Spatiotemporal modelling of induced seismicity with a stress-based statistical approach applied to different production sites

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In the framework of the Geo:N project SECURE (Sustainable dEployment and Conservation of Underground Reservoirs and Environment) we developed a Python software toolbox to model the rate and distribution of seismicity induced by anthropogenic stress changes at various production sites (gas production, hydrofracturing, gas storage). This toolbox tests different frictional behavior of the underground (linear or rate-and-state stressing rate dependent, critically or subcritically prestressed faults) and takes into account the uncertainties of the production site parameters. The knowledge on the location and orientation of pre-existing faults can be considered as well. Model parameters are estimated by fitting the model to recorded historical seismicity using a maximum likelihood approach. We discuss applications at conventional gas fields, hydraulic fracturing experiments and an aquifer gas storage site, covering a wide range of spatial and temporal scales of induced seismicity in different settings and for different production schemes. This enables to investigate the underlying physical processes by the comparison of the different models. Additionally, the model parameters are linked to frictional material properties and the best performing model can be used to forecast the seismicity rates in space and time with their uncertainties according to the production plans.

Induced seismicity at gas fields in the Northern Netherlands and in Germany have similar tectonic settings but very different extents, depths and production histories. The data set of two sites are compared which both show a large delay of the first recorded seismicity after the start of production. Using our model we can reproduce the long delay for both sites. Thanks to the long and detailed data set we successfully reproduce the spatiotemporal pattern of the seismicity of one site, whereas the limited number of seismic events result in large uncertainties for the other site. In the comparative testing of the models the critically prestressed rate-and-state model performs best. This means that the complete stressing history influences the resulting seismicity. We also applied the model to a hydraulic fracturing experiment in granite comparing data sets for different fracturing methods and different phases of a stimulation experiment. Hundreds of microearthquakes are localized in a volume of roughly 15x15m with increasing number of events for later refraction stages indicating the growth of rock fracturing. A third application is run for a gas storage in an aquifer layer, which is loaded by injection and production operations. Here the
proportion of the tectonic versus the anthropogenic induced seismicity is investigated analyzing the varying number of small local earthquakes in the region.