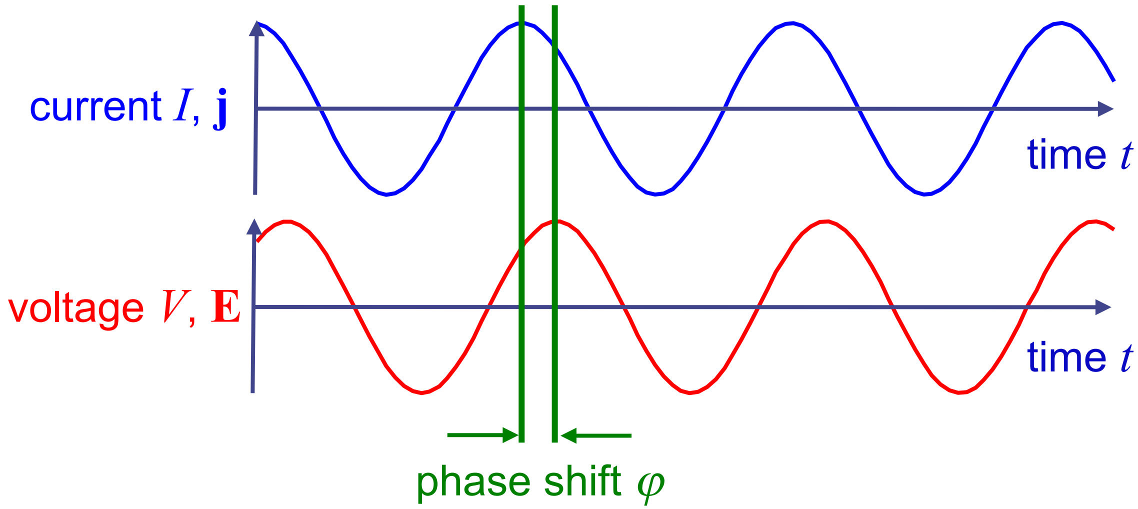
ice-free: $\sigma^*(\omega) = |\sigma|\, e^{i\varphi} = \sigma_{DC} + \sigma^*_{surf}(\omega)$

with ice: $\sigma^*(\omega) = \sigma_{DC} + \sigma^*_{surf}(\omega) + \sigma^*_{ice}(\omega)$

$$\sigma^* = \sigma_{DC} + i\,\omega\,\varepsilon^* = 1/\rho^*\,, \quad i^2 = -1$$



pore scale



Electrical properties of water and ice

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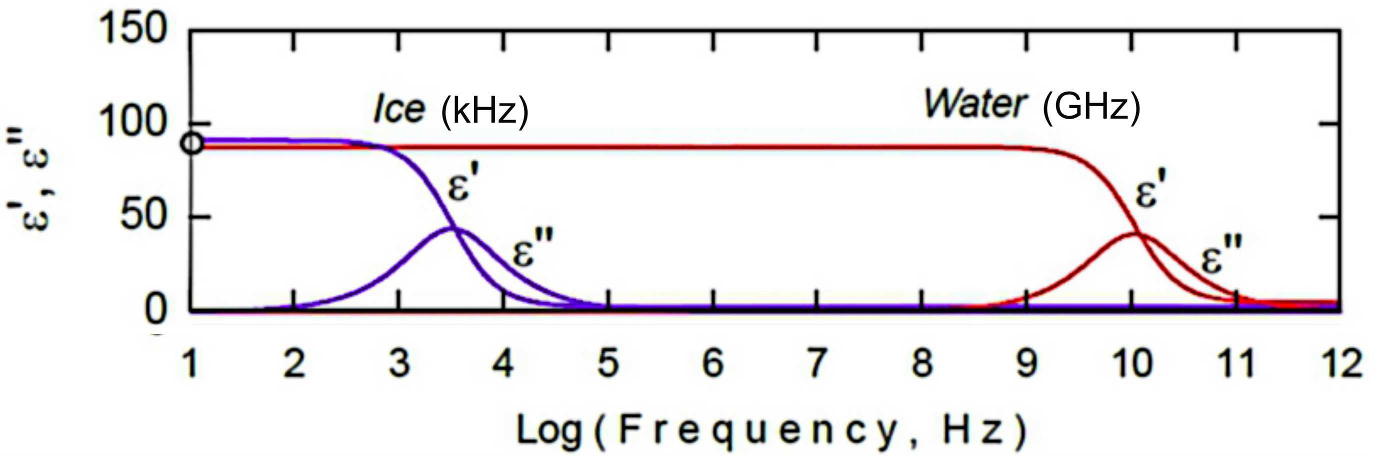
- Polarization of ice (polarization of point defects in the crystal lattice) at much lower frequencies than polarization of water

