FAULT SLIP IN HYDRAULIC STIMULATION OF GEOTHERMAL RESERVOIRS:
GOVERNING MECHANISMS AND PROCESS-STRUCTURE INTERACTION

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ABSTRACT

Hydraulic stimulation of geothermal reservoirs in basement or crystalline igneous rock can enhance permeability by reactivation and shear-dilation of existing fractures. The process is characterized by interaction between fluid flow and the fractured structure of the formation. The flow is highly affected by the fracture network, which in turn is deformed because of hydromechanical stress changes caused by the fluid injection. This process-structure interaction is decisive for the outcome of a stimulation and, in analysis of governing mechanisms, physics-based modeling has potential to complement field and experimental data.

Here, we show how recently developed simulation technology is a valuable tool to understand governing mechanisms of hydro-mechanical coupled processes and the reactivation and deformation of faults. The methodology fully couples flow in faults and matrix with poroelastic matrix deformation and a contact mechanics model for the faults, including dilation because of slip. Key elements are high aspect ratios of faults and strong nonlinearities in highly coupled governing equations. Example simulations illustrate direct and indirect hydraulic fault reactivation and corresponding permeability enhancement. We investigate the effect of the fault and matrix permeability and the Biot coefficient. A higher matrix permeability leads to more leakage from a conductive fault that is critically stressed and thus suppresses reactivation and slip compared to the case where with a lower matrix permeability. If a fault is a barrier to flow, increased pressure due to the fluid injection results in stabilization of the fault, while the situation
is opposite if the fault is conductive. For the given setup, lowering the Biot coefficient results in more slip than the base case. While conceptually simple, the examples illustrate the prospects of physics-based numerical models in investigating coupled subsurface dynamics.

INTRODUCTION

Low-pressure stimulation to cause natural existing fractures to slip and dilate, typically termed shear stimulation or hydroshearing, was identified by Pine and Batchelor (1984) as a key mechanism to enhance the permeability of conduction-dominated geothermal systems in basement and crystalline igneous rocks (petrothermal systems) (Moeck, 2014). Depending on subsurface conditions, it has proven successful for this purpose at several sites (Breede et al. 2013). For example, at the Soultz experimental geothermal site in Alsace, France, the injectivity index (flow rate per unit wellhead pressure under steady state conditions) for three of the four stimulated wells improved by factors in the range of ~15–20; the last well, which had the highest index prior to stimulation, only improved by a factor of about 1.5 (Genter et al., 2010).

Unstable slip along faults manifests as seismicity, which is generally observed related to hydraulic stimulation of petrothermal systems (Zang et al., 2014) as well as in other subsurface operations involving fluid injection (Ellsworth, 2013). Related to stimulation by hydroshearing, most induced seismicity at geothermal fields has been below magnitude three, with some notable exceptions where fluid injection has resulted in stress-perturbations that trigger earthquakes which release significant tectonic stress. In Basel, Switzerland, stimulation of a granitic geothermal reservoir caused a moment magnitude (M_w) 3.4 earthquake. This event occurred five hours after shut-in of the injection well and was caused by preceding increased levels of seismicity. Additionally, three earthquakes of M_w >3 were recorded one to two months after the
well was bled off (Bethmann et al., 2011; Deichmann and Giardini, 2009). In Pohang, South Korea, stimulation of a petrothermal reservoir activated a previously unknown fault and induced a $M_w$ 5.5 magnitude earthquake almost two months after the final stimulation of the reservoir (Geological Society of Korea, 2019). Analysis of the Pohang event disproved the hypothesis that the largest induced earthquake magnitudes are bounded by the injected volume. Rather, the maximum magnitude in Pohang was sensitive to preexisting tectonic conditions and structures as well as the number of earthquakes induced (Lee et al., 2019). Furthermore, faults can be reactivated far from the injection point. For example, the 1967–1968 Denver earthquakes, which were induced by wastewater injection into crystalline rocks beneath the Denver basin, were mainly triggered 3–8 km from the injection well. The three largest events, up to $M_w$ 4.5–4.8, were triggered one to two years after injection had been stopped (Herrmann et al., 1981; Hsieh and Bredehoeft, 1981).

