Passive monitoring and 3D imaging of the bedrock response to the 2018 Espoo/Helsinki geothermal stimulation

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In recent years several deep geothermal energy projects have been forced to close following the occurrence of large seismic events associated with the stimulation of the surrounding bedrock. In 2018, an enhanced geothermal system (EGS) experiment performed in Helsinki, Finland concluded with no seismicity exceeding the threshold magnitude and thus provides an intriguing showcase for future stimulation experiments in similar environments. During the 49 days of the experiment, the five-stage injection of ~18,000 cubic meters water stimulated many thousands of earthquakes. Like in all previous stimulation cases the earthquake data constitute the primary source for the assessment of the scientific and operational aspects of the reservoir response. Here we apply ambient noise based monitoring and imaging techniques to data collected by 100 short period three-component stations that were organized in three large arrays consisting of nominally 25 stations, in addition to three small four-station arrays, and 10 single stations, during a 100 day period. We compute daily nine-component noise correlations between all stations pairs except for the intra-array pairs in a frequency range between 0.5 and 10 Hz. We measure waveform delays within our correlation functions as a function of frequency and lag time using the Continuous Wavelet Transform. We then invert these observations using a Markov chain Monte Carlo method to obtain the temporal variation in seismic velocity dv/v during the injection. By exploiting the variable spatial sensitivities of the surface- and body-wave components at different coda-wave lapse times and frequencies, we are able to image the medium response to the stimulation in both time and space. We compare the estimated seismic velocity variations to other observations such as H₂O/V₂, as well as dv/v observations obtained from collocated borehole data. Importantly, we also compare the observed medium response to seismicity and pumping parameters. Our results suggest that we are able to resolve medium changes that are not solely associated with the induced earthquakes, but also potential signatures of fluid content or pressure changes in the bedrock. The combined observations of seismicity, pumping parameters and dv/v changes collected in this experiment can further advance passive monitoring techniques in the context of enhanced geothermal systems, and facilitate a more comprehensive analysis of fluid-rock interactions that may occur aseismically.

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