ε' : real component of ε^*

ε'' : imaginary component of ε^*



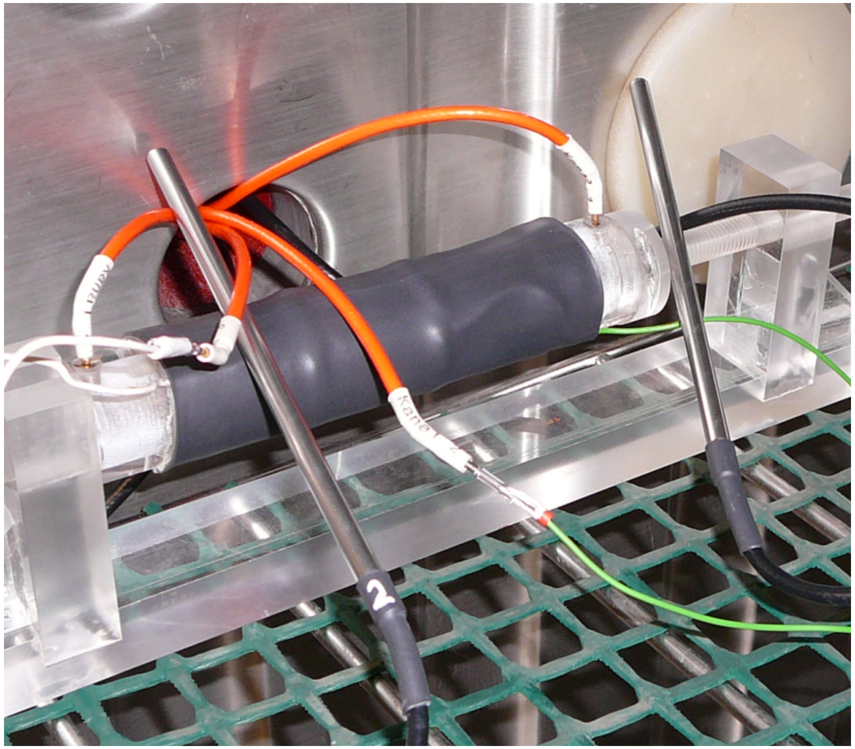
(Artemov, 2013)

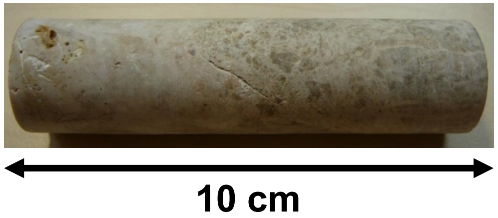
measurement range of Spectral Induced Polarization (SIP) method (extension of ERT)

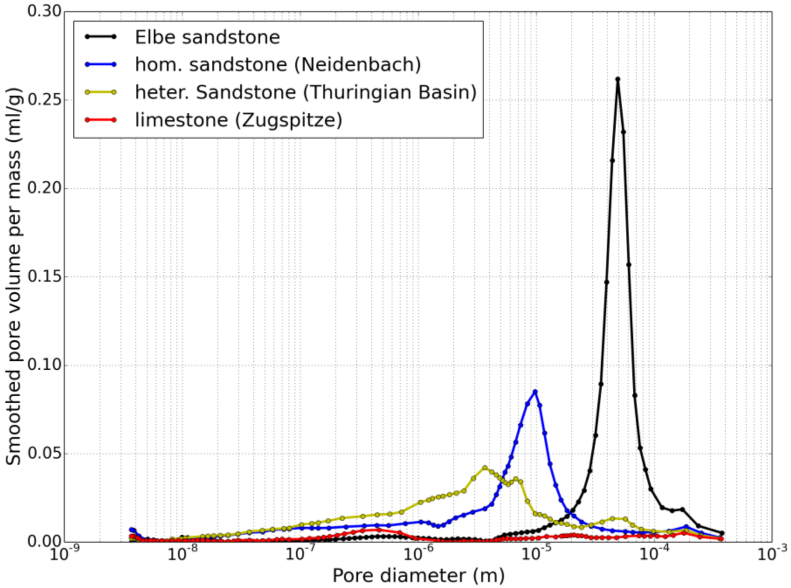
Electrical polarization measure of ice content?