The examples above show that fault reactivation and slip represent coupled interactions between induced hydro-mechanical dynamics and the initial state and faulted structure of the reservoir. While analysis of field data is decisive in understanding the coupled phenomena, the mechanisms resulting in fault slip and reactivations are challenging to study and analyze. Meso-scale experiments in a single fault have informed the study of injection-induced slip and seismicity, showing that fluid pressure changes cause aseismic fracture slip and dilation, with corresponding static stress-redistribution that in turn can trigger seismic slip (Guglielmi et al., 2015). Hence, while seismicity is associated with slip along faults, slip and permeability enhancement of faults also occur without seismic manifestation. The location of seismic events also has an associated uncertainty (Eisner et al., 2009) that results in further limitations in interpretation.
In recent years, physics-based modeling of the dynamics of hydraulic reservoir stimulation has developed substantially. While available data still limits predictive capabilities, numerical models are important as supplementary tools to understand the coupled process-structure interaction between governing processes—in particular hydro-mechanical—and the faulted structure of the formation. This requires physically consistent mathematical models and corresponding simulation tools that fully acknowledge the coupled dynamics and dominating structural effects and solve the resulting equations with stable and convergent numerical schemes.

In the following, we discuss reactivation and permeability enhancement of faults as a consequence of low-pressure stimulation. Using simulation studies, we examine and illustrate different mechanisms and characteristics that affect dynamics. We base our model on a formulation of physical principles and constitutive relations, coupling flow in and deformation of explicitly represented faults with flow and deformation of their surrounding matrix domain, which also incorporates finer-scale structures. For simplicity, the model does not incorporate geochemical and thermal effects, which also may be influential. Geochemistry can, for example, alter fault friction (Wintsch et al., 1995), and cooling leads to thermal contraction and corresponding reduction of fault strength (Ghassemi, 2012).

FACTOR REACTIVATION, SLIP AND DILATION

Conceptually, one can distinguish between fault reactivation caused directly and indirectly by pressure changes due to fluid injection (Fig. 1). In direct hydraulic reactivation of a fault, increased fluid pressure in the fault—which reduces the effective normal stress on the fault—induces slip (Hubbert and Rubey, 1959). Once a part of the fault is hydraulically re-
activated and slips, the immediate stress redistribution can cause further slip along the same fault, indirectly induced by the fluid injection. Indirect fault reactivation can also occur if poroelastic stress changes cause a fault to slip even if the fault is not at all or only weakly hydraulically connected to the injection region (Fig. 1). This occurs, for example, if direct hydraulic reactivation of a fault causes stress changes that reactivate other faults. In hard rocks, slip along a fault also results in shear-induced dilation due to contacting asperities on the fault surface; fault permeability can thus increase by orders of magnitude (Guglielmi et al., 2015; Lee and Cho, 2002) leading to significant improvements in reservoir injectivity (Genter et al., 2010).

The extensively used Coulomb friction law incorporates the main mechanisms for reactivation and slip of faults. The Coulomb law gives an approximation of the threshold value for the frictional force on the surface (i.e., the contact shear traction) above which sliding occurs. Let $\mathbf{e}_n$ denote the unit normal to the fracture surface in direction of the normal force exerted from the fracture to the matrix and $\mathbf{e}_t$ denote the unit normal in the direction of the shear force.

Figure 1 Illustration of fault reactivation in stimulation of a reservoir. The fault can be directly hydraulically reactivated through increased fluid pressure in the fault and indirectly through induced changes in the local thermo-poroelastic stress regime around the fault.
on the matrix from the fracture. For a contact traction on the surface $\mathbf{t}_c = t_c^n \mathbf{e}_n + t_c^\tau \mathbf{e}_\tau$, a Coulomb friction law is given by

$$
t_c^\tau \leq \mu t_c^n + c,
$$

where $\mu$ is the friction coefficient and $c$ represents cohesion. The right-hand side of the equation represents the critical shear traction for sliding. Under crustal conditions, $c$ is normally negligible. Typical values for $\mu$ are between 0.3 and 1. The lower values apply for faults with clay fillings, which also have non-negligible cohesion. In general, $\mu$ is not constant, and calibration to shear experiments and observations of fault reactivation have introduced various models for the friction coefficient depending on the time of contact, displacement and sliding velocity (Dieterich, 1979; Guglielmi et al., 2015; Marone, 1998; Ruina, 1983). The richer models, however, face a risk of over-parameterization considering limited available data and the associated uncertainty. Additionally, such models may incorporate mechanical effects which could also be modeled otherwise. An example is slip-strengthening friction models which introduce strengthening of the fault with shear-induced dilatancy (Segall & Rice, 1995). The same effect will also be apparent in models correctly coupling dilation of faults with stress-redistribution in the surrounding formation, resulting in strengthening of the fault with dilation.

