

Temperature dependence of complex surface conductivity

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Abstract

The complex electrical conductivity of water-saturated rocks is affected by temperature. The main reason for the temperature dependence of fluid conductivity is that the mobility of the ions in the pore fluid is increased with temperature. In addition to the fluid conductivity, surface conductivity is influenced by temperature.

We measured the complex electrical conductivity of different sandstone samples at temperatures between 0 and 40 °C. Additionally, one sample was measured at varying ion concentrations from 1 to 2000 mol/m³ to determine the dependence of the conductivity both on temperature and salinity. The experimental results are compared to calculations of a membrane polarization model.

Theory

The temperature dependence of the electrical conductivity of an electrolyte is caused by the influence of temperature on ion mobility μ , which depends on dynamic viscosity η (Sorensen and Glass, 1987):

$$\mu(T) = \mu(T_0) \left(\frac{\eta(T_0)}{\eta(T)} \right)^\alpha \quad (1) \quad \alpha = 0,8 \dots 0,97$$

If surface conductivity is small, the real part of conductivity can be described by

$$\sigma'(T) = \sigma'(T_0) \left(\frac{\eta(T_0)}{\eta(T)} \right)^\alpha \quad (2)$$

The temperature also affects the electrical double layer, for example the zeta potential and the Debye length (figure 1). For surface conductivity an empirical linear equation can be used to quantify the temperature dependence:

$$\sigma'(T) = \sigma'(T_0)(1 + a(T - T_0)) \quad (3)$$

The fitting parameters α and a represent the strength of the conductivity increase with increasing temperature.

