CO-EVOLUTION OF FRACTURE PERMEABILITY AND FRICTION:

ROLES OF PRESLIP FRICTIONAL HEALING AND DYNAMIC STRESSING,

AND IMPLICATIONS FOR SEISMICITY

A Thesis in

Energy and Mineral Engineering

by

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ABSTRACT

In the following, we examine fracture permeability–seismicity relationships in two separate studies. These combined studies separately elucidate (1) the role of preslip frictional healing, and (2) the combined effect of dynamic stressing and fluid-pressure-induced shear deformation on the evolution of fracture permeability and friction throughout the phases of the seismic cycle.

Fracture permeability is a dynamic property under conditions of varying stress and responds to fluid overpressures applied during hydraulic stimulation. We use samples from the SIGMA-V site (Sanford Underground Research Facility (SURF), SD) to measure the co-evolution of fracture permeability and friction throughout phases of the seismic cycle. This is accomplished via slide-hold-slide and pore pressure stepping experiments completed in double direct shear. Fracture reactivation results in permeability enhancement only after sufficiently long interseismic repose periods. The magnitude of permeability increase from each reactivation, following the long hold periods, is critically dependent on the degree of fracture healing achieved in each pre-slip hold period. Shear dilation and permeability enhancement only results following a threshold repose period. Permeability enhances continuously with each pressure step with the highest permeability increase rate being with the first reactivation event. Our study establishes a direct linkage between fracture permeability and friction evolution throughout the seismic cycle and hydraulic shear, which applies across different fracture surface roughnesses.

Mechanisms controlling fracture permeability enhancement during dynamic stressing remain unresolved. We probe these mechanisms through a series of fluid pressure pulse reactivations on saw-cut fractures in impermeable rock samples confined under in situ stresses. Each spiked pore fluid pressure pulse returns to the background control pore pressure while the evolution of fracture permeability and friction are continuously monitored. Peak magnitudes of the
pore pressure pulses are successively incremented to both exclude and then include shear reactivation. Fracture permeability is shown to increase, both in the absence and then presence of reactivation by shear slip. Fracture permeability enhancement is permanent in the short-term despite the transient nature of the pressure pulses. The initiation of injection-induced slip significantly magnifies permeability increase over that due to changes in normal stress alone. The shear-induced permeability increase is apparent with a short delay after the first observed shear slip. Differentiation between the contribution of shear dilation and normal stress-only related processes, including unclogging and asperity damage and reseating, is apparent with a major slope change in permeability increase. Permeability increase scales with pore pressure amplitude and permeability increment scales with the amount of pre-stimulation sealing. This sealing and unsealing behavior is systematic and reversible. Enhanced permeability eventually returning to the pre-stimulated value over the long-term once the effective stress perturbations cease.
The chapters of this thesis correspond with the following papers:


- Yildirim, E. C., Im, K., Elsworth, D. 2018. Injection-induced dynamic triggering of fracture permeability evolution [to be submitted].
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Elif Cihan Yildirim

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Chapter 1

Co-Evolution of Fracture Permeability and Friction in Rocks from the EGS Collab Experiment 1 Site

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Abstract

Fracture permeability is a dynamic property under conditions of varying stress and responds to fluid overpressures applied during hydraulic stimulation. We use samples from the SIGMA-V site (Sanford Underground Research Facility (SURF), SD) to measure the co-evolution of fracture permeability and friction throughout phases of the seismic cycle. This is accomplished via slide-hold-slide and pore pressure stepping experiments completed in double direct shear. Fracture reactivation results in permeability enhancement only after sufficiently long interseismic repose periods. The magnitude of permeability increase from each reactivation, following the long hold periods, is critically dependent on the degree of fracture healing achieved in each pre-slip hold period. Shear dilation and permeability enhancement only results following a threshold repose period. Permeability enhances continuously with each pressure step with the highest permeability increase rate being with the first reactivation event. Our study establishes a direct linkage between fracture permeability and friction evolution throughout the seismic cycle and hydraulic shear, which applies across different fracture surface roughnesses.
1. Introduction

Fluid injection for secondary recovery (i.e. hydraulic stimulation), hydraulic fracturing of unconventional reservoirs, and oil and gas field depletion are known to cause major pore pressure changes in hydrocarbon reservoirs (Davies et al., 2013; Elsworth et al. 2016; Davis and Pennington, 1989; King, 2010; Yerkes and Castle, 1976). These activities together with enhanced geothermal systems operations (Majer et al. 2007), mining (Bennett et al., 1996), subsurface waste and CO₂ sequestration (Frohlich et al., 2011) have long been documented to induce seismicity via alteration of the effective stress field. Understanding the hydro-mechanical processes induced during such fracture reactivation events is of interest to both secure the success of these activities (Fang et al., 2017; Ishibashi et al., 2016) and to explore the mechanics of earthquakes (Scholz, 1990).