SIP measurements during freezing/thawing

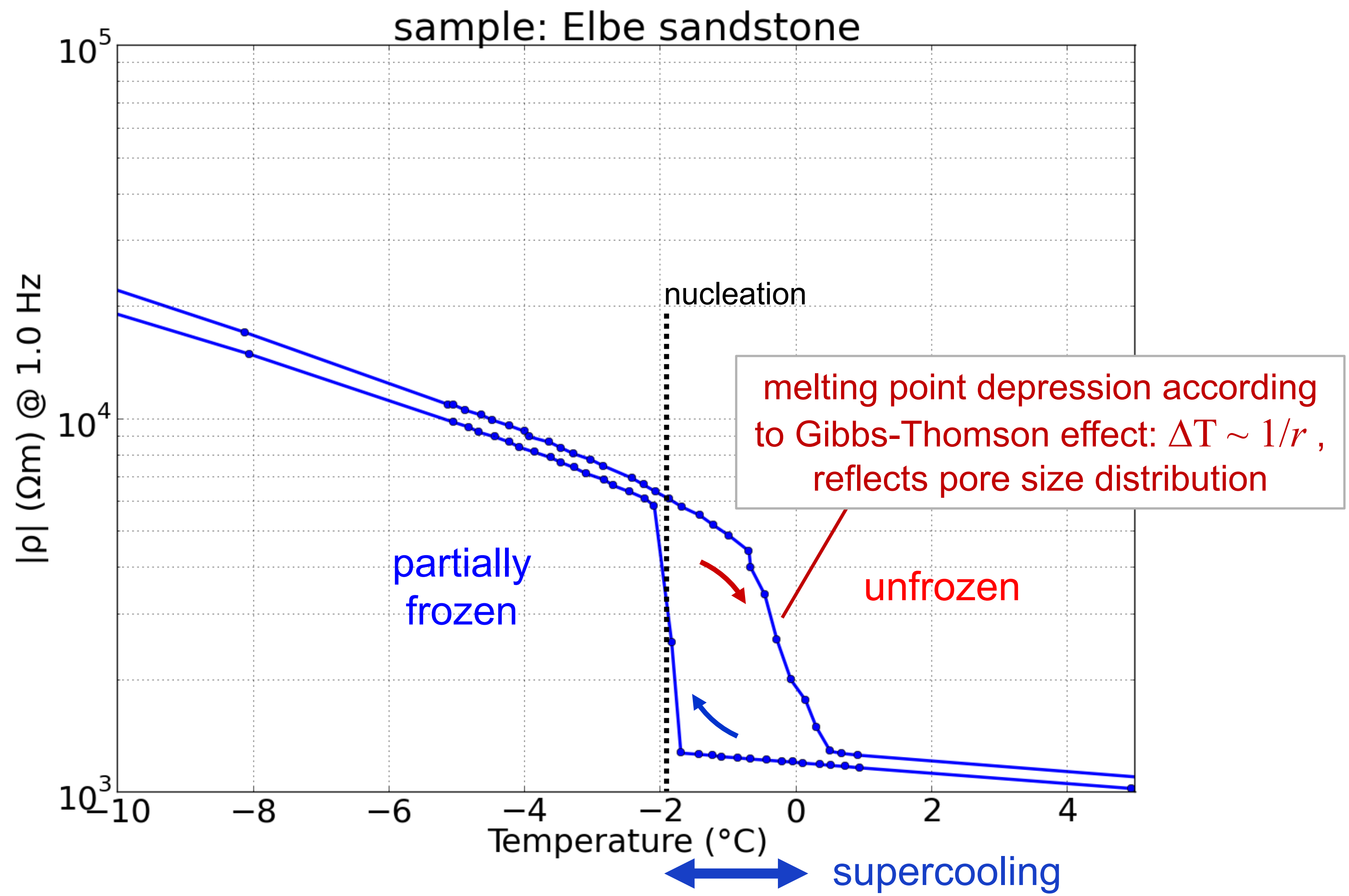
- SIP measurements on 6 sandstone and limestone samples (saturated with deionized water, different pore sizes/porosity)
- Frequency range: 1 mHz to 45 kHz
- +10 to –40 °C, waiting for thermal equilibrium at each temperature step





