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Coupled Hydromechanical Modeling of the hydraulic stimulation in an Enhanced Geothermal System to Determine Triggering Mechanisms of Post-Injection Induced Seismicity

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Abstract

To understand and distinguish the mechanisms that cause fault reactivation during and after injection, we build a model based on the Basel EGS site, with the pre-existing fault network derived from the analysis of monitored seismic events occurring during the stimulation. We estimate injection-induced pore pressure and stress variations, as well as fault reactivation by solving the fully coupled hydromechanical problem during both fluid injection and after its stop. We analyze the impacts of pore pressure diffusion, poroelastic stressing, stress transfer and slip-induced fault friction weakening on the activation of nearby faults. We observe different combinations of mechanisms occurring in the co- and post-injection stages. Pore pressure buildup triggers the reactivation of faults close to the well during injection, while the combination of poroelastic stressing and stress transfer reactivates farther faults, during and after the stop of injection.

1. Introduction

Geothermal energy is a promising technology to provide long-term and secure green energy to reduce carbon emissions. Yet, hydraulic stimulation of the reservoir can induce seismicity in Enhanced Geothermal Systems (EGS) (Majer et al., 2007). High magnitude induced seismic events may lead to project cancellation, as has occurred in the EGS projects at Basel (Switzerland, 2006) and Pohang (South Korea, 2017). In both of which the largest earthquake occurred after the stop of injection (Ellsworth et al., 2019; Häring et al., 2008).

To better understand and distinguish the mechanisms that cause fault reactivation during and after injection, we build a model based on the Basel EGS site, with the pre-existing faulting network derived from the monitored seismic events induced by the hydraulic stimulation. We are able to reproduce the observed seismic pattern through the reactivation of the pre-existing fractures. We distinguish the effects of pore pressure diffusion, poroelastic stressing, stress transfer and slip weakening as triggering mechanisms.

2. Methods

We design the faulting network based on the clouds of clusters, and their focal mechanisms as reported in Deichmann et al. (2014). We estimate pore pressure and stress variations due to water injection solving the fully coupled hydromechanical problem with the Finite Element Method (FEM) simulator CODE_BRIGHT (Olivella et al., 1996), both during and after the stop of fluid injection. Slip along the pre-existing faults is simulated adopting a visco-plastic behavior.

3. Results

Pore pressure diffusion effects on fault reactivation are studied by comparing pressure variation with the critical pressure, i.e., the pressure required to induce shear failure, which is determined for each one of the clusters. Faults located nearby the injection well undergo a pressure higher than their critical pressure during injection (Figure 1a), meaning that pore pressure could trigger their reactivation. After the stop of injection, pore pressure diffuses in the reservoir, but with a smaller value that cannot explain further fault reactivation. Thus, we take into account the poroelastic stressing and static stress transfer effects as additional triggering mechanisms. We compare a first model with faults having elastic behavior, highlighting the poroelastic response of the faults, with a second one with faults having visco-plastic mechanical behavior following a Mohr-Coulomb failure criterion. The latter simulates the response of the faults to the poroelasticity and to the stress transfer resulting from fault reactivation. Poroelasticity, as pore pressure diffusion, spreads during injection but with a velocity larger than pressure diffusion, thus reaching farther faults. Depending on the slip direction of the faults and the initial stress conditions, poroelastic stressing acts on the destabilization of faults or on their stabilization. At the stop of injection, the abrupt relaxation of the poroelastic stress can potentially induce the reactivation of the co-injection stabilized faults (Figure 2b). Stress interaction between nearby faults (Figure 1c) has an important triggering effect, especially for the post-injection reactivations. We quantify the mechanism by comparing our model with simulations of elastic-behavior faulting domains having only one fault following a visco-plastic behavior, and we observe the interactions between the different fault reactivations. Slip weakening is represented in our simulations by a linear decrease of the friction coefficient when the stress state reaches the shear failure surface of faults. We compare models with and without a possible slip weakening, and we observe that the slip weakening that occurs as a result of damages of fault asperities is responsible of multiple reactivations for some faults (Figure 1d).

Co-injection fault reactivations are triggered mainly by pore pressure buildup diffusion, combined with poroelastic stressing. This type of failure corresponds to the faults located in the vicinity of the well, represented by fault F1 (Figure 1e). Post-injection seismicity, represented by fault F2, is induced mainly by the abrupt relaxation of the poroelastic stressing, added to the stress transfer of nearby fault reactivations (Figure 1f). Slip weakening also plays an important role in enhancing the potential of fault reactivation.