The reactivation and displacement of faults will be affected by hydro-mechanical stress changes on the fault as well as alterations in fault pressure. To see this coupling, it is instructive to consider the force balance on the fault surface. Due to the roughness of the fracture surfaces, asperities on the fracture surfaces can keep the fracture hydraulically open while the two sides of the fracture are mechanically in contact. Hence, a combination of forces act on the matrix: A contact force $\mathbf{t}_c$ resulting from contacting fracture asperities across the fault’s surface and a normal force $p_f \mathbf{e}_n$ on the fault’s surface exerted by the fluid pressure in the fracture (Hubbert
and Rubey, 1959). This total force is balanced by the traction on the fracture surface from the matrix, \( t_m = t^n_m(-e_n) + t^r_m(-e_r) \), caused by hydro-mechanical stress. The force balance can be written

\[-t_m = t_c + p e_n.\]

Evaluating normal and shear forces, the friction law in Equation (1) becomes

\[t^r_m \leq \mu(t^n_m - p_f) + c. \tag{2}\]

Based on this formula, a fracture is stable if the strict inequality is satisfied, while the fracture slips when the two sides of the equation become equal. A classical Mohr diagram (e.g., Jaeger et al., 2007) shows how the stability of a fault is related to its orientation and how both increase of fluid pressure in the fault and changes in hydro-mechanical stress on the fault can reactivate it (Fig. 2). However, fluid injection does not always reduce fault strength; for example, if the fault is a barrier to fluid flow, increase in fluid pressure at one side of the fault will lead to an increase in the normal forces acting on the fault from the matrix and, hence, stabilize the fault.

Figure 2 A fracture oriented at an angle \( \beta \) to the maximum principal stress direction is affected by normal forces and shear forces caused by the stress field. Left: Illustration of fracture and the forces acting on it. Right: Mohr diagram illustrating the Coulomb friction law. From an initial state of the forces acting on the fracture surface (black dot), the fracture can be reactivated by an increase of fluid pressure (blue dot), or a change in the hydro-mechanic forces from the matrix on the fracture surface (green dot). The stress states of fractures with other orientations subjected to the same stresses and fluid pressure are illustrated by the dashed lines.
Once a fault is reactivated, the slip is governed by equality in Equation (2). By balance of forces in Equation (2), coupled with the corresponding hydro-mechanical model for the surrounding domain discussed in the following section, displacement can be computed on the fault. In hard rocks, fault slip is associated with dilation as sliding alters the contact of asperities and moves the fracture’s two sides farther apart. The increase in hydraulic aperture is typically proportional to slip up to a threshold value where production of gauge can explain the prevention of further permeability increase (Lee and Cho, 2002). Fault dilation interacts with the hydro-mechanical stresses on the fault, leading to a significant coupling (Stefansson et al., 2020a).

MODELING OF FAULT REACTIVATION AND SLIP ACCOUNTING FOR PROCESS-STRUCTURE INTERACTION

It is crucial for physics-based simulation models to capture the process-structure interaction discussed in the previous section. This requires models that

1) explicitly represent dominating fault structures and
2) couple a) flow, reactivation and deformation of the faults with b) flow and deformation of the formation (matrix) that the explicitly represented faults reside in.

The matrix surrounding the explicitly represented faults needs, in general, to be modelled as porous and permeable due to its incorporation of finer-scale fractures and porous rock (Berre et al., 2019). Significant progress has been made in the development of models based on the conceptual principles 1 and 2 listed above. While early models did not consider redistribution of stress as a consequence of slip (Bruel, 2007; Kohl and Mégel, 2007; Rahman et al., 2002; Willis-Richards et al. 1996), simplified models for stress-redistribution based on block-spring models (Baisch et al., 2010), the semi-analytical boundary integral method (Ghassemi and Zhou, 2011;
McClure and Horne, 2011; Norbeck et al., 2016) or simplified models for approximating fracture slip in the coupled problem (Ucar et al., 2018) were later introduced.

Based on conservation principles and constitutive relations, the conceptual principles 1 and 2 result in a coupled system of partial differential equations governing fault reactivation and deformation. Recently, numerical models based on discretization and fully-coupled solutions of the governing system of equations have been developed (Berge et al., 2020; Garipov and Hui, 2019; Garipov et al., 2018; Keilegavlen et al., 2019; Stefansson et al., 2020b), which also show appropriate grid convergence properties (Stefansson et al., 2020a). These models are based on conceptualizing the faults as two-dimensional surfaces in the three-dimensional domain. This avoids elements with large aspect ratios on the fault (Karimi-Fard et al., 2003) and facilitates modeling of slip and dilation (Cappa and Rutqvist, 2011; Ucar et al., 2018). We have based the model used below on this principle.