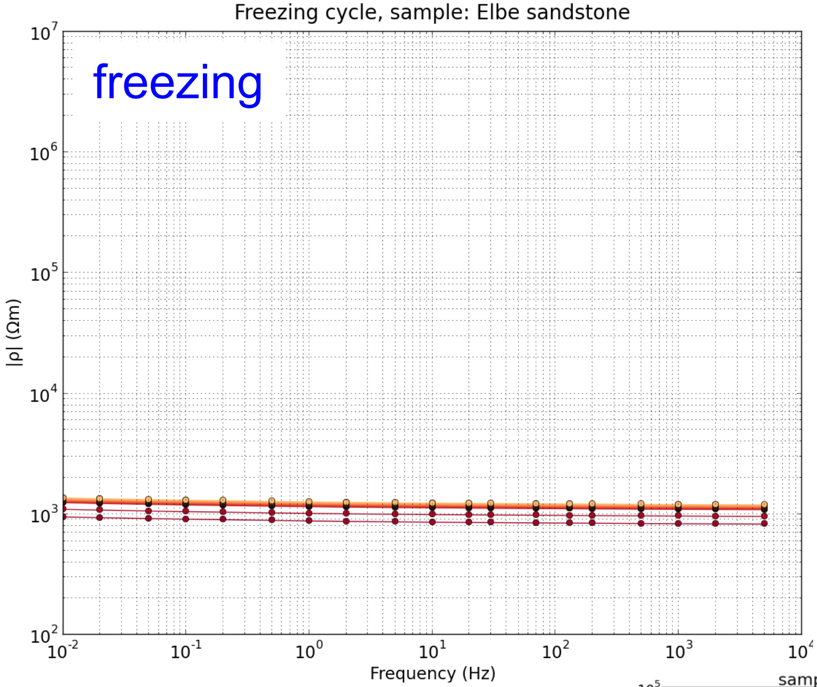


Resistivity freezing/thawing curve

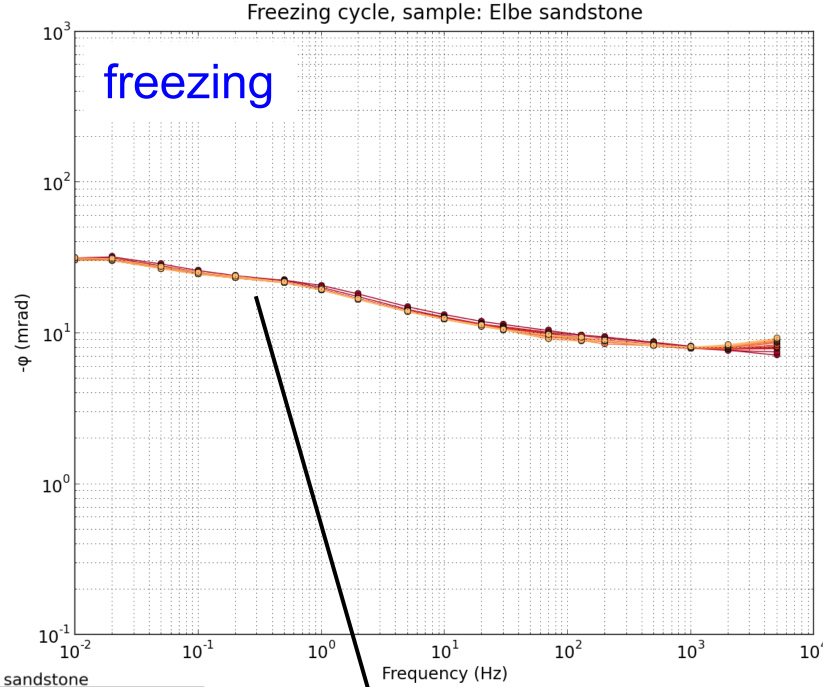


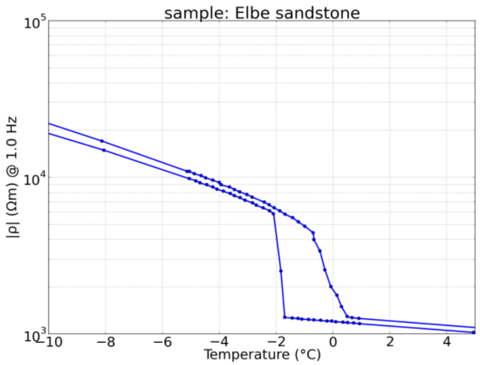
SIP spectra: Elbe sandstone

resistivity magnitude

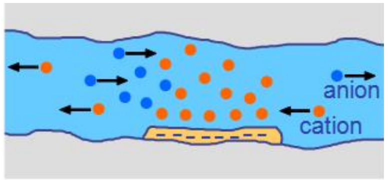


resistivity phase





polarization at
mineral-water interfaces



SIP spectra: Elbe sandstone

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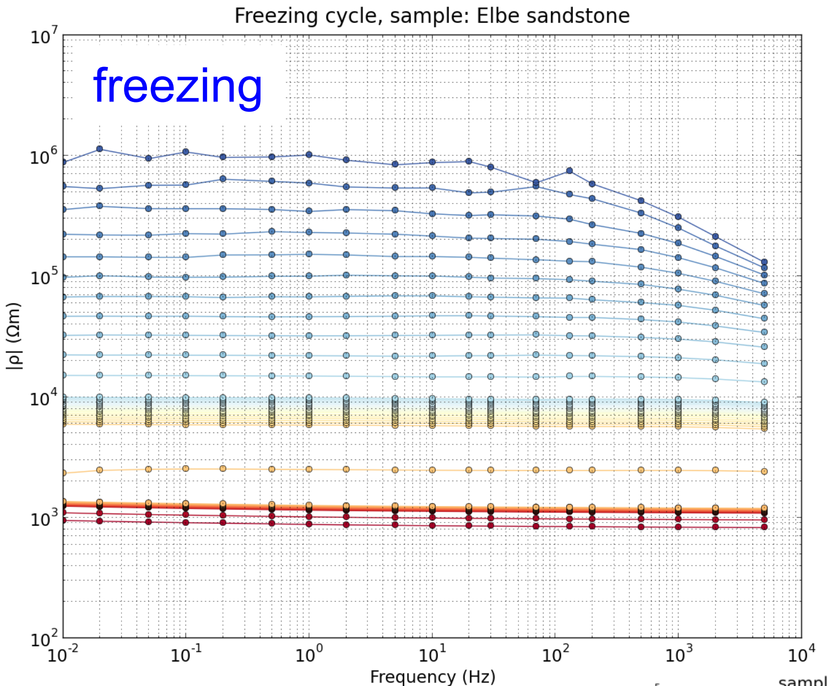
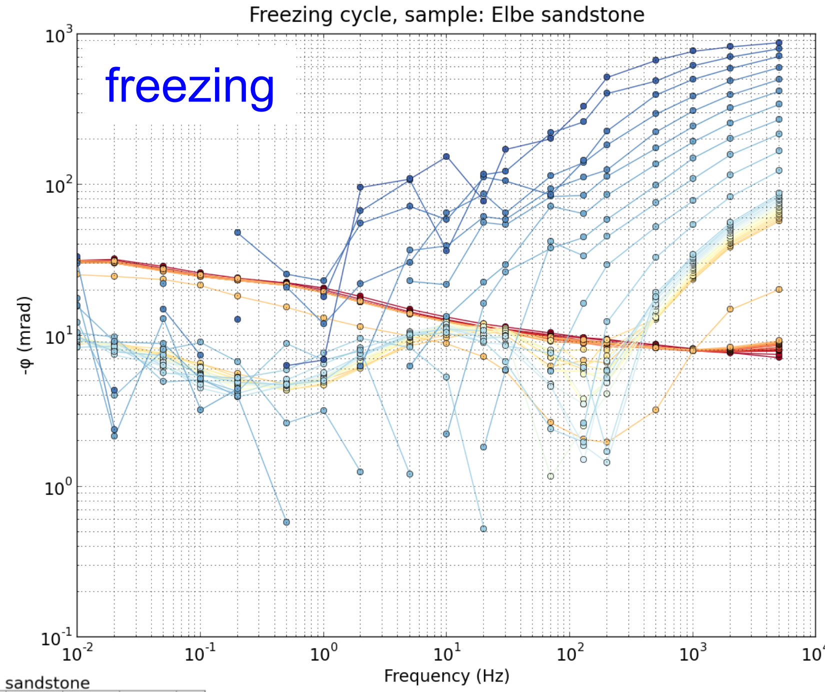
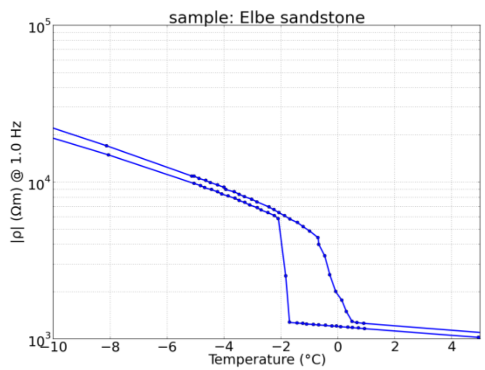
resistivity magnitude



