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Summary

Fracture networks in underground reservoirs are important pathways for fluid flow and therefore a deciding factor in the development of geothermal reservoirs. Yet, they are difficult to characterize since they usually cannot be directly accessed. Subject of the doctoral project is to study induced seismicity in enhanced geothermal systems to characterize the underground fracture network. The main objectives are to get a better understanding of the structures controlling the fluid flow and the processes responsible for induced seismicity.

The first part of this work focuses on the case study of the Rittershoffen deep geothermal reservoir. It is demonstrated how the integration of advanced processing techniques like template matching detection, relative relocation and waveform clustering can lead to a deeper insight into the structure of the fault system and its reaction to repeated fluid injection. The well GRT1 at Rittershoffen offers unique conditions for such a study. It underwent a sequence of thermal, chemical and hydraulic stimulation, giving the opportunity to perform a detailed monitoring of the seismic response of the fault systems to fluid injections with different operational set-ups. By the applied processing, a much higher level of detail in the tempo-spatial resolution was derived then in previous studies on the induced seismicity at Rittershoffen. The results demonstrate the development of the successively activated fault network over the injection steps by tracing the influence of the different stimulations and allow for an analysis of the mechanisms behind the induced seismicity.

Two spatially separated fault segments became seismically active over the course of the stimulation sequence, one during the injections itself, the other at the very end of the hydraulic stimulation and then again four days after shut-in. Seismicity on this two fault segments shows distinct characteristics in terms of event migration and waveform clusters, hinting at different fault activation mechanism. Seismicity on the first fault shows similar characteristics for the thermal and hydraulic stimulation in the area active during both injections. The well-known geological setting and unique operational set-up in combination with the detailed analysis allowed to derive a deeper understanding of the hydro-mechanical interactions in the reservoir and demonstrated a change in the mechanically state of the fault between seismicity onset during thermal and hydraulic stimulation.

In the case of the seismicity induced at Rittershoffen, the relative re-location of the events made two planar fault segments apparent, whose orientations and extends are well confined. Yet, it may be that despite the precise re-location of induced seismic events, the associated structures in other underground reservoirs remain unclear because the seismicity forms a rather dense spatial cloud, which makes individual features difficult to detect.

Therefore, in the second part of this work, a new method is proposed to highlight the fracture network in seismic clouds that do not form apparent planar structures. With this method, the likelihood of having a fracture at a given location is computed from the distribution of seismic events and their source parameters. The result takes the form of a so-called Pseudo Probabilistic Fracture Network (PPFN). Contrary to other methods that try to highlight fracture networks in seismic clouds, the PPFN takes into account not only the event hypocenters but also their magnitudes and focal mechanisms, to keep a closer link with the geophysical properties of the earthquakes.

The basic principle of the PPFN is to estimate the connectivity between any spatial position in the seismic cloud and the events based on the distance to each event, the minimum size

of the rupture plane derived from the event magnitude, and the orientation provided by the focal mechanism. The PPFN is tested on a set of synthetic datasets, where it is demonstrated that the method is able to reproduce fault planes placed in a cloud of randomly distributed events. The PPFN is then applied to the seismic cloud induced during the stimulation of the GPK2 well, at Soultz-sous-Forêts deep geothermal site. It reveals a large prominent fault in the deep-northern part of the seismic cloud, supporting conclusions from previous work, and a minor structure in the southern upper part, which may be a branch of the main fault.