Insights into complex sub-decimeter fracturing processes occurring during a water-injection experiment at depth in Äspö Hard Rock Laboratory, Sweden

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Introduction
We investigate the source characteristics of picoseismicity recorded during a hydraulic fracturing in-situ experiment performed in Äspö Hard Rock Laboratory, Sweden. The experiment consisted of six stimulations driven by three different water injection schemes and was performed inside a 28 m long, horizontal borehole located at 410 m depth. The fracturing process was monitored with a variety of seismic networks covering a wide frequency band between 0.01 Hz and 100000 Hz including broadband seismometers, geophones, high-frequency accelerometers and acoustic emission sensors.

Figure 1: The 3D visualization of the project site at 410 m depth. The seismic activity is shown with spheres of various colors reflecting the stimulation stage and size corresponding to the moment magnitude. The schematic position of injection intervals for stimulations HF1-HF6 are presented as semi-transparent discs of arbitrary chosen size with the color reflecting the stimulation (from right to left: green – HF1, blue – HF2, red – HF3, teal – HF4, magenta – HF6, and yellow – HF6). The dimension of the checkerboard pattern square is 10×10m. The AE and accelerometers and their orientation are shown along boreholes using yellow and green bottle-shaped objects.
The combined seismic network allowed for detection and detailed analysis of 196 seismic events with moment magnitudes Mw<-3.5 (source sizes of dm- scale) that occurred solely during the stimulations and shortly after (Figure 1). The double-difference relocated seismic catalog of source parameters was used to investigate the physical characteristics of induced seismicity and compared them to the stimulation parameters. We observe spatio-temporal migration of picoseismic events (propagation away and towards wellbore injection interval, cf. Figure 2) is controlled by changes in fluid injection pressure times the injection rate. We find that the total radiated seismic energy is extremely low with respect to the product of injected fluid volume and pressure (hydraulic energy). The radiated energy correlates well with the hydraulic energy rate. The obtained fault plane solutions are consistent with the local stress field orientation, and signify the reactivation of pre-existing rock defects and influence of pore fluid pressure on activated fault plane orientations.

Figure 2. Dependence between the time since the beginning of stimulation and distance of AE events from injection interval for the fifth stage of first and second stimulation. The AE events are shown as black circles. The injection pressure and fluid flow rate are presented as solid orange and green lines, respectively. The dashed black curves represent expected space-time evolution of a fluid pressure perturbation front triggering seismicity assuming that it is solely controlled by scalar fluid pressure diffusion in homogeneous isotropic medium. The dashed curves are parameterized using different values of apparent hydraulic diffusivities.