resistivity phase





SIP spectra: Elbe sandstone

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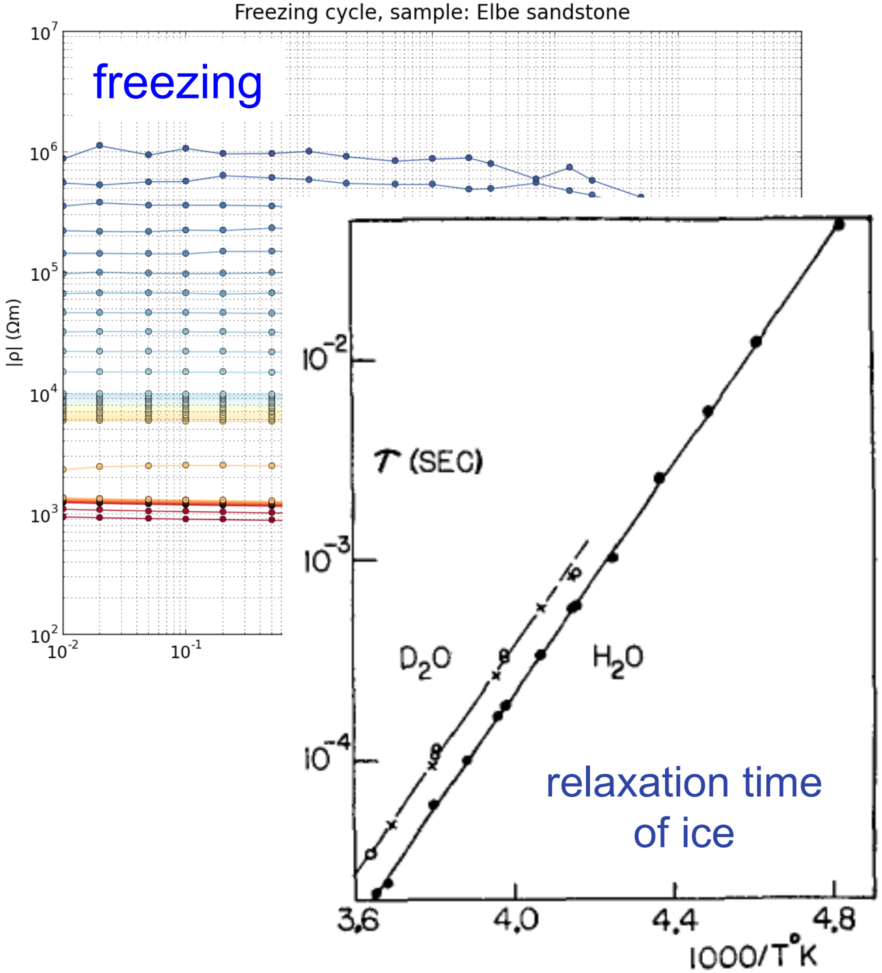
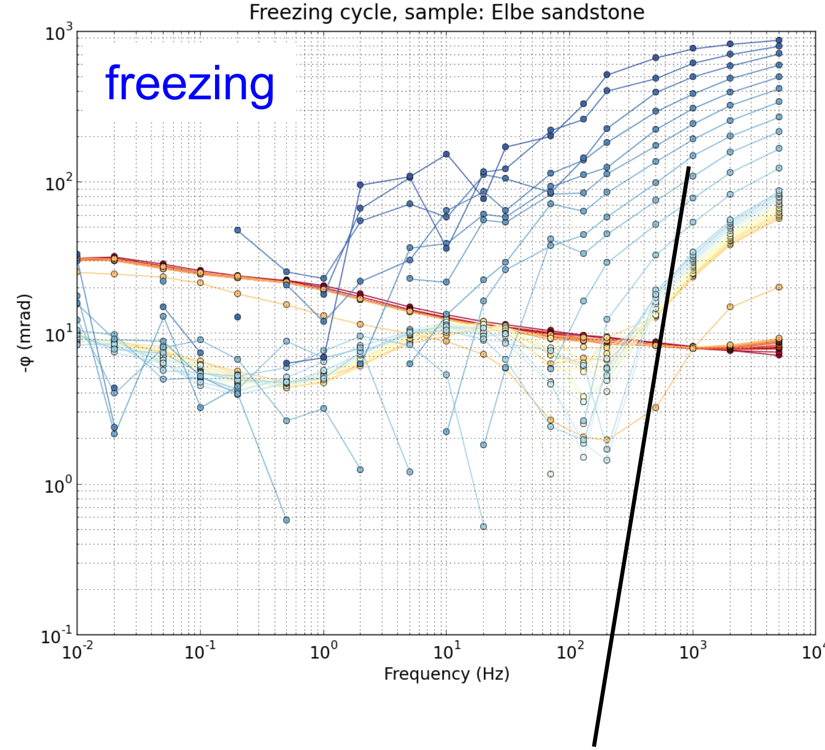
resistivity magnitude