Fracture permeability is a dynamic property under conditions of varying stress and together with the evolution of friction has been the focus of many studies exploring numerous aspects of seismic phenomena (Zhang et al. 1998; Guglielmi et al, 2015; Vogler et al. 2016; Fang et al. 2017; Im et al., 2018). Fractures heal and seal during interseismic repose periods (Marone et al., 1995; Zhong et al., 2015; Im et al, 2018) while fracture reactivation events may result in either increases (Elsworth and Goodman, 1986; Guglielmi et al, 2015) or decreases in permeability (Teufel, 1987). Permeability enhancement may result from shear dilation (Elsworth and Goodman, 1986), mineral dissolution, and free-face dissolution (Rose et al., 2007) and reduction from pressure solution, stress corrosion and mineral precipitation (Revil, 1999; Yasuhara et al., 2004, Yasuhara & Elsworth, 2008). These controls determining why certain mechanisms dominate permeability evolution at shear slip have been probed via numerical models and laboratory experiments (Marone, 1998b; Taron et al., 2009; Fang et al., 2017) including the combined effect of static loading and shear deformation on permeability evolution (Im et al., 2018).
In this study, we reevaluate the role of pre-slip frictional healing on fracture permeability evolution on reactivated samples from the SIGMA-V site (Sanford Underground Research Facility (SURF), SD). We report additional results comparable to those previously reported on Westerly granite and Green River shale, including the role of pore pressure pulses on permeability evolution.

2. Methods

We perform a series of flow-through experiments using double direct shear configuration within a triaxial pressure cell. Continuous and concurrent measurements of fracture permeability and friction throughout these experiments probe the effects of fracture healing, fracture reactivation, and pore pressure changes on fracture permeability.

We use core samples from the Poorman Formation (kISMET site). These samples are saw-cut into a rectangular prism (0.004 x 0.024 x 0.038 m³) flanked by two half-cylinders to conform to the double direct shear geometry (Figure 1-1). The desired fracture surface roughness is achieved by grinding the contacting fracture surfaces with #150 grit (rougher) or #600 grit (smoother) abrasive powder. The samples are then jacketed with a latex membrane and placed within a triaxial pressure cell (Figure 1-1a). Confining stress, shear stress, and pore pressures are controlled independently by three servo-hydraulic pumps (Pump A, B, C respectively). Pressure, flow rate, and pump fluid volume are monitored for each pump, allowing normal stresses, shear displacement rates, and fluid pressures to be prescribed. Shear displacements are continuously monitored by an LVDT mounted to the loading piston. This allows the evolution of friction and permeability to be determined. In these experiments, a constant confining pressure of 3 MPa and a shear velocity of 10 μm/s is applied. Fracture permeability (k) for steady flow-through tests is evaluated from Darcy’s law (Eq. 1) as:
where $\mu$ is the fluid viscosity ($8.9 \times 10^{-4}$ Pa·s), $L$ is the flow path length (23mm), $A$ is the cross sectional area of the sample perpendicular to the flow path ($6.937 \times 10^{-7} m^2$), $Q$ is the flow rate, and $\Delta P$ is the pore pressure difference between the inlet and outlet.

We perform two main types of experiments: Slide-hold-slide (SHS) and pressure stepping experiments. All the experiments initiate when the confining pressure reaches to 3 MPa. Then we prescribe a pore pressure difference across the sample, which drives the fluid through the fractures, and shear the initial 3-4 mm offset with a constant shearing velocity of 10 $\mu$m/s. In the case of the slide-hold-slide experiments, we perform two single hold experiments where we hold the sample for extended duration (~ 7 hours); and two repeating slide-hold-slide experiments where we subject the samples under successive increments of hold durations (10 s, 30 s, 100 s, 300 s, 1000 s, 3000 s, and 10000 s) with intervening shearing of 1 mm at 10 $\mu$m/s between each hold. These two types of experiments allow the observation of fracture healing and reactivation. In pressure stepping experiments, the sample is held over an extended period (~ 10 hours) after the initial shearing. Shear stress continuously reduces due to creep during this hold, requiring that it is reapplied to be near critically stressed and ready to slip with the application of the pressure perturbation. Pore pressure pulses are applied in successive step-wise increments (50 kPa) for 5 s with an intervening return to the control pore pressure difference for 120 s between each pulse step. The starting differential pore pressure pulse is 262 kPa and the final pressure pulse is 512 kPa.
Figure 1-1: (a) Experimental setup. (b) Fracture surfaces before experiment. Rock samples from the SIGMA V site are metamorphosed (schist); therefore, the surfaces already incorporate heterogeneities and planes of weaknesses initially. (c) Fracture surfaces after experiment, Wear products (striations) as a result of the experiment are observable.

3. Results

We examine the individual and combined effects of fracture healing, fracture reactivation, and pore pressure changes on the evolution of fracture permeability and friction.

3.1. Hold duration and permeability reduction

Figure 1-2 shows the results of the single hold experiments on fractures with two different surface roughnesses for ~ 7 hours. We observe that fracture permeability declines continuously throughout the hold periods and does not stabilize. Interestingly, the log-log plot (Figure 1-2a) shows that the permeability decay is significantly promoted for the rougher surface at around 15
minutes from the initiation of hold. The overall permeability decrease that is achieved in the single hold experiments is 79% for the rougher fracture surfaces (from $7.800 \times 10^{-14} \text{ m}^2$ to $1.620 \times 10^{-14} \text{ m}^2$) and 67% for the smoother surfaces (from $3.497 \times 10^{-15} \text{ m}^2$ to $1.145 \times 10^{-15} \text{ m}^2$).