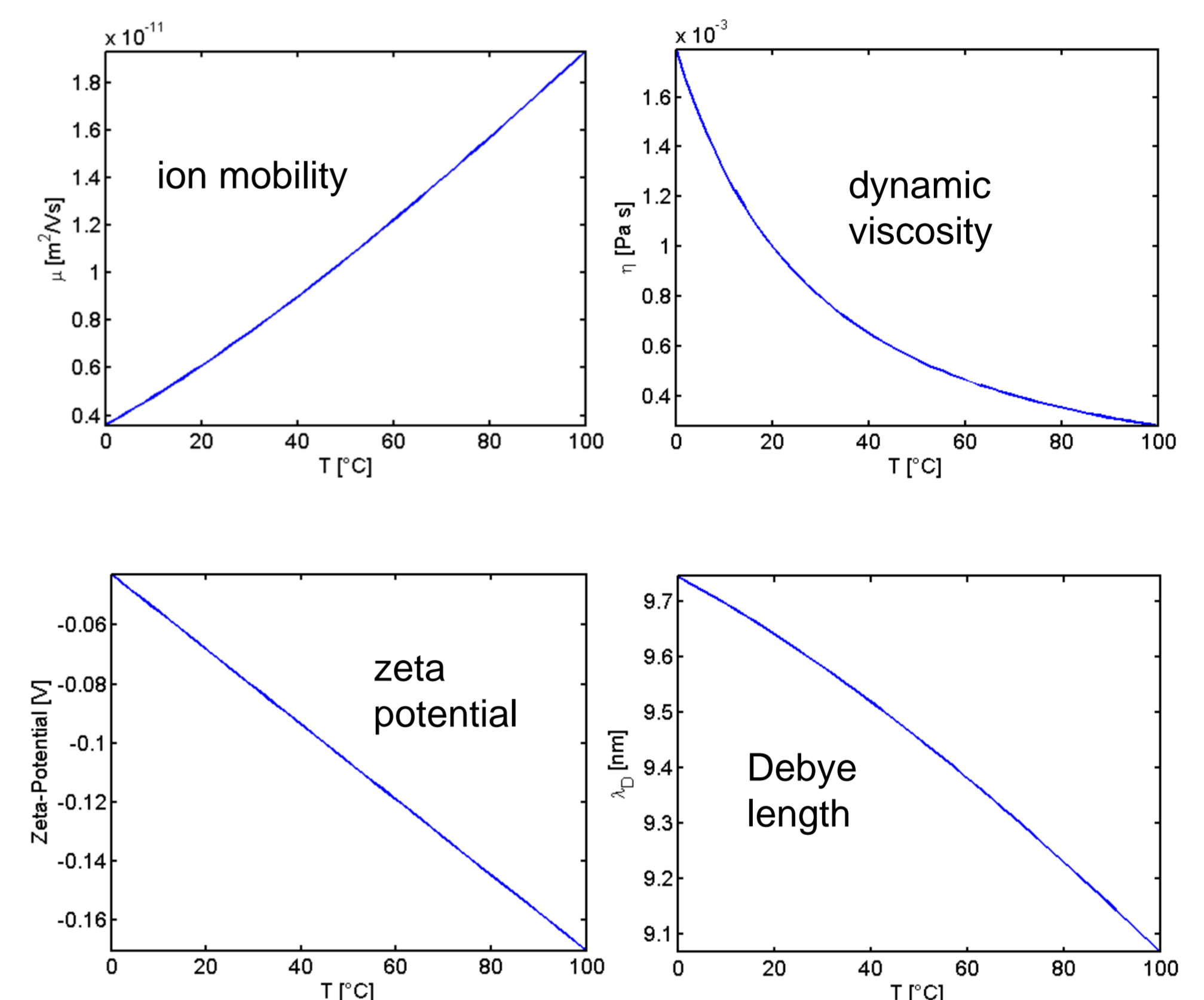


Fig. 1: Temperature dependence of parameters influencing the electrical conductivity of a saturated rock: ion mobility and dynamic viscosity of the electrolyte solution, zeta potential and Debye length.

MEASUREMENTS

Measurements on different sandstones saturated with NaCl solution with approximately $\sigma_f = 50$ mS/m and pH 7 were performed at temperatures between 0 and 40 °C. The examples in figure 2 show that real and imaginary conductivity increase with increasing temperature, whereas the shape of the spectra remains the same. In the spectra of the imaginary part a shift to higher frequencies with increasing temperature is visible.