(Auty and Cole, 1952)

resistivity phase



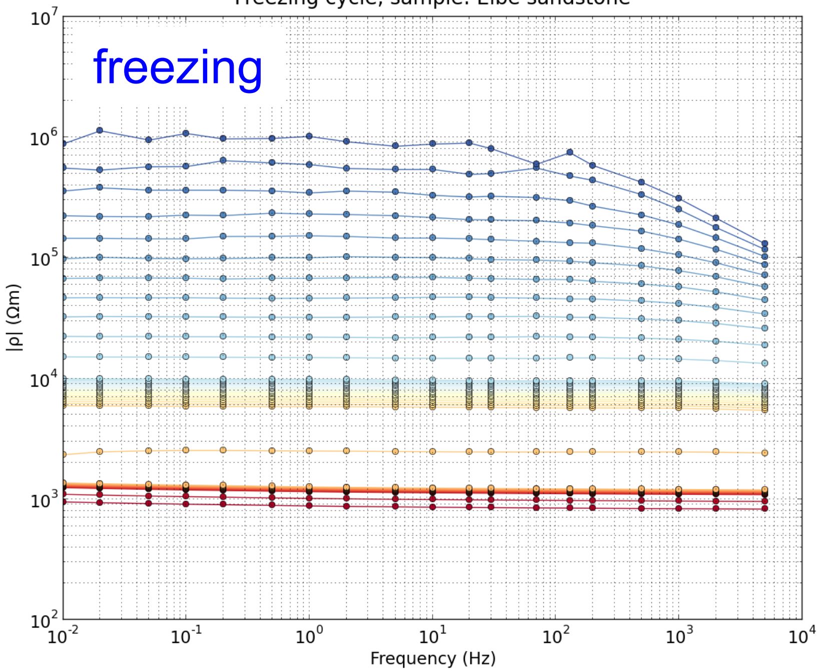
polarization response of ice

$$\sigma^*_{\text{ice}}(\omega) = \sigma_\infty \left(1 - \frac{m}{1 + i\omega\tau}\right)$$

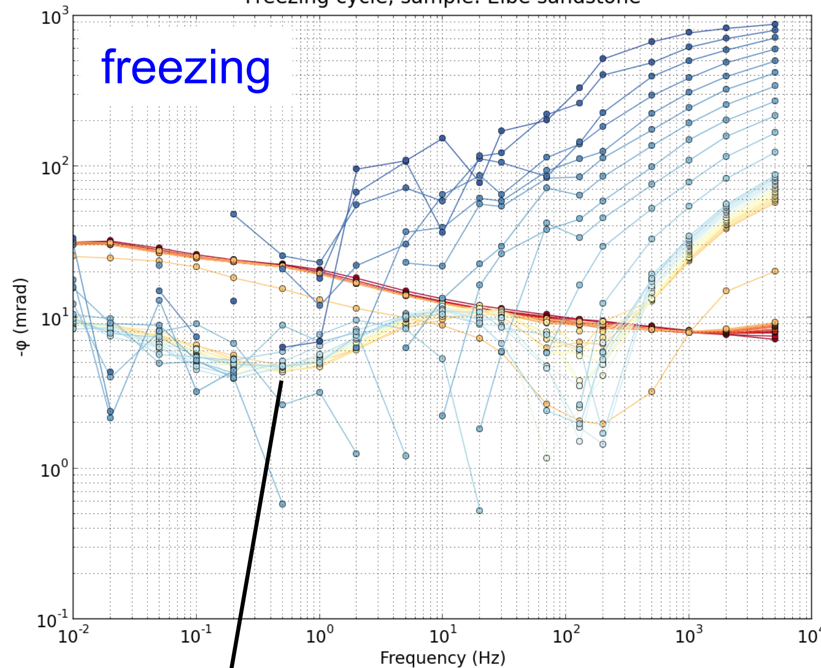
(m: chargeability)