Figure 1-2: Permeability decline during single hold experiments on (a) log-log and (b) semilog scales. Hold starts at $t=0$, right after initial shearing.

3.2. Fracture Reactivation and Permeability Enhancement

Friction and permeability results of the repeating slide-hold-slide experiments are summarized in Figure 1-3, 1-4, and 1-5. Overall shear stresses for the rougher surfaces are higher than for the smoother surfaces for all SHS experiments (Figure 1-3a & 1-3b). This is expected and consistent with Byerlee’s observations of friction. Given the same hardness, rougher surfaces show higher friction than the smoother surfaces due to the interlocking of surface asperities (Byerlee, 1967b). We observe that frictional response to fracture reactivation is a sharp initial increase in shear stress. The longer the pre-slip hold duration, the higher the shear stress peak upon reactivation. This suggests that frictional healing is time-dependent.
Figure 1-3: (a, b) Friction and permeability responses of (c) rougher and (d) smoother fracture surfaces in repeating slide-hold-slide experiments. Shear loading begins at t=0 for the initial shearing. Hold and slip periods are marked on the top by light and dark green respectively. Reactivation events are numbered from 1-7.
Experiments show that fracture reactivation results in permeability enhancement provided that the samples are subjected to a pre-slip hold period of at least 1000 s for the rougher samples, and 10000 s for the smoother samples. Figure 1-4 shows the evolution from net reduction to net increase upon reactivation throughout the successive increments in pre-slip hold duration. Figure 1-5 illustrates the amount of permeability increase in relation to the pre-slip hold durations. Longer hold duration prior to fracture reactivation results in a larger permeability enhancement due to reactivation. Interestingly, we observe that the permeability decay rate on the smoother sample, during the hold, is accelerated after event #6 (Figure 1-3d), which precedes the first permeability enhancement (event #7). This further implies that shear permeability evolution is strongly linked to pre-slip hold duration and related behavior.

Figure 1-5 shows the effect of surface roughness on permeability enhancement. It is apparent that the permeability enhancement of a rougher surface is far larger than that on a smoother surface (Figure 1-5a), implying that shear permeability enhancement likely results from roughness-driven dilation. In these experiments, we observe that normalized permeability enhancement is also larger on a rougher surface than a smoother surface (Figure 1-5b), which is generally opposite to that observed in previous experiments with Westerly Granite (Im et al., 2018). The 6th reactivation event on a rougher surface results in a twice the normalized permeability increase observed during the 7th event on the smoother surface.

3.3. **Initial Fracture Reactivation and Permeability Reduction**

Shearing the fresh fracture surfaces before applying any hold leads to permeability reduction. The reduction is much faster and higher in magnitude than the permeability change with other reactivation events in the repeating SHS experiments. Figure 1-3a and 1-3b show that the first loading of the fresh fracture surfaces is marked by the fast and steady increase of shear stress. That is followed by frictional yield, in turn marked by the inflection of the shear stress increase with time, identifying the initiation of sliding along the fracture.
Figure 1-4: Permeability evolution demonstrated with reactivation events aligned at t=0 for the SHS experiments exhibited in Fig. 1-3. Black dashed lines outline the duration of the slide. (a) rougher fracture surfaces, (b) smoother fracture surfaces.

Figure 1-5: Permeability increase vs. pre-slip hold duration. Numbered events are from the SHS experiments shown in Fig. 3 and 4. Black diamond in (b) refers to the permeability increase achieved at a reactivation event after a much longer hold duration in a different experiment with smoother fracture surfaces.
Figure 1-3a and 1-3b show that 3 mm of initial shear-in is completed within ~10 mins. Fracture permeability during this initial shearing over 3 mm shows a strong decline of 65 - 75% on the rougher surfaces and 42 - 49% on the smoother surfaces. In the SHS experiment with the rougher fracture surfaces (Figure 1-3c), the permeability reduction (1.910×10^{-13} m^2) during the initial shearing is 35 times the maximum permeability reduction (5.5×10^{-15} m^2) and 30 times the maximum permeability enhancement (6.3×10^{-15} m^2) that is achieved during reactivation events after the pre-slip hold periods. For the smoother fracture surfaces (Figure 1-3d), the initial permeability reduction (3.650×10^{-15} m^2) is 12 times the maximum permeability reduction (3.0×10^{-16} m^2) and 16.5 times the maximum permeability enhancement (2.2×10^{-16} m^2) that is achieved during reactivation events on the same SHS experiment. Given that the fractures are reactivated at the same constant shearing velocity of 10 µm/s during all shearing events (both initial and after long hold periods), the higher rate of permeability change during the initial shearing suggests an additional/different factor contributing to the initial permeability response.

3.4. Pore Pressure Change and Permeability Enhancement

Shear stress and displacement responses illustrated in (Figure 1-6) show that fractures experience reactivation as a result of the hydraulically induced shearing. Each pore pressure pulse causes a sudden slip along the fracture followed by a slower creep. Shear stress decreases stepwise corresponding to shear displacement. The magnitude of displacement and shear stress drop in response to the pressure pulses are the largest in the first event. The following pulses result in smaller displacements and shear stress changes which are comparable across the remainder of the events.

