Temperature-dependence of broadband complex electrical conductivity in unconsolidated porous media with variable clay content

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The complex electrical conductivity of porous media depends on temperature because the mobility of ions increases with increasing temperature. Although this dependence has long been recognized, temperature differences are not yet commonly considered in the interpretation of the complex electrical conductivity. Physically, it is not yet clear whether the temperature dependence of the real and imaginary part of the electrical conductivity is necessarily similar. The real part of the electrical conductivity is mainly determined by ions that can freely move in the bulk solution of the porous medium. Therefore, the temperature dependence of the real part of the electrical conductivity is expected to be similar to that of pure ionic solutions in the case of unconsolidated porous media. The imaginary part is determined by polarisation processes in the pore space, which are assumed to occur in the electrical double layer (EDL) at the mineral-electrolyte interface. This EDL can be separated in a diffuse layer with ionic mobilities similar to the bulk solution, and the Stern layer in which ions are tightly associated with the mineral surface and are typically assumed to have a reduced mobility. Depending on the dominant source of polarization and the associated ionic mobilities, the temperature dependence of the imaginary part of the electrical conductivity may be different. Within this context, the aim of this study is to investigate the temperature dependence of the complex electrical conductivity of unconsolidated porous media with varying amounts of clay in order to better understand polarization mechanisms in soils.

The complex electrical conductivity was determined in the frequency range between 1 mHz and 1000 Hz using spectral induced polarization (SIP). The temperature of the samples was varied from 5 to 25 °C. Two sample types are considered in this study. First, we obtained sample material from a heterogeneous aquifer at the Krauthausen test site. This aquifer mainly consists of sand and coarse gravel with a variable amount of clay. These samples were saturated with a $CaCl_2$ solution, because Ca^{2+} is the dominant cation at the Krauthausen test site. Second, we analyzed artificial sand-clay mixtures with variable amounts of Montmorillonite clay. These samples were saturated with NaCl solution because several experimental and modelling studies have previously used this type of solution. The measured complex electrical conductivity was first normalized to 25 °C for each frequency, and then the linear slope of the increase in real and imaginary part of the electrical conductivity was determined to obtain the frequency-dependent temperature sensitivity of the complex electrical conductivity.

The real part of the electrical conductivity showed the expected 2 % change per degree K for the artificial sand-clay mixtures (Fig. 1). The temperature dependence of the imaginary part of the electrical conductivity also varied around 2 % change per degree K, but consistent deviations were observed for different measurement frequencies and clay contents. The phase showed almost no change with temperature, but the same variations with frequency were observed as for the imaginary part of the electrical conductivity. In the remainder of this study, we prefer to interpret the phase of the complex electrical conductivity because it is less affected by errors in the temperature measurements. The presence of clay resulted in a measurable decrease in the temperature dependence of the phase of the electrical conductivity in case of the sand-clay mixture.

The samples from the Krauthausen test site also showed a measurable decrease in the temperature sensitivity of the phase (Fig. 2). No strong correlation with clay content was found here, because the higher clay content in the top of the aquifer was not associated with a decreased temperature sensitivity of the phase for frequencies below 10 Hz. X-ray analyses were performed to determine the mineral type in the clay fraction. In the upper meters of the aquifer, the clay content was about 7 % and mainly contained muscovite/illite and chlorite. In the middle part of the aquifer, the clay content varied between 1 and 2 % and the main clay minerals were feldspars (microcline and albite). In the lower part of the aquifer, the clay content increased again and the main mineral type was albite followed by microcline. These results seem to indicate that the variations in temperature sensitivity of the phase are also related to the mineral composition of the clay fraction.