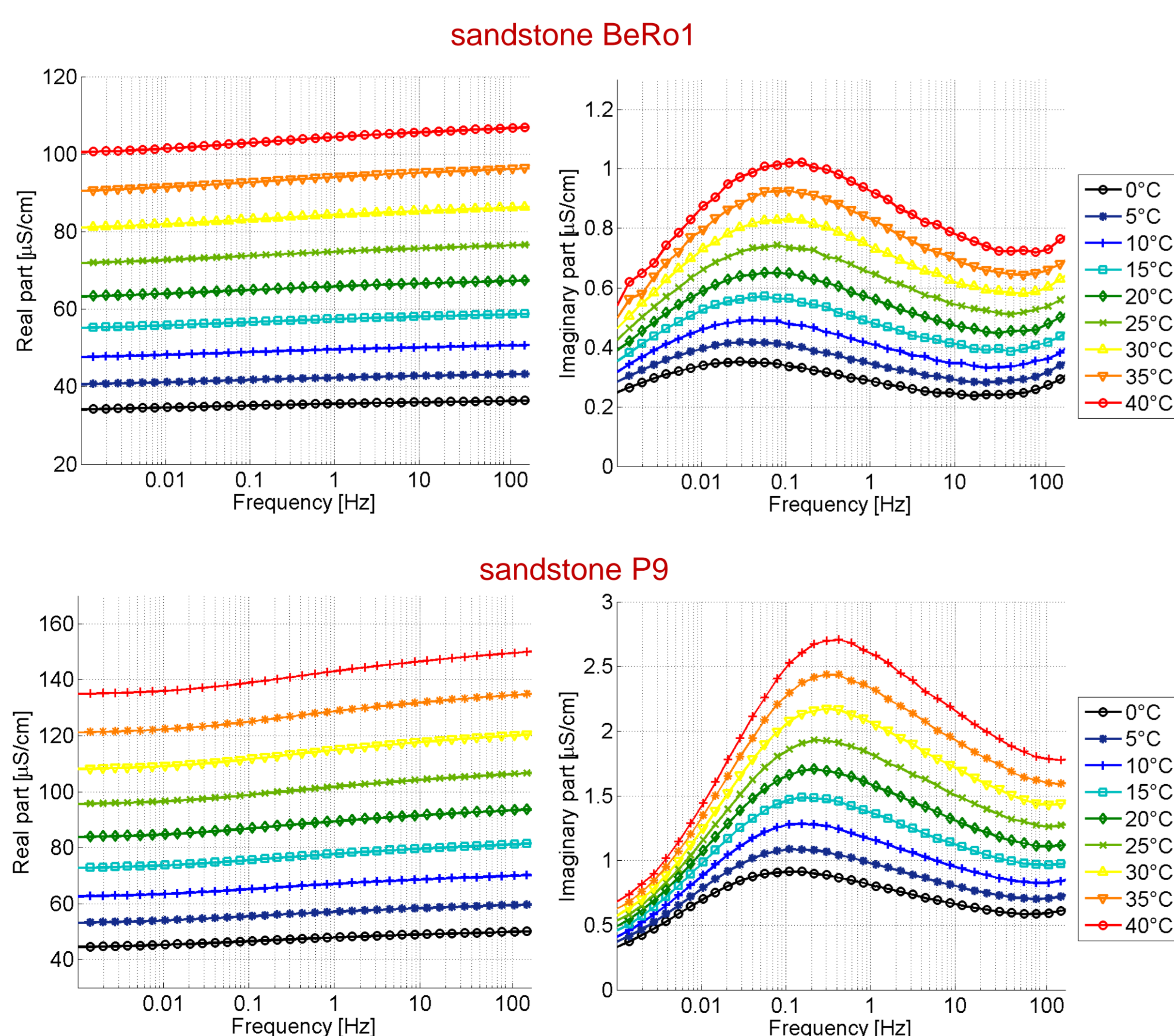


Fig. 2: Spectra of the real and imaginary part of the electrical conductivity of sandstone samples BeRo1 (top) and P9 (bottom) at temperatures from 0 °C to 40 °C in steps of 5 °C.

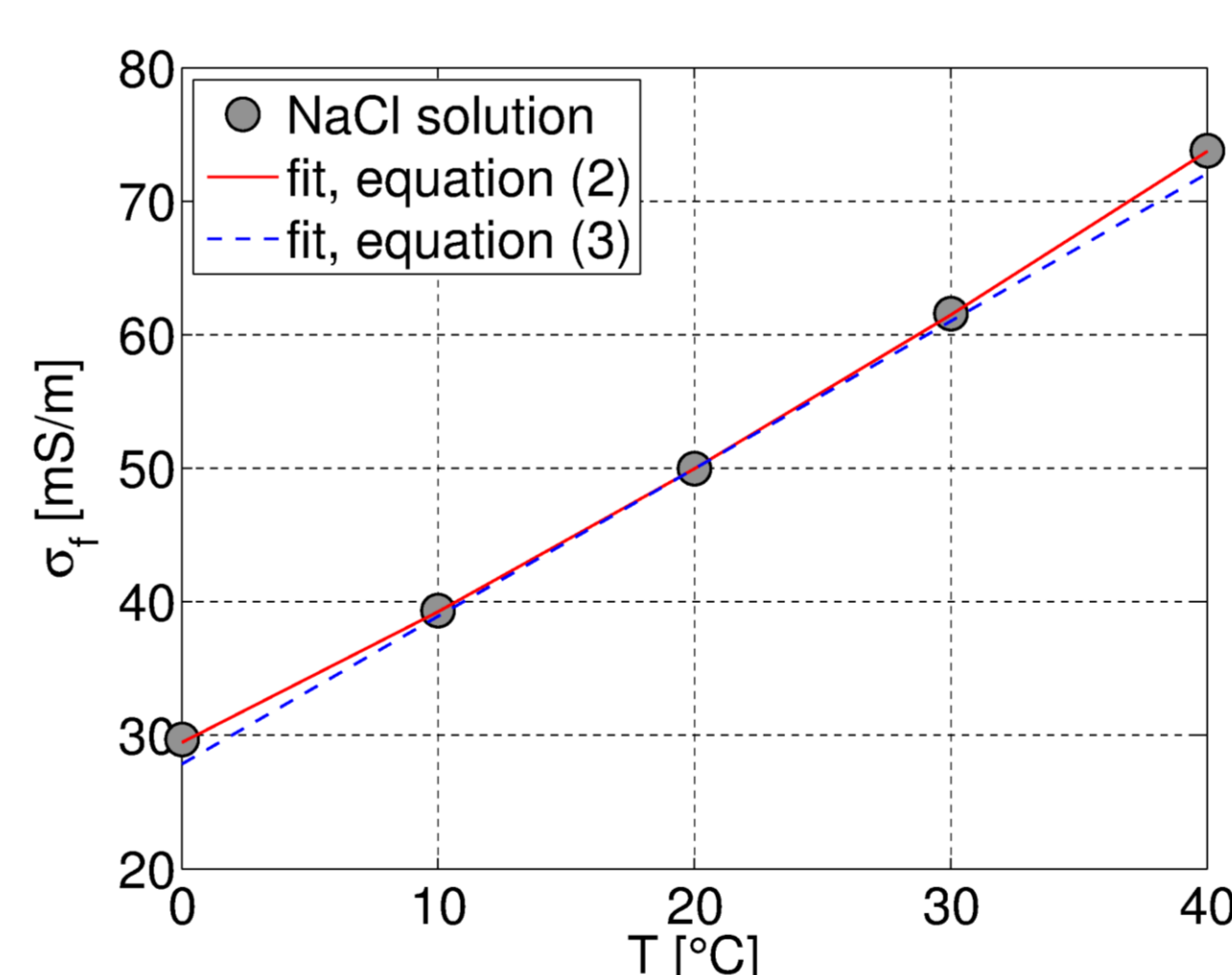


Fig. 3: Conductivity of sodium chloride solution with an ion concentration of 5 mol/m³ vs. Temperature. The solid and dashed line show the fits of equations (2) and (3) to the data.