Fracture permeability is enhanced with each successive pressure pulse and does not stabilize throughout the 6 pulses that are applied (Figure 1-7). Final fracture permeability (7.5×10^{-14} m^2) as a result of 6 pulses is ~ 5.5 times the initial permeability (1.4×10^{-14} m^2). 66%
of the total permeability enhancement is achieved during the first pulse. Fracture permeability after the first pulse \((5.4 \times 10^{-14} \text{ m}^2)\) is almost 4 times the initial permeability \((1.4 \times 10^{-14} \text{ m}^2)\).

4. Discussion

These slide-hold-slide experiments show that fracture permeability always declines during hold periods. Conversely, fracture reactivation may result in permeability decline or enhancement. We observe that the hold periods, broadly representing interseismic repose within the seismic cycle, are characterized by permeability decline. The slow permeability decline may implicate chemomechanical compaction as a key process. In this, the invariant effective normal stress manifesting during the hold periods would induce pressure solution (Yasuhara et al., 2004) and/or stress corrosion (Yasuhara & Elsworth, 2008) resulting in the closure of the fracture. This is consistent with the decline rates of permeability observed during both single hold and repeating slide-hold-slide experiments.

All experiments show rapid permeability reduction during the initial shearing of the fresh artificial fractures. This reduction is greater in magnitude on the rougher surfaces than on the smoother surfaces. Since the post-experiment state of the fracture surfaces (Figure 1-1e) suggests generation of abrasive wear products (striations, due to frictional sliding at shear slip), we attribute the entire shear permeability reduction (both initial and following the hold periods) to comminution of fracture surface asperities as a result of shear slip. The comminution results in a reduction of pore-throat sizes by compaction and clogging of fine wear products into those pore throats. The much higher rate of permeability change observed during the initial reactivation, relative to that during the remainder of the reactivations, may be due to the “comminution-refreshed” state of the fracture surface. Similarly, the early reactivations in the experimental sequence may result in an uncharacteristically high permeability enhancement on the freshly-prepared surfaces, relative to
Figure 1-6: Friction and permeability responses to pore pressure stepping. Following “seating-in” over an extended hold period, this experiment initiates with the reapplication of shear stress (sharp increase in the top panel) to reset it from the diminished magnitude during the hold. The concurrent increase in displacement at the initial loading is not an actual slip, but an artificial response arising due to the compaction of experimental materials at shear loading. Pore pressure pulses are applied with a duration of 5 s and successively incremented every 120 s by 50 kPa ($\Delta P_1 = 262$ kPa and $\Delta P_6 = 512$ kPa). Hydraulically-induced shearing reopens the sealed fractures and results in successively incremented permeability magnitudes.
later reactivations when the surfaces are no-longer in fresh conditions. We conclude that the initial fracture reactivation for the first 2-3 mm of the sample might be considered important to break the artificial conditions along the fracture surfaces but the permeability response might not be representative of the natural phenomenon.

Figure 1-7: Summary of the permeability enhancement at $\Delta P = 20$ kPa as a result of the fluid injection with high amplitude pore pressure pulses shown in Fig. 6. The highest rate of permeability enhancement is achieved as a result of the first pulse.

The reactivation events induced after the pre-slip hold periods give self-consistent changes in permeability magnitude. Both permeability decline and enhancement are observed during the shear reactivations. In the slide-hold-slide experiments, pre-slip sealing of fractures is tested as the controlling factor on permeability evolution during induced shear slips. Our experiments show that fracture permeability declines at shear slip unless the fracture experiences a threshold duration of
static loading prior to reactivation. The critical pre-slip hold duration resulting in permeability enhancement during reactivation is 1000 s for the rougher samples and 10000 s for the smoother samples. Once the critical pre-slip sealing is achieved, shear dilation becomes the dominant mechanical process leading to permeability increase during fracture reactivation. As suggested in previous studies (Im et al., 2018; Elkhoury et al., 2011), shear dilation and corresponding flux-driven unclogging might be the main responsible mechanism. Similar interpretation of the influence of pre-slip sealing on the mode of permeability change at reactivation was demonstrated previously on the results reported for Westerly granite and Green River shale (Im et al., 2018).

The permeability enhancement observed in the pore-pressure stepping experiments may also be a combined result of both shear-driven dilation and flux-driven unclogging. The pre-slip sealing period of ~10 hours prior to the pressure stepping experiments primes the system for the anticipated shear opening of fractures during hydraulically-induced reactivations. Also, it is well documented that permeability increases with the magnitude of the pore pressure oscillation (Candela et al., 2015; Elkhoury et al., 2011). Hence, the permeability response may be controlled by the combined effect of shear dilation and pressure induced unclogging. Permeability enhancement is clearly dependent on the magnitude of the applied pressure pulse with 66% of the total permeability enhancement achieved during the first pulse. Further experiments need to be performed to investigate shear dilation effect and pressure driven unclogging effect in this process.