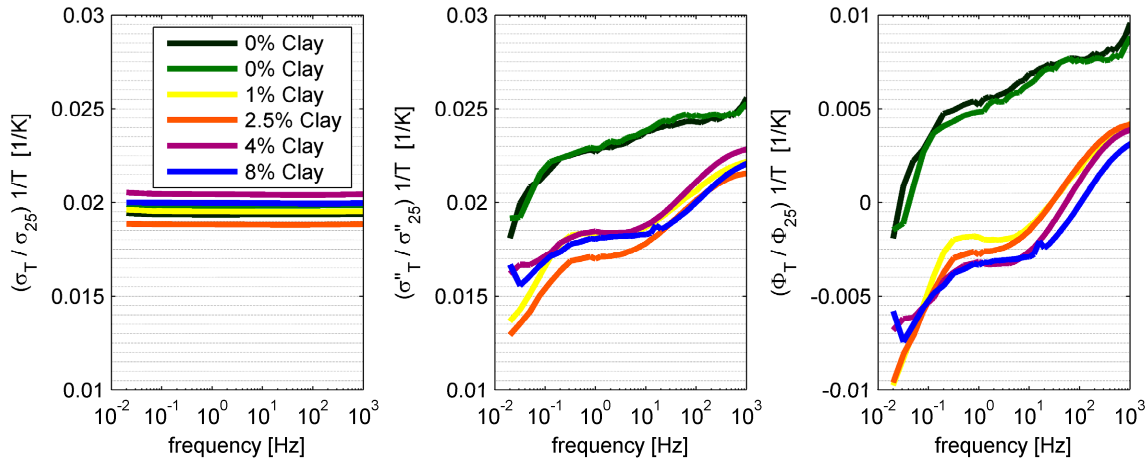
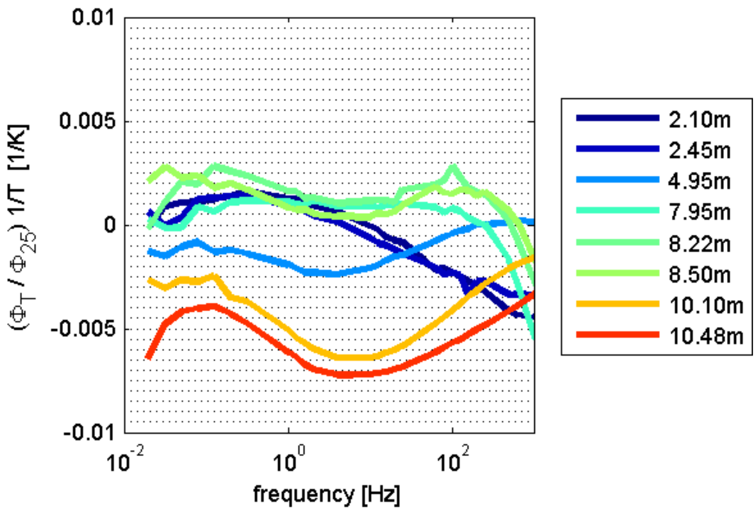


Fig. 1: Temperature dependence of the normalized real (left) and imaginary part (middle) and the phase (right) of the electrical conductivity as a function of frequency for the sand-clay mixtures.

The similarity of the temperature dependence of the real and imaginary part of the electrical conductivity indicates that both conduction and polarization are caused by ions with similar mobility. This seems to suggest that polarization is mainly associated with the diffuse layer. The observed variations in the temperature dependence of the imaginary part of the electrical conductivity could be caused by secondary contributions of the Stern layer. This is supported by the fact that the properties of the Stern layer are known to depend on the clay type.



Depth	Clay	Mineral	colour
2.1 m	7 %	Muscovite/Illit; Chlorite	brown
2.45 m	7 %	"	brown
4.95 m	7 %	"	beige
7.95 m	1 %	Microcline; Albite	beige
8.2 m	1 %	"	beige
8.5 m	2 %	"	beige
10.1 m	9 %	Albite; Microcline	yellow
10.5 m	16 %	"	yellow

Fig. 2: Temperature dependence of the normalized phase of the electrical conductivity as a function of frequency for samples of the Krauthausen test site. Information on the variation in clay content, mineral type, and color with depth are also provided.