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Array based analysis of induced earthquake characteristics using beamforming and back-projection methods in Helsinki, Finland

Bo Li[1], Alice-Agnes Gabriel[1], Annukka Rintamäki[2], and Gregor Hillers[2]
[1]Institute of Geophysics, Department of Earth and Environmental Sciences, Ludwig-Maximilians-University, Munich, Germany
[2]Institute of Seismology, University of Helsinki, Helsinki, Finland

The evolution and characteristics of induced seismicity in geothermal stimulations can shed light on water pathways and fracture network development. However, these seismic sources are usually difficult to characterize due to their small magnitudes and the low signal-to-noise ratio (SNR) of observational recordings. Heterogeneous and ill-constrained 3D subsurface structure further restricts the local-scale application of array based methods, such as the back-projection method. The 2018 st1 Deep Heat geothermal stimulation experiment in Espoo, Finland, induced thousands of seismic events in the 5-6 km depth range with magnitudes smaller or equal to ML 1.8 (Hillers, et al., 2020). The competent bedrock and absence of a dissipating sedimentary layer results in high SNR seismograms collected by three 4-station arrays, three 25-station arrays and tens of standalone stations located within 5 km distance around the wellhead. These high-quality data facilitate the application of multi-array beamforming and the back-projection methods, to image small-magnitude induced seismicity sources and characterize their properties at reservoir scales.

The beamforming results demonstrate array, frequency and phase (P or S) dependent slowness biases of catalog locations, which are obtained using standard location procedures with manually picked P- and S-wave arrivals. This indicates multi-scale heterogeneity in the study region. Specifically, we find that the back azimuth of the slowness at each array points to inconsistent locations and leads to poorly constrained epicenters. We show that the systematic slowness variability can be reduced and multi-array location estimates can be greatly improved by calibration using well-constrained catalog events.

To perform the back-projection, we select unclustered stations from narrow epicentral distance ranges to avoid unfavorably large variations in the duration of the body phases, and we set the azimuth gap threshold to less than 40 degrees. The locations determined by the back-projection are close to the catalog locations, with the majority of them within 150 m, suggesting a successful application of the back-projection technique using local stations to study small events. We repeatedly observe "swimming" artifacts (Ishii et al., 2007; Walker and Shearer, 2009), i.e. the back-projection locations migrate in a certain direction with time. This is typically attributed to array-source directivity effects in teleseismic applications, but in our case the stations are well-

distributed around the source. We next use numerical wave propagation simulations, with receivers homogeneously azimuthal distributed at constant epicentral distance to a point-source. We apply the back-projection using synthetic seismograms. The results confirm the consistent appearance of “swimming” patterns and the apparent migration direction which changes in dependence on the focal mechanism of the point source. We conclude that the back-projection method may provide useful proxies for source mechanisms to help track and link the evolving fracture network.