Real and imaginary conductivity at 1 Hz

Only for a few samples the temperature dependence of the real conductivity is similar to that of the NaCl solution of $a = 0.020$ (figure 4), indicating that the temperature dependence of surface conductivity is different from that of fluid conductivity. For most of the samples the fitting parameters $a(\sigma'')$ are larger than $a(\sigma')$.

Fluid conductivity

The temperature dependence of surface conductivity can be estimated qualitatively if the influence of temperature on fluid conductivity is known. Measurements on NaCl solution, similar to the fluid used for saturating the sandstone samples, and fitting equations (2) and (3) to the data gives $\alpha = 0.896$ and $a = 0.020$.

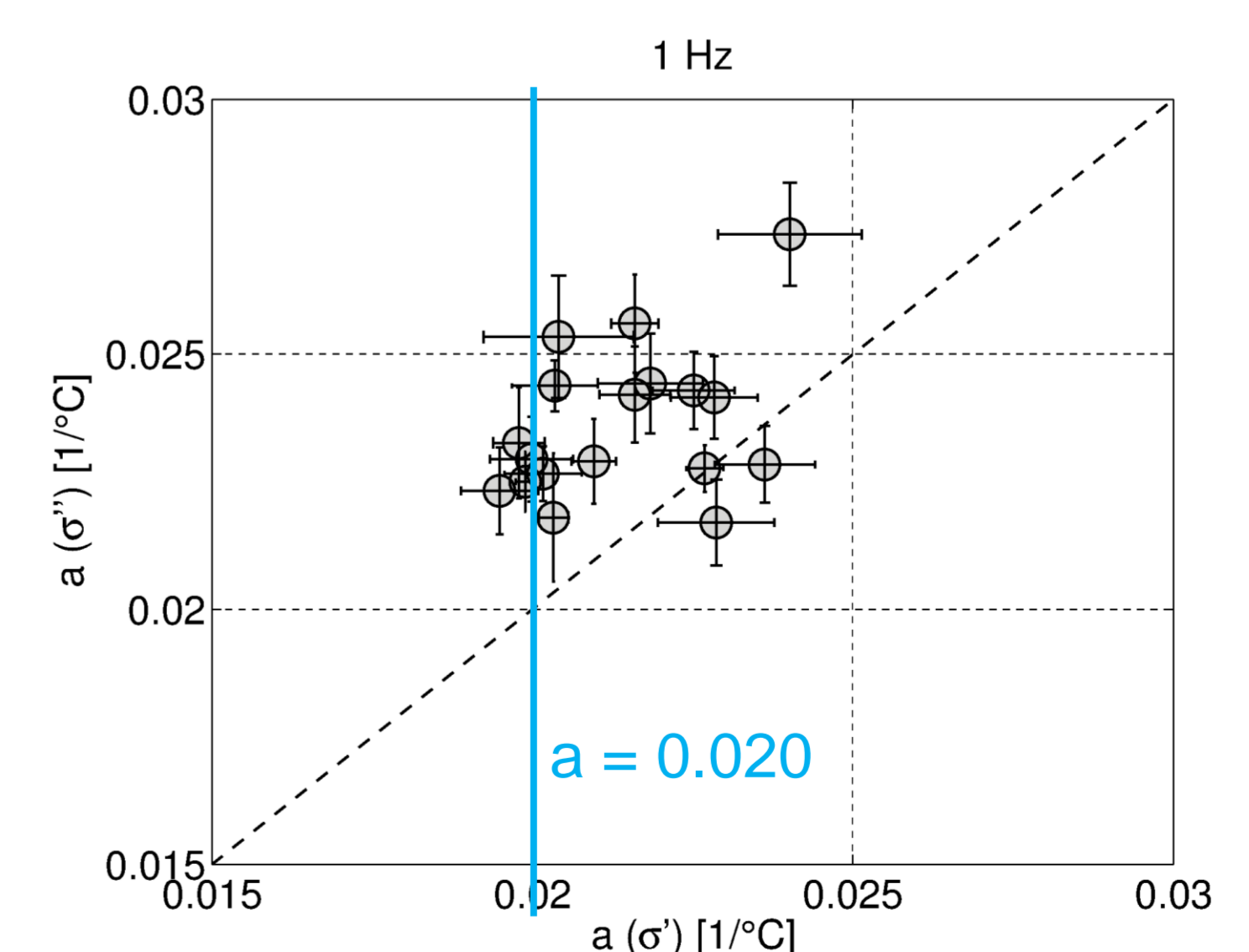


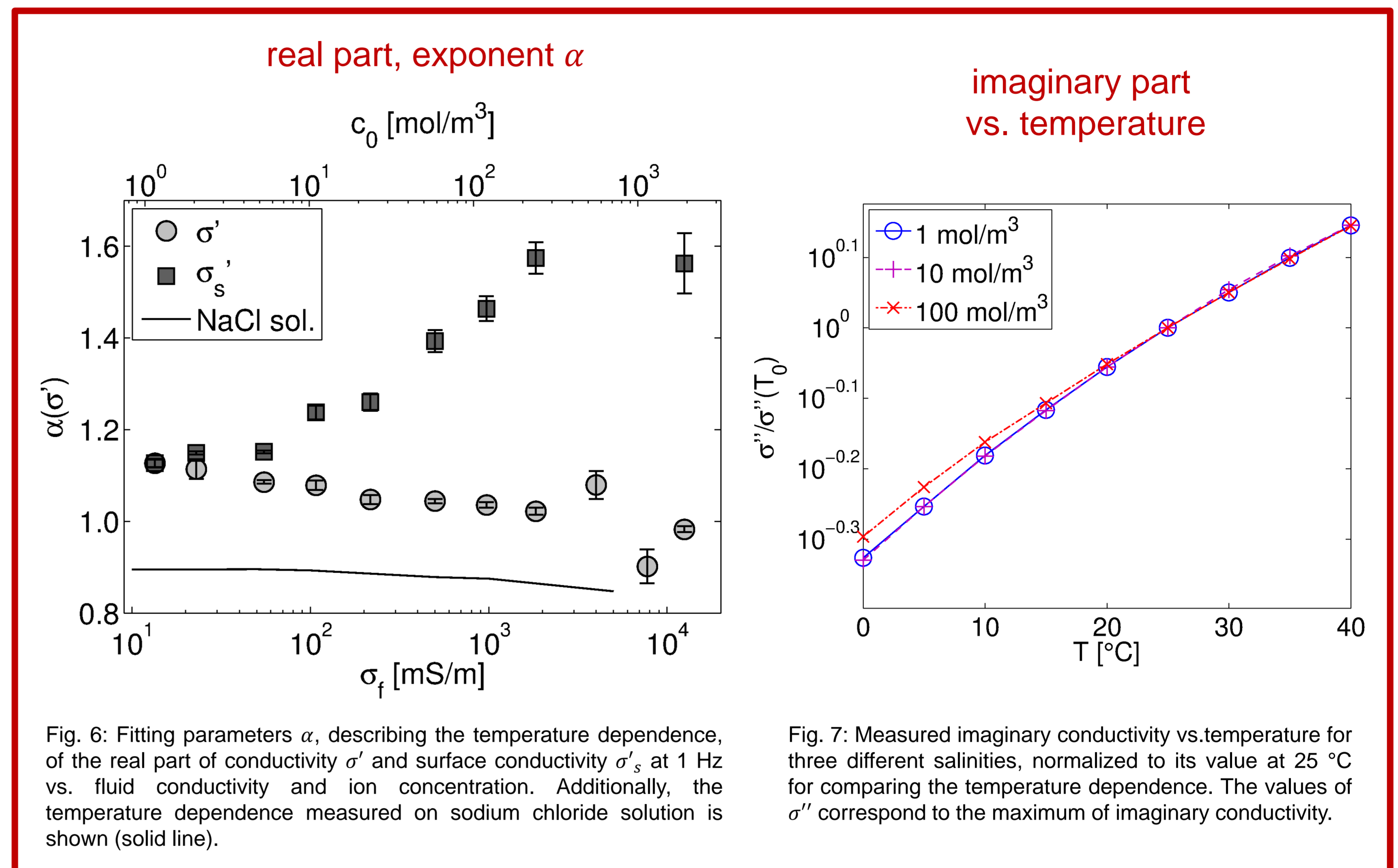
Fig. 4: Fitting parameters of the temperature dependence (equation 3) of the imaginary conductivity vs. fitting parameters of real conductivity at 1 Hz. The blue line indicates the temperature dependence of the fluid conductivity.

SALINITY DEPENDENCE

The ion concentration of the pore fluid influences the temperature dependence of the fluid conductivity. To observe the influence of salinity on surface conductivity, measurements with both varying temperature and salinity were performed on a sandstone sample (figure 5) saturated with NaCl solution of different salinities (1 - 2000 mol/m³). The temperature dependence of the bulk conductivity decreases with increasing salinity, whereas an increase is visible for the real part of surface conductivity, displayed in figure 6 by the fitting parameter α . The temperature dependence of imaginary conductivity slightly decreases at high salinities (figure 7).