In the mathematical model, the slip along each fault is governed by the constitutive Coulomb friction law (Equation 2). Furthermore, the governing system of equations incorporate fluid flow in the faults and hydro-mechanics in the matrix. For this, flow in both faults and matrix is assumed to be single-phase and governed by Darcy’s law, and the matrix deformation is assumed to be poroelastic. Shear-induced dilation is governed by a constitutive law which relates mechanical aperture increase to slip distance along a fault through a dilation angle. Excluding thermal effects, we use the same full set of model equations as Stefansson et al., (2020a).
MECHANISMS AFFECTING FAULT REACTIVATION AND SLIP THROUGH COUPLED PROCESSES

In this section, we utilize the advantages of physics-based modelling and discuss aspects affecting fault reactivation and slip illustrated by numerical examples. The test cases are set up using the open-source software PorePy (Keilegavlen et al., 2019) including the recent developments by (Stefansson et al., 2020a). The software as well as all details of the simulations, including run scripts, are available at GitHub (Stefansson, 2020c).

We have designed the examples to illustrate several of the mechanisms discussed earlier based on a rather simple geometry. The domain is located with its top at the earth’s surface and extends 2 km in the vertical direction and in both horizontal directions. Two square faults (Fault 1 and Fault 2) are located in the center of the domain as shown in Fig. 3, both with an extension of 170 m in both directions along the fault plane. The boundary conditions on the stress are given by a background stress with principal axis aligned with the coordinate system. Vertical stress,

![Figure 3 Fault geometry of Fault 1 and Fault 2 (numbered in the figure) and computational domain. Water is injected in one of the top corners of Fault 1, illustrated with an arrow.](image)
\( \sigma_y = \sigma_z \), is set as lithostatic and principal horizontals stresses are \( \sigma_H = \sigma_x = 1.3\sigma_z \) and \( \sigma_h = \sigma_y = 0.6\sigma_z \), respectively. For pressure, boundary conditions are given as hydrostatic.

Table 1 lists the parameters for the simulation of a reference case (Case 0). For simplicity, the fault aperture, \( a \), equals both mechanical and hydraulic aperture, and, in the case of conductive faults, an isotropic fault permeability is given by the cubic law; that is, it equals \( a^2/12 \). The domain is meshed with 27215 cells in the matrix and 1092 cells in the faults.

Assuming zero cohesion, \( c \), a measure of each fault’s tendency to slip based on Equation (2) is given by \( t_m^n/(t_m^n - p_f) \). Before injection starts, the slip tendency of Fault 1 is 0.18 implying that the fault is far from being critically stressed; Fault 2 has a slip tendency of 0.47, which is close to the frictional threshold of 0.5 for slip.

From the described initial state, water is injected into Fault 1 (Fig. 3) at a rate of 60 l/s. The hydraulic stimulation is done for five days. To illustrate different mechanisms in fault reactivation and slip due to the fluid injection, we introduce three cases, each showing the result of changing one central parameter compared to Case 0. In Case A, the matrix permeability is

| Table 1 Rock and fluid parameters for base case. |
|-----------------------------------------------|
| Bulk modulus                                  | \( 2.2 \cdot 10^{10} \) Pa                  |
| Shear modulus                                 | \( 1.7 \cdot 10^{10} \) Pa                  |
| Solid density                                 | \( 2.7 \cdot 10^{3} \) kg/m³                |
| Biot coefficient                              | 0.7                                          |
| Porosity                                      | \( 1.0 \cdot 10^{-2} \)                      |
| Matrix permeability                           | \( 2.5 \cdot 10^{-15} \) m²                 |
| Viscosity                                     | \( 1.0 \cdot 10^{-3} \) Pa s                |
| Fluid compressibility                         | \( 1.0 \cdot 10^{-10} \) 1/Pa               |
| Fluid reference density                       | \( 1.0 \cdot 10^{3} \) kg/m³                |
| Initial fault aperture                        | \( 1.0 \cdot 10^{-3} \) m                    |
| Friction coefficient (\( \mu \))              | 0.5                                          |
| Cohesion (\( c \))                            | 0                                            |
| Dilation angle                                | 5°                                           |
changed from the Case 0 value of $2.5 \cdot 10^{-15}$ m$^2$ to $4.0 \cdot 10^{-15}$ m$^2$. In Case B, the permeability of Fault 2 is set to the constant value of $1.0 \cdot 10^{-1}$ m$^2$ during the entire simulation, resulting in Fault 2 effectively being a barrier to flow. In Case C, the Biot coefficient is reduced from 0.7 to 0.6. For each case, we show the following results at the end of the stimulation: slip tendency (Fig. 4), fluid pressure (Fig. 5) and total aperture increase (Fig. 6), which is proportional to slip distance along the fault.