5. Conclusions

In order to elucidate the role of pre-slip fracture healing as a determining factor on the mode of permeability evolution upon fracture reactivation, we report a series of slide-hold-slide and pore pressure stepping experiments, monitored for the co-evolution of fracture permeability and friction. These experiments broadly represent the response through the phases of seismic cycle.
We find that interseismic repose plays a critical role in enabling fracture healing and sealing and ultimately defines the mode of permeability change that results upon fracture reactivation. The magnitude of permeability increase from each reactivation is strongly dependent on the degree of fracture healing achieved during the pre-slip hold period. Pore pressure stepping experiments demonstrate that seismicity induced by fluid injection enhances the permeability presumably by shear dilation and flux driven unclogging. Pressure pulses and permeability enhancement are positively correlated although the maximum rate of permeability increase is achieved following the first injection pulse.

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Chapter 2

Injection-Induced Dynamic Triggering of Fracture Permeability Evolution

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Abstract

Mechanisms controlling fracture permeability enhancement during dynamic stressing remain unresolved. We probe these mechanisms through a series of fluid pressure pulse reactivations on saw-cut fractures in impermeable rock samples confined under in situ stresses. Each spiked pore fluid pressure pulse returns to the background control pore pressure while the evolution of fracture permeability and friction are continuously monitored. Peak magnitudes of the pore pressure pulses are successively incremented to both exclude and then include shear reactivation. Fracture permeability is shown to increase, both in the absence and then presence of reactivation by shear slip. Fracture permeability enhancement is permanent in the short-term despite the transient nature of the pressure pulses. The initiation of injection-induced slip significantly magnifies permeability increase over that due to changes in normal stress alone. The shear-induced permeability increase is apparent with a short delay after the first observed shear slip. Differentiation between the contribution of shear dilation and normal stress-only related processes, including unclogging and asperity damage and reseating, is apparent with a major slope change in permeability increase. Permeability increase scales with pore pressure amplitude and
permeability increment scales with the amount of pre-stimulation sealing. This sealing and unsealing behavior is systematic and reversible. Enhanced permeability eventually returning to the pre-stimulated value over the long-term once the effective stress perturbations cease.

1. Introduction

Dynamic stressing has been long implicated in promoting fluid redistribution (Steinbrugge & Moran, 1954), undrained pore pressure variations (Manga et al., 2012) and in triggering changes in the fluid transport characteristics (Elkhoury et al., 2006) of natural systems. Observations from hydrocarbon reservoirs and aquifers have noted changes in production rates and water well levels with the passage of seismic waves (Steinbrugge & Moran, 1954; Voytov et al., 1972; Roeloffs, 1998; Brodsky et al., 2003; Elkhoury et al., 2006). These observations are generally attributed to transient increases in effective permeability in the presence of stress perturbation (Rojstaczer, S. & Wolf, 1992; Elkhoury et al., 2006; Xue et al., 2013). This results from the disproportionate sensitivity of permeability in fracture-dominated formations to even small changes in effective stress.

Causative hydro-mechanical processes implicated in this sensitive permeability evolution during dynamic stressing have been partly constrained by laboratory evidence (Roberts, 2005; Ying et al., 2006; Elkhoury et al., 2011; Faoro et al., 2012; Candela et al., 2014; Candela et al., 2015). Mechanisms proposed to explain enhanced fracture permeability include microfracturing and fracture growth (Mitchell and Faulkner, 2008; Liu and Manga, 2009), excess pressurization of the fracture by undrained poroelastic response (Faoro et al., 2012), and flux-driven particle mobilization and related unclogging of pore throats from finer particles (Brodsky et al., 2003; Elkhoury et al., 2011; Candela et al., 2014; Candela et al., 2015). Laboratory experiments reproducing field observations (Brodsky et al., 2003; Elkhoury et al., 2011) and directly testing
these three mechanisms under a variety of experimental conditions (Candela et al., 2014) have suggested flux-driven unclogging as a dominant mechanism of permeability enhancement at the laboratory scale. Regardless, many aspects of the mechanisms involved and their probable interplay in fracture permeability evolution under dynamic stress perturbations remain unresolved.

This study explores the separate and combined effect of normal-stress dominant dynamic stressing and pressure-induced shear deformation to account for their individual impacts. This is completed through the continuous measurement of fracture permeability evolution with stress and frictional shear where repeated fluid pressure pulses are applied in flow-through experiments on pre-stressed fractures.

2. Methods

To explore this impact of dynamic pressures on permeability evolution, we concurrently monitor fracture permeability and friction response to step-increasing pore pressure pulses (175 - 2500 kPa). These are completed in well-controlled flow-through experiments on saw-cut fractures in impermeable rock under recreated in situ stresses (3 MPa). The samples are confined within a triaxial pressure cell where the fractures are subjected to independently controlled confining and shear stresses, and differential pore pressures.

The experiments are conducted on functionally impermeable shales (Green River shale) and schists (Poorman Formation, kISMET, Sanford Underground Research Facility (SURF), SD). The cylindrical core plugs are split into two half-cylinders flanking a rectangular coupon and sheared in double direct shear geometry (Figure 2-1). Fracture surfaces are ground with sand paper and roughened with #150 grit (rougher) and #320 grit (smoother) abrasive powder. The prepared sample is isolated within a latex jacket and placed within the pressure cell.
For each pump attached to the triaxial pressure cell, pump fluid volume, flow rate, and pressure are tracked. An LVDT mounted to the loading piston continuously records the shear offset of the sample (Figure 2-1). We prescribe normal stresses, shear displacement rates, and fluid pressures. Fracture permeability (k) is derived from Darcy’s law (Eq. 1) as:

\[ k = \frac{\mu L Q}{A \Delta P} \]  

where \( \mu \) is the fluid viscosity \((8.9 \times 10^{-0} \text{ Pa} \cdot \text{s})\), \( L \) is the flow path length, \( A \) is the cross-sectional area of the sample perpendicular to the flow path, \( Q \) is the flow rate, and \( \Delta P \) is the differential pore pressure across the sample.

