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High-Resolution Time-Lapse GPR Monitoring of Saline Tracer Flow in Fractured Rock

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The characterization of flow and transport in a fractured rock mass is crucial for several applications, amongst them the environmental risk assessment of soil contaminants and decisions and strategies for remediation, the assessment of nuclear waste disposal strategies, as well as the accessibility of geothermal energy. Flow and transport studies have therefore been a key focus of hydrogeological research for several decades.

Monitoring subsurface processes is challenging, however, as they often cannot be observed directly. Here we present an approach to use ground penetrating radar (GPR) for time-lapse monitoring saline tracer migration through a weakly fractured crystalline rock mass with sub-mm fracture apertures. The experiments were conducted at the Grimsel Test Site (Switzerland) in the framework of a hydraulic stimulation project. Repeated GPR measurements were performed in a decameter size, fully saturated rock mass.

We have developed a new workflow exploiting time-lapse difference imaging techniques, to monitor tracer propagation using repeated single-hole reflection measurements. A pre-injection reference profile is subtracted from the repeatedly recorded monitoring profiles to remove the reflections from the geology and structures that would otherwise overwhelm the tracer signal. Waveform differencing is highly dependent on proper measurement repeatability regarding phase and amplitude and sampling, thus stable acquisition conditions are crucial. Several challenges and error sources have to be taken into account, such as sampling rate drift and timing inaccuracies, antenna mis-positioning, and time-varying ambient noise. We have developed an extensive data processing workflow to overcome these challenges and to ensure the required compatibility of the recorded profiles with the reference profile. Our approach allows to map the tracer signal in great detail, beyond the GPR system's inherent capabilities that are limited by instabilities. Combining different recordings from two surveys in parallel boreholes allows for 3D tracer localization within the rock volume by considering the radial symmetry of the antennas, thereby drastically reducing common localization uncertainties.

Additionally, a further time-lapse cross-hole dataset that was recorded simultaneously with a single-hole reflection survey by using a multichannel GPR module. These data were analyzed with our time-lapse inversion approach to investigate the signal attenuation caused by the saline tracer, which is affected by the volumetric extent of the tracer and the salt concentration.

Overall, we are able to track the saline tracer within the rock volume in space and time with high resolution. Our results are in good agreement with conventional tracer experiments at the same test site. This allows us to determine the actual flow paths and transport properties such as velocities within the fracture network. By combining our GPR-imaging based findings with hydrogeological experiments, a discrete fracture network of the investigated volume can effectively be established and constrained.