For Case 0, both Fault 1 and Fault 2 are destabilized as a consequence of the fluid injection. In Fault 1, the pressure increase (Fig. 4) increases slip tendency along the fault (Fig. 5),

*Figure 4 Fluid pressure difference [Pa] to initial hydrostatic pressure for Case 0, Case A (higher matrix permeability), Case B (Fault 2 blocking), and Case C (lower Biot coefficient). The matrix pressure is shown for a cross-section of the domain in a transparent manner, also indicating the refinement of the grid towards the faults.*
and even results in slip along some elements at the top of the fault (Fig. 6). Fault 2, which was almost critically stressed initially, has slipped entirely by the end of the stimulation. In this case, only relatively small changes in pressure and poroelastic stress conditions were necessary to induce slip.

The higher matrix permeability in Case A compared to Case 0 allows the pressure front to diffuse more easily into the matrix. This gives a reduced pressure in Fault 1 compared to Case 0 (Fig. 4), and consequently a weaker increase in slip tendency than was seen in Case 0. At the same time, the pressure in Fault 2 is increased sufficiently to cause slip of the entire fault, but with lower slip magnitudes and corresponding aperture changes than in Case 0.

Figure 5 Slip tendency of faults for Case 0, Case A (higher matrix permeability), Case B (Fault 2 blocking), and Case C (lower Biot coefficient). Elements that are slipping have the maximum slip tendency of 0.5.
Compared to the initial situation before stimulation, Case B results in a stabilization of Fault 2 as the fluid pressure results in increased loading on the fault due to it effectively being a barrier for the flow. This is recognized by a reduction in slip tendency of the fault from the initial slip tendency of 0.47 (Fig.5).

The lower Biot coefficient of Case C compared to Case 0 results in a weaker Biot coupling. The formation is stiffer and elastically contributes less to the migration of pressure out of Fault 1. In Case C, Fault 1 has a pressure difference to hydrostatic pressure ranging between 14.3 and 15.7 MPa as compared to 13.8 and 15.3 MPa for Case 0. The result is an increased slip tendency along Fault 1 compared to Case 0. Compared to Case 0, significantly larger parts of the

![Image of aperture of faults for different cases](image)

*Figure 6 Aperture of faults [mm] after hydraulic stimulation for Case 0, Case A (higher matrix permeability), Case B (Fault 2 blocking), and Case C (lower Biot coefficient). Arrows illustrating the magnitude and direction of slip for the top surfaces of the faults are included for Fault 2, Case A and Fault 1, Case C, to illustrate the direction and magnitude of slip.*
fault slips. Fault 2 also has more slip and corresponding aperture increase than it has in Case 0. This happens despite the pressure being only slightly increased in Fault 2 compared to Case 0; in Case C, Fault 2 has a pressure difference to hydrostatic pressure ranging between 1.42 and 1.45 MPa larger than hydrostatic pressure as compared to 1.22 MPa and 1.25 MPa for Case 0. This indicates that poroelastic stress changes resulting from the slip of Fault 1 have a significant impact on the slip along Fault 2. However, even for this simple geometry and without parameter heterogeneities in the matrix, the processes are so strongly coupled that it is difficult to distinguish the different mechanisms as to which of them cause slip along the different faults.

CONCLUSIONS

The hydro-mechanical processes in hydraulic stimulation of a geothermal reservoir by fault reactivation and slip are coupled and interact with the deforming fractured structure of the formation. In numerical modeling tools, the strong coupling between processes as well as fracture reactivation, slip and dilation, which affect the fractures’ aperture and consequently its influence on flow, must be acknowledged. The examples presented here, which showcase the effect of various subsurface characteristics and mechanisms for fracture reactivation and slip, demonstrate how such a tool can be used to better understand subsurface dynamics. Combined with field and experimental data, it can be used to forecast outcomes of engineering operations based on various subsurface scenarios.

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