We perform four sets of pore pressure stepping experiments (PS1, PS2, PS3, GRS1). We apply a confining stress of 3 MPa and retain it constant throughout the entire experiment. Then, we initiate flow through the fractures by assigning an upstream pore pressure (70-220 kPa) that discharges to atmospheric pressure downstream. Artifacts of fracture re-assembly (Im et al., 2018) are minimized by shearing the initial 4 mm offset with a constant shearing velocity of 10 \( \mu \text{m/s} \) to bed-in the sample. Following this, the sample is held at a constant confining stress over an extended period (~ 10-17 hours). Pore pressure stepping begins following this hold period. Box-car pore pressure pulses are applied in successive step-wise increments (\( \Delta Pp \)) for 5 s, returning to the background control pore pressure (\( P_{p0} \)) and with an intervening period of 120 s between successive pulses. For the final four pulses, we stop step-increasing the pore pressure and simply apply the same pore pressure amplitude with the reapplication of shear stress immediately before the final pulse. In the first experiment (PS1), shear stress is also reapplied before the initiation of the entire pore pressure pulsing phase. This critically stresses the fractures and immediately primes for slip with the application of the pressure perturbation. For 2 of the pore pressure stepping experiments we apply hold periods of ~ 1000 s before reactivating the fractures as the last step – to evaluate the
role of healing and sealing on response. The experimental suite is documented in Table S1 (Supporting Information).

Figure 2-1 (a) Experimental apparatus, and fracture surfaces both pre- (left) and post-(right) experiment. (b) Samples from the kISET (EGS COLLAB) site are heterogeneous metamorphosed (schist) containing planes of weaknesses. (d) Green River shale is more homogeneous and more durable. (c, e) Evidence of wear and asperity plowing (striations and grooves) are observable on the post-experimental fracture surfaces. Sample size of the rectangular prisms in (a,b) is 0.004 x 0.024 x 0.038 m³.
3. Results

Detailed results are presented for the four pore pressure stepping experiments probing the effect of dynamic stressing and hydraulically-induced shear-reactivation on fracture permeability and friction evolution. In these experiments (Figure 2-2), fractures are subjected to over 45 successively incremented pore pressure pulses with differential pore pressures ($P_p$) ranging between 175 kPa and 2500 kPa. These recover a complete description of fracture permeability and friction behavior under dynamic normal and shear stress perturbations.

3.1. Step-Increasing Pore Pressure Pulses and Permeability Enhancement

Friction, displacement and fracture permeability evolution responses to pore pressure pulsing, hold and slide in experiment PS3 (Poorman, kISMET, SURF) are displayed in Figures 2-2a, b and c. Similarly, permeability responses in GRS1 (Green River shale), PS2, and PS1 are summarized in Figures 2-2d, e, f, and friction and displacement results for each experiment are provided in the supporting information (Figures S2, S3, S4). All experiments result in significantly enhanced permeability with stress perturbations, both in the presence and absence of hydraulically-induced shear deformation.

Following long hold periods, we re-apply shear stress at the initiation of the pulsing phase in PS1 and conduct PS2, PS3, and GRS1 without this initial reapplication of shear stress. While the fractures in PS1 become critically stressed and primed-for-slip due to shear loading, those in PS2, PS3, and GRS1 remain non-critically stressed due to the low creep rates during the preceding hold periods and accordingly require high initial pressure pulse amplitudes to slip.

As expected, the fractures in PS1 reactivate upon application of the first pressure pulse and shear deformation follows each successive pulse. In PS2, we increase the magnitude of the initial pore pressure pulse with reactivation occurring after only the second pulse. In PS3 and GRS1, both initial pressure and pressure pulse increments are reduced and set identical for all pulses. Therefore,
shear reactivations occur only after multiple pulses, allowing a separate analysis of shear associated and non-associated events. The response to reactivation is a sudden shear deformation at each pressure pulse followed by a slower creep resetting at the control pore pressure. We observe spikes in shear stress and displacement associated with higher amplitude pressure pulses (Figure 2-2a). These spikes are an artifact resulting from the upstream pressure pushing the loading piston backward and are not associated with actual fracture slip.

Figure 2-2a shows that shear stresses and displacement remain constant for the first 11 pore pressure pulses ($\Delta P = 30 \text{kPa}$) in PS3. At $P_{p12} = 580 \text{kPa}$, the fractures reactivate and the first induced shear slip occurs with a displacement of 0.001 mm (Figure 2-2a). The next pulse results in a shear slip of 0.004 mm ($\Delta d_{13}$), representing the largest difference between two successive displacement increments in the entire experiment ($\Delta d_{13} - \Delta d_{12} = 0.003 \text{mm}$). The very first pressure pulse in PS3 does not enhance the initial fracture permeability but the successive pulses do. This is the case even in the absence of shear slip, representing that the fracture permeability is significantly perturbed by pore pressure changes. The initiation of shear slip at $P_{p12} = 580 \text{kPa}$ results in an abrupt increase in permeability increment with successive pulses (Figure 2-2b). Fracture permeability increases ~9.5 times the initial value (from $2 \times 10^{-16} \text{m}^2$ to $1.937 \times 10^{-15} \text{m}^2$) as a result of the 53 successive pulses with pore pressures ranging from 250 kPa to 1810 kPa.

