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Imaging the frozen subsurface: Geoelectrical signatures for the diagnosis of thawing permafrost systems

Andreas Kemna
University of Bonn, Institute of Geosciences and Meteorology, Geophysics Section, Germany

The seemingly gradual thawing of permafrost regions due to global warming involves transitions in hydrologic and mechanical states of the subsurface that can lead to natural hazards such as rock slope failure and rapid increase in greenhouse gas emissions. Therefore, a better understanding of the couplings, dynamics and feedbacks of the underlying thermo-hydro-mechanical (THM) processes is of high societal interest. Due to the typically high spatiotemporal variability of the key state variables, i.e. temperature and ice versus (liquid) water content, in permafrost systems – on top of given geological heterogeneity – geophysical methods have been widely used in permafrost studies. In particular geoelectrical methods have been shown to provide pertinent information on subsurface state and, if applied in a time-lapse manner, process dynamics given their sensitivity to ice-water phase transitions. Electrical resistivity tomography (ERT) has almost developed into a routine imaging tool with numerous applications both in (sub)arctic and high-mountain permafrost. However, given the multiple petrophysical controls on resistivity, thermal state characterization based on resistivity alone suffers from inherent ambiguities and strongly relies on calibrated resistivity-temperature relationships. Moreover, resistivity is not directly sensitive to water flow, which due to advective heat transport is one of the key controls on the complex process dynamics in thawing permafrost systems. These limitations have more recently prompted interest in both combining data from different geophysical methods, e.g., resistivity and seismic data, to overcome ambiguities and improve resolution, as well as to explore the potential of complementary geoelectrical methods for permafrost characterization and monitoring. Among the latter, in particular the induced polarization (IP) and the self-potential (SP) methods hold promise. Results of first laboratory and field studies indicate that the spectral IP (SIP) response of frozen soils and rocks is strongly affected by the characteristic electrical polarization response of ice, suggesting potential of the SIP method for an improved imaging and quantification of ice content in permafrost regions. The SP method, on the other hand, offers direct sensitivity to (melt)water flow, which in thawing permafrost systems is typically characterized by complex spatiotemporal patterns. First SP monitoring attempts at a high-mountain permafrost site revealed strong SP signal variations correlated with the seasonal thawing and refreezing of the ground. Although promising, the use of both (S)IP and SP methods in permafrost environments, in particular for long-term monitoring, is technically challenging. The various successful field applications to date demonstrate the high potential of the different geoelectrical methods for characterizing and monitoring permafrost systems in a non-invasive manner with relatively high spatial and temporal resolution. The provided information on system state and dynamics offers new opportunities for an adequate parameterization and calibration of THM process models and, as a consequence, improved predictive understanding of cryospheric environments under the impact of global warming.