Fig. 5: Sandstone sample P9, used for the SIP measurements at varying temperature and salinity.



MODEL

Membrane polarization

Membrane polarization describes ions in the pore fluid moving through zones of different ion mobilities (Marshall and Madden, 1959). In the extended membrane polarization model of Bückner and Hördt (2013) the pores are represented by two cylinders of different size with radius r_1 and length L_1 for the narrow pore and r_2 and L_2 for the wide pore (figure 8). The inner lateral surface of the cylinders is covered by an electrical double layer (EDL), which is characterized by several parameters including zeta potential, partition coefficient and Debye length.

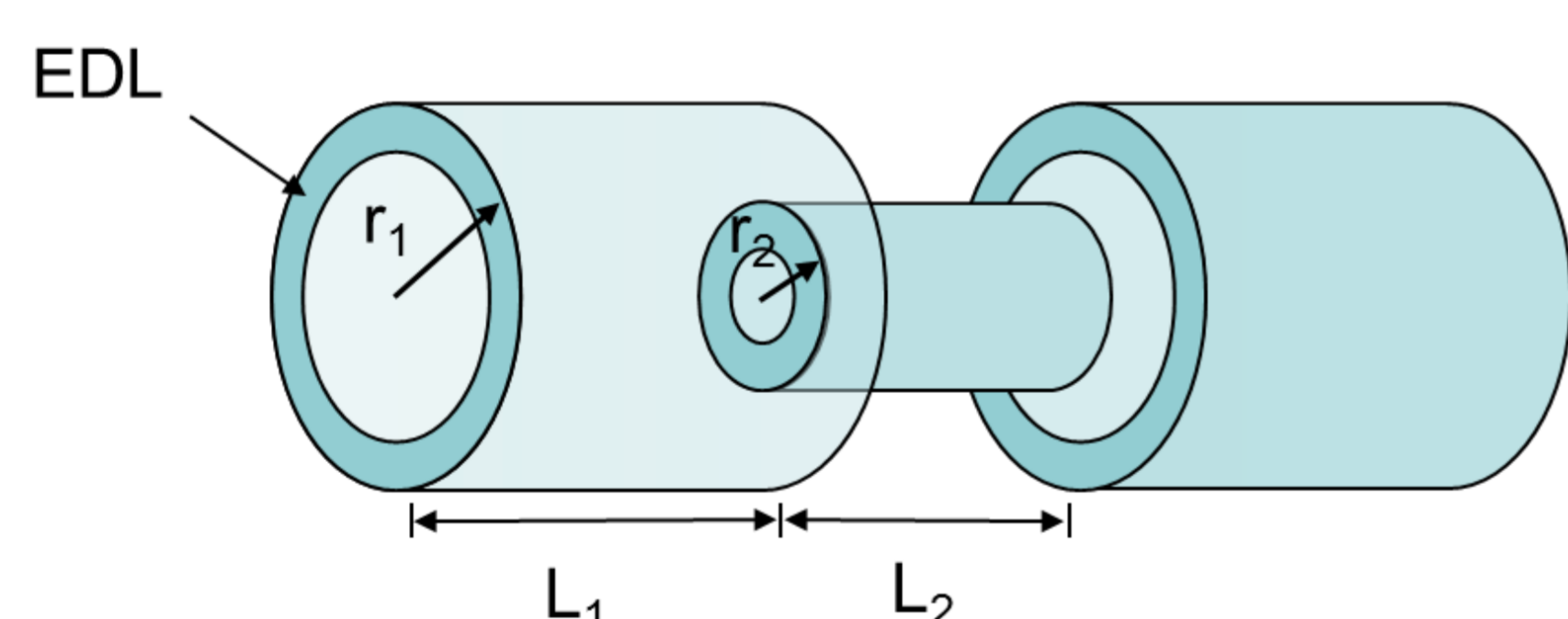


Fig. 8: Sketch of the geometry of the membrane polarization model by Bückner and Hördt (2013).

Salinity dependence

The temperature dependence of the real part of conductivity becomes weaker with increasing salinity, consistent with the measurements (figures 6 and 10). For the surface conductivity the model predicts a decrease of α , whereas the measurements show an increase. The temperature dependence of the calculated imaginary conductivity is weaker for high than for low salinities (figure 11).

Temperature dependence

The influence of temperature on complex conductivity is realized in the model by including the temperature dependence of the ion mobility, zeta potential, Debye length and electrical permittivity. Both real σ' and imaginary part σ'' of the conductivity increase with increasing temperature (figure 9). The real and imaginary part of surface conductivity increase stronger than electrolytic conductivity.