We observe similar response for Green River shale (GRS1) (Figure 2-2d). With pore pressure increments of 25 kPa, fracture permeability begins to enhance following the 7th pulse but without shear reactivation. Initiation of shear slip (25th pulse) results in a large step-wise increase in fracture permeability magnitude (from $7.62 \times 10^{-16} \text{m}^2$ to $2.24 \times 10^{-15} \text{m}^2$ at $P_{p26}$). As in PS3, the shear slip caused by the second pulse (#26) following the initiation of shear deformation is larger than the very first shear slip (the one at the 25th pulse). Similar to the other cases, permeability increases proportional to the magnitude of the shear-associated pulses. Permeability response in
GRS1 is especially uneven with both increases and null-changes in permeability magnitudes throughout the reactivation. As shown in Figure 2-2, GRS1 begins with the lowest initial fracture permeability (3.369×10^{-17} m^2), ends with the maximum resulting enhanced permeability (7.489×10^{-15} m^2) and occurs for the narrowest range of pore pressures of all the tests (Pp_{i} = 175 kPa and Pp_{60} = 1650 kPa).

In PS2 (Figure 2-2e), the first pore pressure pulse (Pp_{i} = 300 kPa) does not result in shear slip – rather, it enhances the initial fracture permeability by 2.6×10^{-16} m^2 (from 4.4×10^{-16} m^2 to 7.0×10^{-16} m^2). This first event is the maximum permeability increment achieved in the entire experiment (Pp_{1} = 300 kPa and Pp_{44} = 2500 kPa), indicating that the permeability enhancement appears to be dependent on the magnitude of the pressure pulse increment since pore pressure increment at the first event is the largest in this experiment (ΔPp_{1} = 130 kPa, with the remainder being ΔPp = 50 kPa). This first pore pressure pulse is responsible for the 13% of the total permeability enhancement (1.96×10^{-15} m^2). In total, fracture permeability increases 5.5 times over the initial value, at the same background pore pressure.

Results in PS1 show that the permeability response to the first pressure pulse is the maximum permeability increment achieved when compared to the remainder of the pulses. Fracture permeability doubles over the initial permeability after the first pulse and this enhancement as a result of a single pulse comprises 37% of the total permeability increase achieved throughout the next 45 pulses. Displacement results (Figure S2) also show that the shear slip as a result of this first pulse (Δd = 0.021 mm) remains as the maximum displacement increment achieved over a pressurization pulse for the next 37 pulses until the 38th pulse results in 0.024 mm offset (Pp_{38} = 2150 kPa). Fracture permeability enhancement as a result of these 45 pulses (4.895×10^{-15} m^2) is ~3.8 times the initial permeability (1.278×10^{-15} m^2). Our results show that
fracture permeability may increase absent shear reactivation as observed elsewhere (Elkhoury et al., 2011; Candela et al., 2014; Candela et al., 2015).

3.2. Permeability Response to Presence/Absence of Induced Shear Slip at Dynamic Stressing

Figure 2-3 shows the detailed permeability evolution in PS3 and GRS1. Fracture permeability is perturbed and enhances both with and without shear reactivation during dynamic stressing in both experiments. Systematic increases in pore pressures reactivate the fractures by reducing effective normal stress. Initiation of hydraulically-induced shear slip results in a slope change in permeability enhancement with pulse number (Figure 2-3a and 2-3c). Fracture permeability enhancement is significantly accelerated by an increase in permeability increments (Figure 2-3b and 2-3d). Both shear displacement and permeability increase data from PS3 and GRS1 (Figure 2-2 and 2-3) show that a significant change in increments particularly following the second pore pressure pulse after the start of shear slip. Surprisingly, the maximum permeability increment in each of the two experiments occurs with the second shear reactivation - not the first. Only 21% of the total permeability increase in PS3 and 10% in GRS1 takes place in the absence of shear slip. However, the detailed response of the slip-associated permeability response in GRS1 and PS3 are not identical. Unlike PS3, we observe a large step-wise increment in fracture permeability gain in GRS1 after the initiation of shear slip.

