Geophysical Research Abstracts
Vol. 21, EGU2019-15670, 2019
EGU General Assembly 2019

Characterization of permafrost systems through petrophysical joint inversion of seismic and geoelectrical data

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Characterizing the spatiotemporal distribution of liquid water, ice, and air pore fractions is crucial for a process-based understanding of permafrost systems and their hazard potential upon climate-induced degradation. While borehole information is expensive and limited to discrete locations, geophysical techniques offer opportunities to image permafrost in a non-invasive manner at high spatial and temporal resolution. Seismic and geoelectrical methods are sensitive to the phase change of water between its liquid, frozen, and gaseous states and are therefore widely used in cryospheric geophysical applications.

We present an approach that uses apparent resistivities and seismic traveltimes simultaneously in a petrophysically coupled joint inversion to estimate the volumetric fractions of liquid water, ice, and air. By formulating the inverse problem in terms of the petrophysical target parameters, the underlying petrophysical relations (including volume conservation) as well as non-geophysical data (e.g., information on water content inferred from soil moisture measurements) can be honored during parameter estimation. We demonstrate advantages and limitations of the approach based on a synthetic model. In comparison to post-inversion transformation of conventional tomograms, the joint inversion leads to quantitatively improved and physically plausible images, but does not overcome some inherent petrophysical ambiguities (e.g., between ice content and porosity).

We further apply the approach to a field data set acquired in a watershed near Teller, Alaska, during the summer of 2018. The resulting tomograms exhibit lateral changes in liquid water and ice content, which are in agreement with changes in vegetation, topography, soil moisture, and temperature. While ambiguity in the absolute values remains in the absence of additional laboratory and borehole information, the spatial distributions are consistent. Through spatial clustering of water, ice, air, and rock contents, we developed a conceptual subsurface model, which could provide a basis for the parameterization of process models that simulate the dynamics and evolution of permafrost environments.