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Statistical analysis and modeling of seismicity related to the exploitation of geothermal energy

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Geothermal energy is an integral and important part of renewables but it is frequently observed that its production induces seismicity. Here we analyse in detail seismicity from two hydrothermal reservoirs in Germany and one hydrothermal field in Italy. We focus on temporal changes of seismicity rates. This study was motivated by the results of numerical simulations. The modeling of stress changes caused by the injection and production of fluids revealed that the seismicity rate should decrease on a long-term perspective which does not match the observed seismicity rates. To understand this mismatch we analyse the waiting time distributions of the seismic events in both time domain (inter event times) and fluid volume domain (inter event volume). We find clear indications that the observed seismicity contains two components: (1) seismicity that is directly triggered by the production and re-injection of fluid, in other words, induced events, and (2) seismicity that is triggered by earthquake interactions also known as aftershock triggering. In order to calibrate and better constrain our numerical simulations using the induced seismicity we apply a catalog declustering the separate the two components and remove the aftershocks from the observed catalogs. We use the magnitude-dependent space-time windowing approach introduced by Gardener and Knopoff (1974) and tested several published algorithms to calculate the windows. We choose the final space-time window for a given catalog based on the waiting time distribution of the events after the declustering. Technically speaking, we suppose that the probability density of waiting times in the fluid volume domain corresponds to a homogeneous Poisson process (HPP, Langenbruch et al., 2011). After catalog declustering, we conclude that the different reservoirs show a comparable response to the production and re-injection of fluids and the additional triggering of seismicity by earthquake interactions. The declustered catalogs of the considered reservoirs contain approximately 50 per cent of the number of events in the original catalogs. Furthermore, we perform ETAS modeling (Epidemic Type Aftershock model, Ogata, 1985,1988) for two reasons. First, we want to understand if the different reservoirs are also comparable in the earthquake interaction patterns and hence in the aftershock triggering following larger magnitude induced events. Second, if we identify systematic patterns, the ETAS modeling can contribute to the forecast and consequently to the mitigation of seismicity during production of geothermal energy. We find that stationary ETAS models can not accurately capture the observed seismicity rate changes. One reason for this finding is given by the rate of induced events (or the back-ground activity in the ETAS model) which is not constant with time. Therefore we apply non-stationary ETAS modeling which results in a good agreement between observation and model. However, the needed non-stationarity in the process complicates the application of ETAS modeling for the forecast of seismicity during production. Thus, its implementation in so-called traffic-light-systems for the mitigation of possible seismic hazard requires further detailed analysis.