The influence of the heterogeneous asperity distribution on induced seismicity and permeability evolution during hydraulic fault zone stimulation

Linus Villiger¹, Dominik Zbinden¹, Antonio Pio Rinaldi¹, Paul Antony Selvadurai¹, Hannes Krietsch², Valentin Gischig³, Joseph Doetsch³, Mohammadreza Jalali⁴, Florian Amann⁴, and Stefan Wiemer¹

¹Swiss Seismological Service, ETH Zurich, Zurich, Switzerland
²Department of Earth Sciences, ETH Zurich, Zurich, Switzerland
³CSD Ingenieure, Bern, 3097, Switzerland
⁴Department of Engineering Geology & Hydrogeology, RWTH Aachen, Aachen, Germany

Several decameter-scale in-situ stimulation experiments were conducted in crystalline rock at the Grimsel Test Site, Switzerland, with the aim to advance our understanding of the seismo-hydro-mechanical processes associated with deep geothermal reservoir stimulation. To allow comparability between the experiments, a standardized injection protocol was applied for all experiments. Induced seismicity was recorded using acoustic emission sensors and accelerometers, which were distributed along tunnel walls and within four boreholes. Hydro-mechanical responses of the fault zones were measured using grouted longitudinal fiberoptic strain sensors and open pressure monitoring borehole intervals. A total of four ductile shear zones (with brittle overprint) and two brittle-ductile shear zones have been stimulated during these experiments.

Here we present an analysis of heterogeneous permeability evolution within a target shear zone during ongoing stimulation. The shear zone in question is an originally ductile shear zone which contains a single fracture in the injection interval. The observed planar seismicity cloud indicates that most of the stimulation process was confined within the target shear zone. Hydraulic characterization of the injection interval before and after stimulation revealed an enhancement in interval transmissivity from 8.3 \( \times 10^{-11} \) m²/s to 1.5 \( \times 10^{-7} \) m²/s. Within the reservoir, the seismo-hydro-mechanical data (i.e. seismicity cloud, pressure peaks and local deformation) spatiotemporally coincide, suggesting that permeability enhancement along the shear zone is highly localized and heterogeneous. Thus, we argue that the permeability evolution is linked to asperity distribution and breakdown within the shear zone.

The conceptual model developed from the experimental analysis is implemented in a three-dimensional numerical model, with which we attempt to simulate the directional permeability creation observed in the experiment. The model accounts for a discrete planar fault zone of finite thickness with distributed low-permeability, brittle asperities embedded in a more permeable damage zone mimicking the ductile shear zone at Grimsel. The hydro-mechanical processes are
modeled with the TOUGH-FLAC simulator, which sequentially couples fluid flow and poroelastic deformation within the fault and the surrounding medium. A Mohr-Coulomb failure criterion is used to simulate asperity reactivation, which can lead to permeability enhancement of the reactivated area.