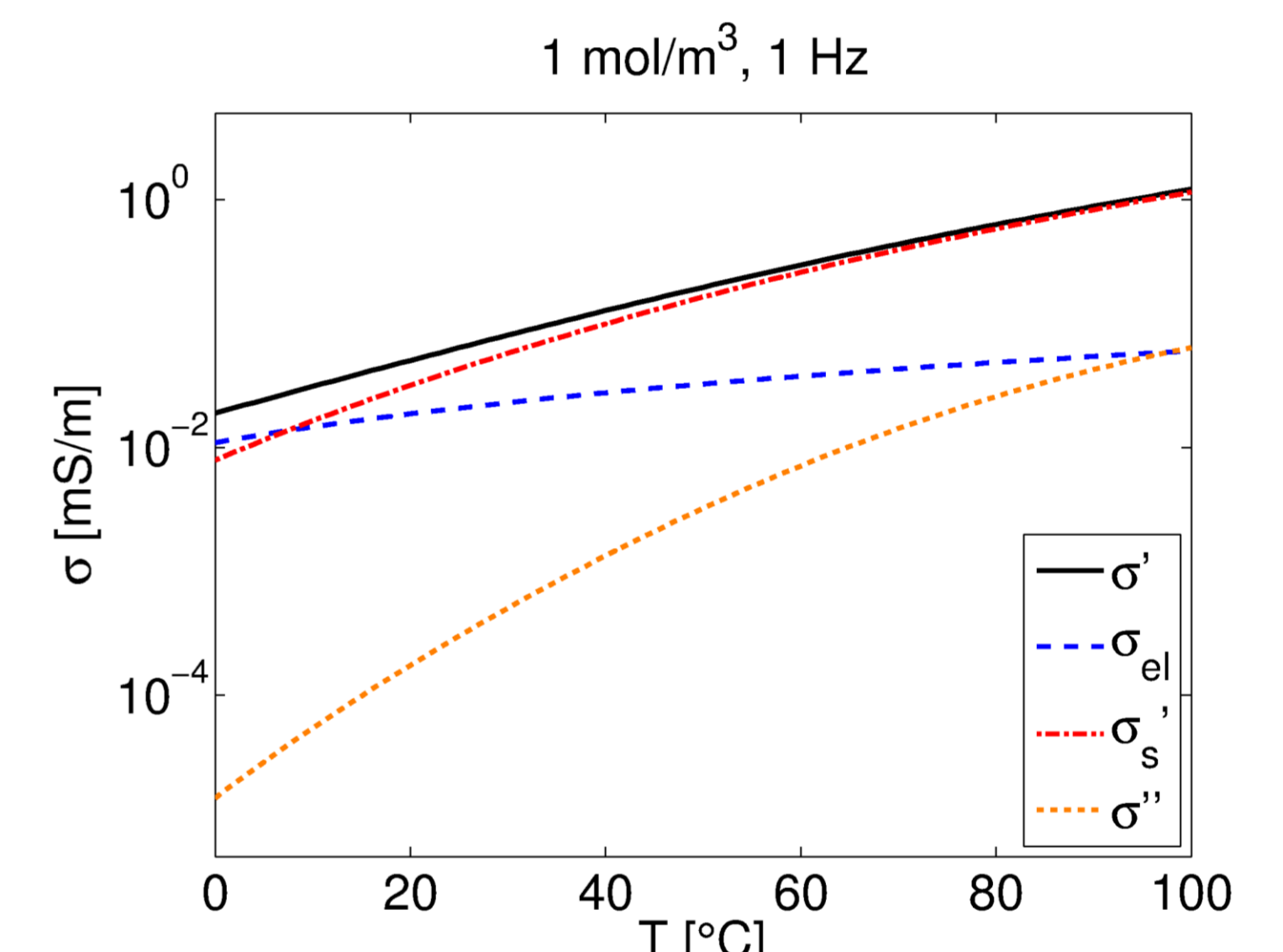
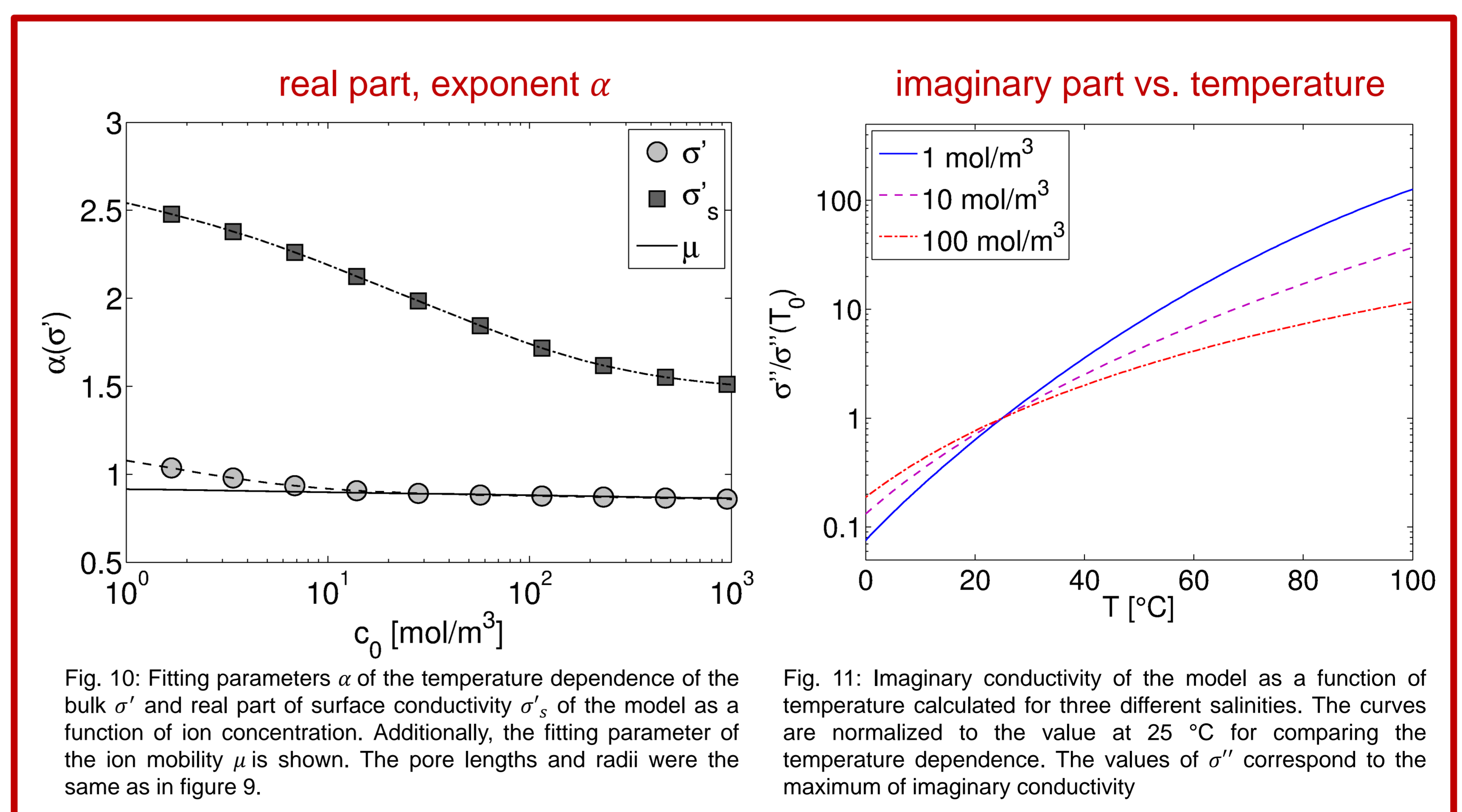