SIP spectra: Elbe sandstone

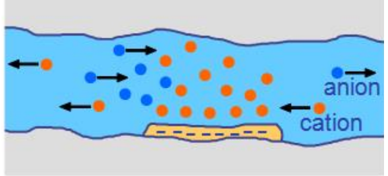
resistivity magnitude



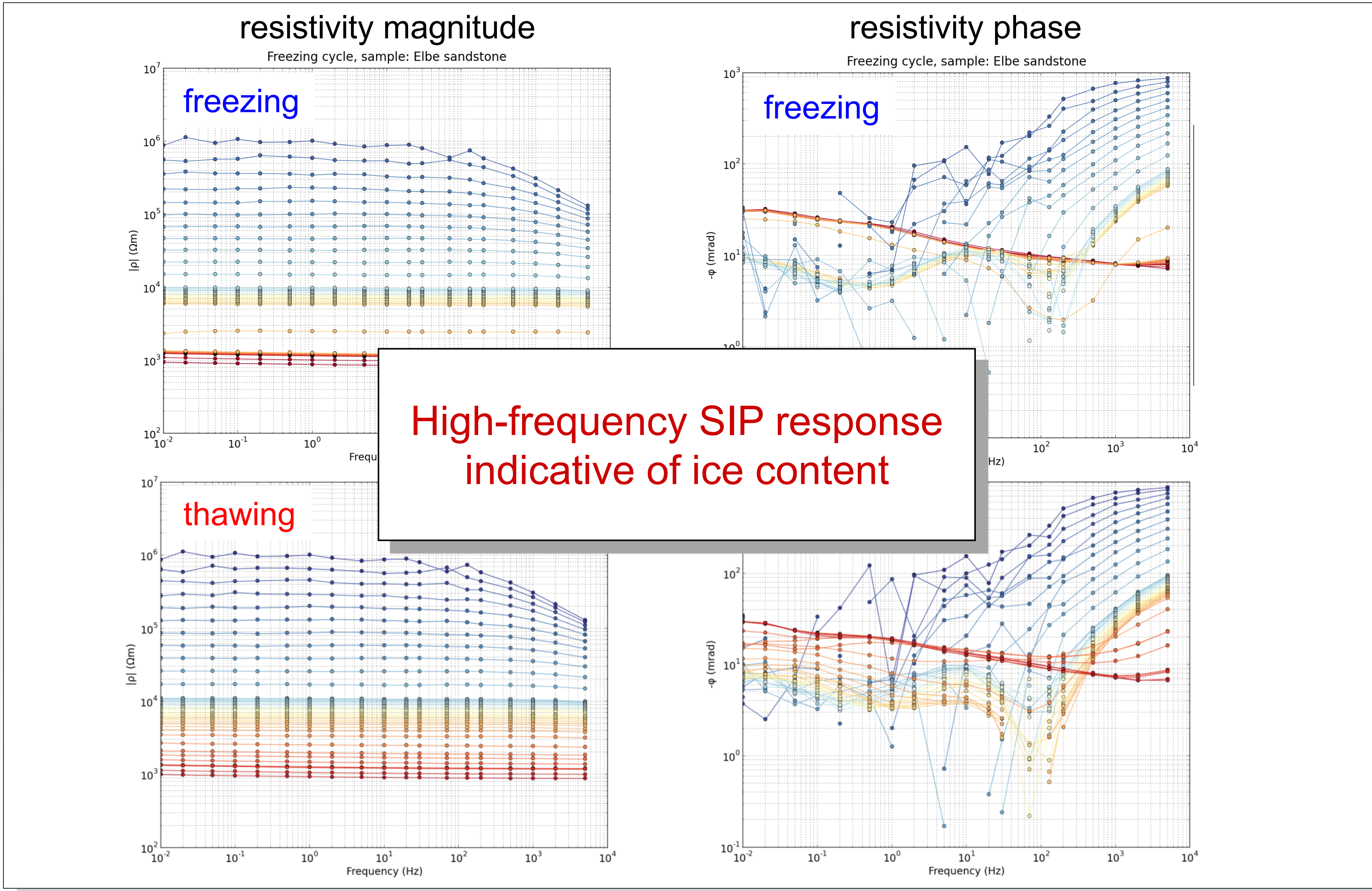
resistivity phase



decrease of polarization at mineral-water interfaces



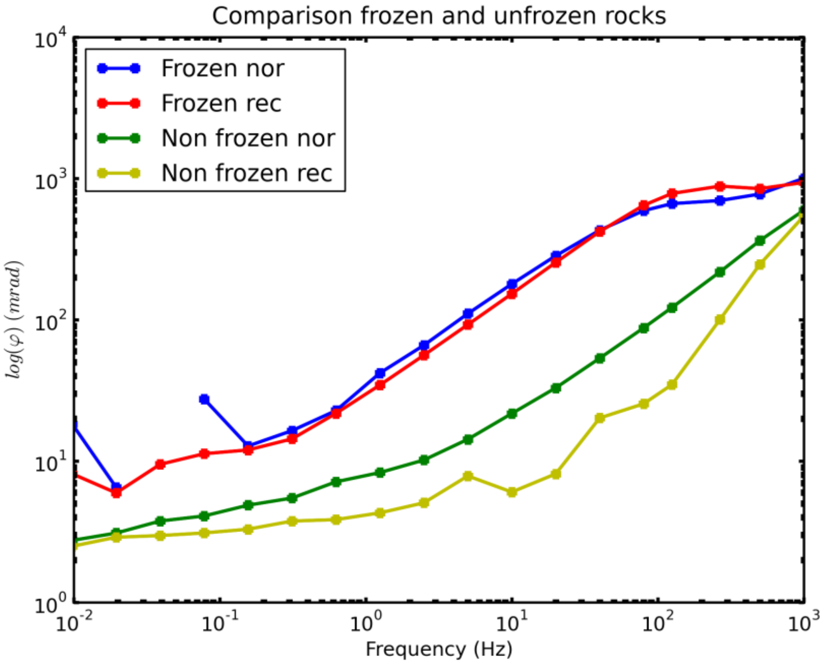
SIP spectra: Elbe sandstone



High-frequency SIP response indicative of ice content

Outlook

- Development of SIP model for partially frozen rocks:
  - matrix/ice/water fractions dependent on temperature and pore size (Gibbs-Thomson effect)
  - representation of polarization based on Debye decomposition into relaxation time distribution
- Analysis of SIP field data measured at the Zugspitze (German Alps)



