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

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Geoelectrical methods are increasingly being used for non-invasive characterization and monitoring of permafrost sites, since the electrical properties are sensitive to the phase change of liquid to frozen water. Here, electrical resistivity tomography (ERT) is most commonly applied, using resistivity as a proxy for various quantities, such as temperature or ice content. However, it is still challenging to distinguish between air and ice in the pore space of the rock based on resistivity alone due to their similarly low electrical conductivity. Meanwhile, geoelectrical methods that utilize electrical polarization effects to characterize permafrost are also being explored. For example, the usage of the spectral induced polarization (SIP) method, in which the complex, frequency-dependent impedance is measured, can reduce ambiguities in the subsurface conduction properties, considering the SIP signature of ice. These measurements seem to be suitable for the quantification of ice content (and thus the differentiation of ice and air), and for the improved thermal characterization of alpine permafrost sites. However, to improve the interpretation of SIP measurements, it is necessary to understand in more detail the electrical conduction and polarization properties as a function of temperature, ice content, texture, and mineralogy under frozen and partially frozen conditions.

In the study presented here, electrical impedance was measured continuously using SIP in the frequency range of 10 mHz to 45 kHz on various water-saturated solid rock and loose sediment samples during controlled freeze-thaw cycles (+20°C to -40°C). These measurements were performed on rock samples from different alpine permafrost sites with different mineralogical compositions and textures. For all samples, the resistance (impedance magnitude) shows a similar temperature dependence, with increasing resistance for decreasing temperature. Also, hysteresis between freezing and thawing behavior is observed for all measurements. During freezing, a jump within the temperature-dependent resistance is observed, suggesting a lowering of the freezing point to a critical temperature where an abrupt transition from liquid water to ice occurs. During thawing, on the other hand, there is a continuous decrease in the measured resistance, suggesting a continuous thawing of the sample. The spectra of impedance phase, which is a measure for the polarization, exhibit the same qualitative, well-known temperature-dependent relaxation behaviour of ice at higher frequencies (1 kHz - 45 kHz), with variations in shape and strength for different rock texture and mineralogy. At lower frequencies (1 Hz - 1 kHz), a polarization with a weak frequency dependence is observed in the unfrozen state of the samples. We interpret this response as membrane polarization, which likewise depends on the texture as well as on the

mineralogy of the respective sample. This polarization response partially vanishes during freezing. Overall, the investigated SIP spectra do not only show a dependence on texture and mineralogy, but mainly a dependence on the presence of ice in the sample as well as temperature. This indicates the possibility of a thermal characterization, as well as a determination of the ice content, of permafrost rocks using SIP.