Fig. 9: Complex electrical conductivity at 1 Hz as a function of temperature, calculated with the membrane polarization model with $c_0 = 1 \text{ mol/m}^3$, $L_1 = 100 \text{ }\mu\text{m}$, $L_2 = 1 \text{ }\mu\text{m}$, $r_1 = 10 \text{ }\mu\text{m}$ and $r_2 = 0.1 \text{ }\mu\text{m}$. Bulk σ' , electrolytic σ_{el} , surface σ_s and imaginary conductivity σ'' are shown.



Literature:

- Bückner and Hördt (2013):** Analytical modelling of membrane polarization with explicit parametrization of pore radii and the electrical double layer, *Geophysical Journal International*, 194(2), 804-813.
- Marshall, D. and Madden, T. (1959):** Induced polarization, a study of its causes. *Geophysics*, 24(4):790-816.
- Sorensen and Glass (1987):** Ion and temperature dependence of electrical conductance for natural waters, *Analytical Chemistry*, 59(13), 1594-1597.

Conclusions

The dependence of complex surface conductivity on temperature varies for different samples and slightly differs from the temperature dependence of the fluid conductivity. The salinity influences the strength of the temperature dependence of the fluid and surface conductivity. The membrane polarization model is consistent with the temperature dependence of the measurements in general, but deviates from measurement results in the temperature dependence when salinity is varied.