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Controlling induced seismicity during hydraulic stimulation of a 6 km deep Enhanced Geothermal System in Finland

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We show that near-realtime seismic monitoring of fluid injection allowed control of induced earthquakes during the stimulation of a geothermal well near Helsinki, Finland. The injection well, OTN3, was drilled down to 6.1 km-depth into Precambrian crystalline rocks. Well OTN3 was deviated 45° from vertical and an open hole section at the bottom was divided into several injection intervals. A total of 18,159 m^3 of fresh water was pumped into crystalline rocks during 49 days in June- and July, 2018. The stimulation was monitored in near-real time using (1) a 12-level seismometer array at 2.20-2.65 km depth in an observation well located 10 m from OTN3 and (2) a 12-station network installed in 0.3-1.15 km deep boreholes surrounding the project site. Earthquakes were processed within a few minutes and results informed a Traffic Light System (TLS). Using near-realtime information on induced-earthquake rates, lo-cations, magnitudes, and evolution of seismic and hydraulic energy, pumping was either stopped or varied between wellhead-pressures of 60-90 MPa and flow rates of 400-800 l/min. This procedure avoided the nucleation of a project-stopping red alert at magnitude M2.1 induced earthquake, a limit set by the TLS and local authorities. The stimulation resulted in detection of >43,000 earthquakes with $-1.2<M_L<1.9$. The original catalog was relocated using double-difference technique to improve hypocenter precision. The 4032 relocated earthquakes were used to investigate the spatio-temporal evolution of seismicity, seismic energy release, and maximum magnitude in response to injection. We found hypocenter distribution, Gutenberg-Richter (GR) distribution and relation between hydraulic and radiated energy suggest (re-)activation of size limited network of distributed fractures. The temporal behavior of G-R b-value, as well as a lack of temporal (Omori-type) correlations in a presence of spatial localization of earthquakes suggest very limited earthquake triggering and stress transfer at low level of ambient stress. The maximum observed magnitudes scale with stored elastic (=hydraulic) energy, following a fracture-mechanics based model of Galis et al. (2017). Our results suggest a possible physics-based approach to controlling stimu-lation induced seismicity in geothermal projects.