Conclusions

- Resistivity and SIP of investigated rock samples exhibit freeze-thaw hysteresis
- Ice polarization response represents indicator for thermal state (frozen vs. unfrozen) of rocks, provides access to presence and amount of ice
- Hysteretic behaviour of SIP strongly depends on considered frequency due to change of spectral shape during freezing/thawing
- Electrical hysteresis must be taken into account if temperature is to be inferred from ERT/SIP images (e.g. in the course of permafrost monitoring)

Resistivity hysteresis for different samples

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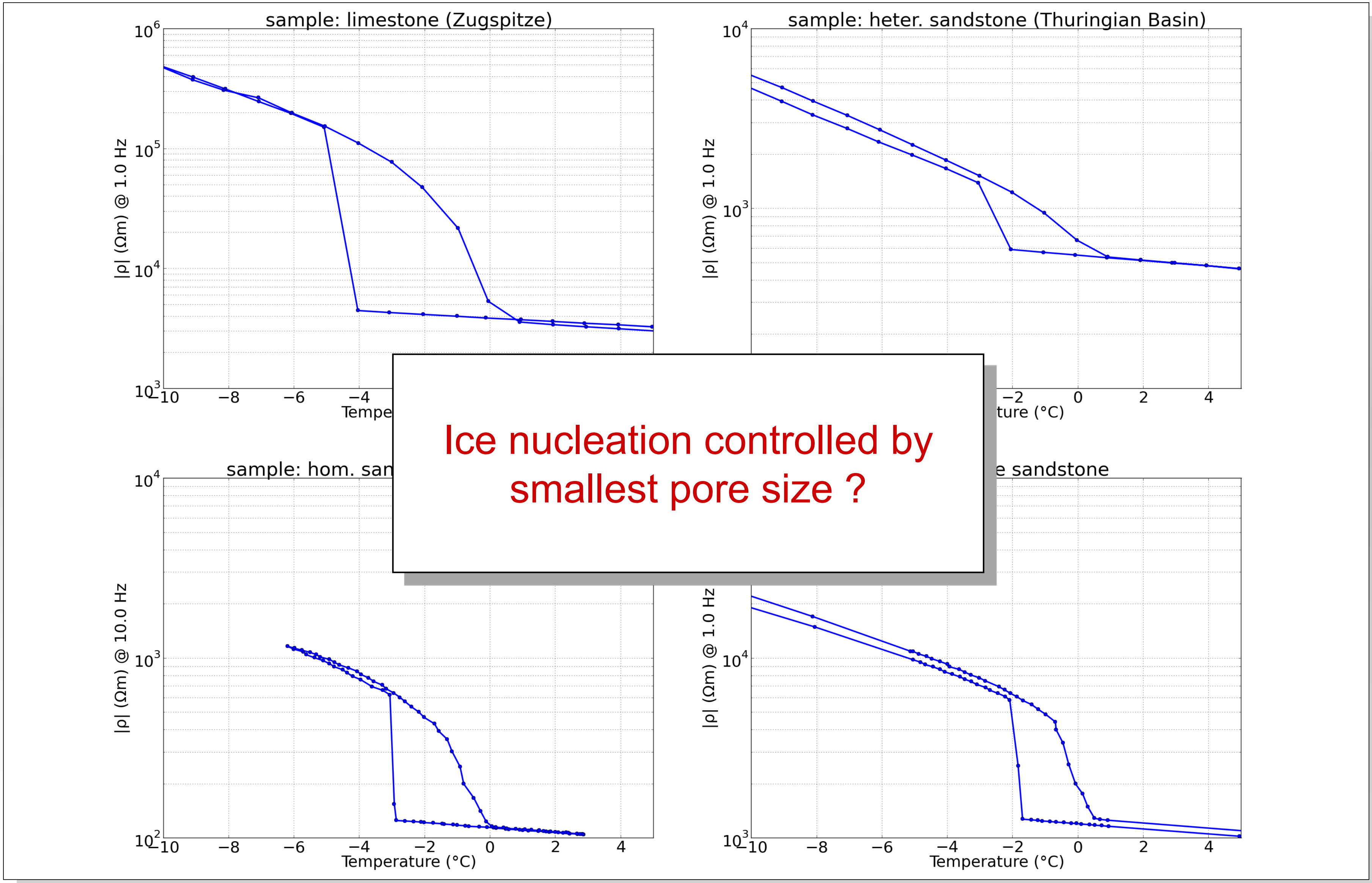

Ice nucleation controlled by smallest pore size ?