4. Conclusions

Our coupled hydromechanical modeling approach allows to determine the triggering mechanisms of fault reactivation during hydraulic stimulation of EGS. Different processes of reactivation are noticeable for faults as a function of their orientation and location. Co-injection fault reactivation is mainly due to pore pressure variations, while post-injection induced seismicity is triggered by the combination of poroelastic stressing, stress transfer and pore pressure diffusion. Slip weakening affects the fault stability, either during and after injection. This hydromechanical model is coherent with the monitored seismic events of the study case, i.e., Basel EGS, and it can be used as a tool to define injection strategies to mitigate induced seismicity.

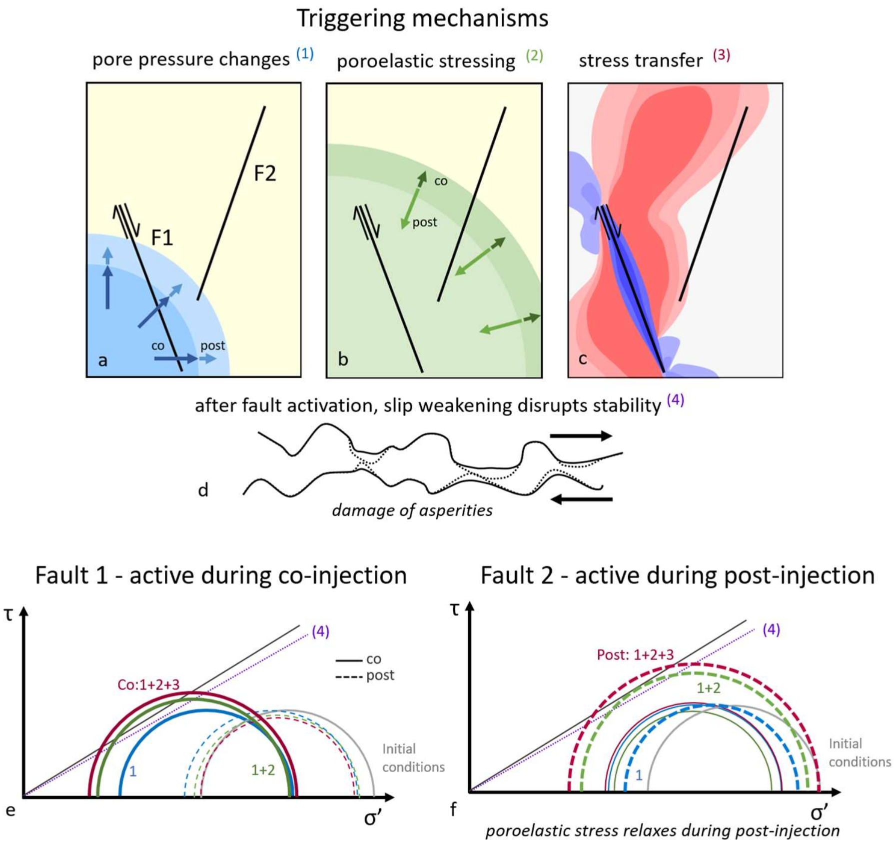

Figure 1 Conceptual illustration of triggering mechanisms: (a) Pore pressure buildup diffuses both during injection and post-injection stages, while (b) poroelastic stressing propagates farther and then contracts after the stop of injection. (c) Stress transfer due to shear slip of fault F1 disrupts the stability of the adjacent fault F2. (d) Fault asperities damage due to friction from fault activation weakens friction properties of the fault. (e) and (f) Mohr-Coulomb diagrams illustrating the combination of the three mechanisms on faults in the region of F1 and F2, respectively. Each colored circle represents the addition of a mechanism starting from the initial conditions. Solid circles represent co-injection mechanisms while dashed circles illustrate post-injection processes. In the region of F1 (e), pore pressure increase displaces the circle (solid blue) to the left during the injection, but failure on certain orientations is only driven if the effects of poroelastic stressing (solid green), slip stress transfer and slip weakening (solid red) are considered. Shear-induced stress drop combined with pressure drops leads to more stable conditions in the post-injection. In the region of F2, (f), pore pressure changes are smaller and poroelastic stressing increases stability during injection, while after the stop of injection, poroelastic effect reduction, combined with stress transfer and slip weakening effects, leads to failure of faults with specific orientations.

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