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Time-lapse GPR reflection imaging of saline tracer movement in a fractured crystalline aquifer, Brittany, France

Caroline Dorn (1), Niklas Linde (1), Tanguy Le Borgne (2), Olivier Bour (2), and Ludovic Baron (1)

(1) Institute of Geophysics, University of Lausanne, Lausanne, Switzerland, (2) Geosciences Rennes, UMR CNRS 6118, University of Rennes, Rennes, France.

Hydrogeological techniques can only sample tracer concentrations within boreholes implying a limited ability to constrain possible flow geometries in heterogeneous media. Geophysics can image tracer movement away from boreholes and may thus provide valuable information to hydrogeologists. Single-hole ground penetrating radar (GPR) reflection monitoring is a promising tool to image saline tracer transport in fractured rock, as reflections originating from fractures are sensitive to changes in the electrical conductivity of fluids. We present here the first migrated single-hole GPR reflection difference sections to image tracer transport.

We consider one out of six tracer injection experiments that were conducted in fractured granite at a hydrogeological observatory site in Ploemeur, France. In the injection well, 70 L of saline tracer (50 g NaCl/L) were injected at a rate of 5.5 L/min above a packed-off interval to ensure injection in a transmissive fracture at 55 m depth. After the end of injection, we continued to push the tracer with fresh water. In the observation well located 6 m away, we pumped water at the same rate (5.5 L/min) and acquired single-offset single-hole GPR sections (250 MHz) every 5 minutes with a depth sampling of $\Delta z = 0.1$ m over z = 35-75 m depth. The locally increasing fluid conductivity (initial tracer salinity is 30 times higher than the background salinity) leads to a decrease in wave propagation velocity and an increase of signal attenuation in the fractures, thus changing phases and amplitudes of reflections. To image waveform changes that occur within the rock formation, we must first remove effects associated with increasing salinities in the monitoring well as they affect the effective source signal. The higher frequencies get significantly attenuated with increasing borehole fluid conductivity thereby creating changes in time-lapse reflection amplitudes. To remove borehole-induced changes we developed a processing scheme that included denoising in the wavelet domain, wavelet-normalization filtering, envelope scaling, eigenvector filtering, subtraction of the reference dataset and division by the envelope of the reference dataset. The final depth migrated images allowed us to clearly identify consistent temporal changes at locations corresponding to fractures previously imaged in static GPR sections. The tracer moves with $\sim$0.4 m/min trough at least 6 fractures, dipping 30-70°, and it arrives at 3 different depths in the observation well. The presented methodology is a promising and complementary tool for near-field imaging of tracer transport in fractured media. Data from all six experiments will in the future be integrated with hydraulic head, tracer concentration, and flowmeter data to invert for fracture geometry and properties.