Permeability behavior in the absence of shear slip over prolonged dynamic stressing beyond our experimental data is not clear (see notation in Figures 2-3a and 2-3c). However, the anticipated contribution of “pure” dynamic stresses absent shear deformation are conceptually outlined in the extrapolations of Figures 2-3a and 2-3c.
Figure 2-2 Fracture permeability evolution due to both dynamic stressing and from holding (healing/sealing) then sliding (reactivation) for samples from the Poorman formation (schist) (PS1, PS2, PS3) and Green River shale (GRS1). Panels (a), (b), and (c) exhibit friction, permeability, and pore pressure changes in PS3 only. Panels (d), (e), and (f) display fracture permeability results from GRS1, and PS2, and PS1. All experiments initiate after “seating-in” over an extended hold period (~10-17 hours). Pore pressure pulses are applied with a duration of 5 s and successively [cont.]
incremented after a repose of 120 s. The pulse amplitude is held constant for the final four pulses in each test. The application of shear stress is marked by the black dashed lines. Red dashed lines with red stars mark the initiation of shear slip resulting from the hydraulic stimulation. Light and dark green bars in each panel mark the hold and then slide periods, respectively. Insets in Figure 2-2a and 2-2d are the displacement responses to stress perturbations at the moment flow-induced shear reactivation initiates in PS3 and GRS1, respectively. Both experiments show a larger induced shear displacement upon application of the second pulse following the initiation of shear displacement.

3.3. Permeability Response to Pore Pressure Pulses of the Same Amplitude

We apply the same pressure pulse amplitudes for the final four pulses in all experiments. The first three pulses are conducted without any additional treatment so that the second and third pulses do not induce shear reactivation (pulse numbers 53 through 55 in Figure 2-3b). Conversely, before the fourth pulse (number 56 in Figure 2-3b), we re-apply shear stress up to near a critical state to generate a controlled induced shear slip. We observe that fracture permeability is no longer enhanced with the application of the same pressure pulse amplitude (first three pulses in normal stressing mode) but enhances further when shear slip is associated with the pulse (fourth pulse in shear stressing mode). Induced shear slip that occurs with the final pulse increases the fracture permeability by ~8.7–46.4%, the values measured immediately after the reapplication of shear stress. As a result of the same pore pressure pulse differential ($Pp = 2500$ kPa), fracture permeability enhances from $4.73 \times 10^{-15} \text{ m}^2$ to $5.145 \times 10^{-15} \text{ m}^2$ ($\Delta k = 4.15 \times 10^{-16} \text{ m}^2$, 9%) in PS1 and from $2.01 \times 10^{-15} \text{ m}^2$ to $2.86 \times 10^{-15} \text{ m}^2$ ($\Delta k = 8.5 \times 10^{-16} \text{ m}^2$, 42%) in PS2. Respective shear stress drop at induced shear slip is much higher in PS1 than in PS2, showing that shear induced permeability enhancement does not necessarily positively correlate with the pre-seismic fracture permeability or with the amount of shear stress drop. Fracture permeability enhances from $1.77 \times 10^{-15} \text{ m}^2$ to $2.01 \times 10^{-15} \text{ m}^2$ ($\Delta k = 3.29 \times 10^{-16} \text{ m}^2$) in PS3 after the final pulse ($Pp = 1810$ kPa). Induced seismicity with a differential pressure of 1650 kPa in GRS1 results in an enhanced fracture
permeability of $7.81 \times 10^{-15} \ m^2$ with a pre-seismic permeability of $5.33 \times 10^{-15} \ m^2$ ($\Delta k = 2.48 \times 10^{-15} \ m^2$).

In PS1, the permeability increment from the final pulse ($4.15 \times 10^{-16} \ m^2$) is double the maximum prior increment ($k_3 - k_2 = 2.1 \times 10^{-16} \ m^2$) resulting from the previous pulses, excluding the initial pulse. The increment upon the initial pulse ($1.339 \times 10^{-15} \ m^2$) is considerably larger than that resulting from the final pulse. In PS2, the final pulse gives 3 times the maximum permeability increment, a maximum increment that in this case results from the initial pressure pulse ($2.6 \times 10^{-16} \ m^2$). In PS3, this final increment ($3.29 \times 10^{-16} \ m^2$) is more than 3 times the maximum permeability increment (achieved upon the second pulse after shear slip begins) ($0.98 \times 10^{-16} \ m^2$).

Net displacement does not change significantly over the pulses we apply the same pore pressure amplitude. However, the final pulse in each experiment results in shear slip significantly larger than maximum displacement achieved in the previous pulses.

Figure 2-3 Permeability evolution at dynamic stressing in both the absence (blue) and then presence (orange) of flow-induced shear slip in PS3 (a and b) and GRS1 (c and d). Panels (a) and (c) show the increase in absolute permeability, (b) and (d) show the increment in permeability versus differential pore pressure.
3.4. Fracture Permeability Behavior at Hold and Reactivation Following Dynamic Stressing

We hold fractures under a normal stress of 3 MPa and reactivate them for ~5 mm to observe fracture permeability response following dynamic stressing. Hold periods typically result in a decline in fracture permeability similar to that observed during the prolonged hold periods prior to dynamic stressing (Im et al., 2018). In GRS1 (Figure S3) ~94% of the maximum enhanced fracture permeability is destroyed within the 4 hour duration hold period following the stress perturbations (from $7.81 \times 10^{-15}$ m$^2$ to $4.45 \times 10^{-16}$ m$^2$). During the ~15 min duration hold periods in PS2 and PS3, fracture permeability declines from $2.879 \times 10^{-15}$ m$^2$ to $1.892 \times 10^{-15}$ m$^2$ (34%) and from $2.157 \times 10^{-15}$ m$^2$ to $1.658 \times 10^{-15}$ m$^2$ (23%), respectively. Average fracture permeability decline rates ($m^2/s$) from these experiments are consistent among themselves (PS2, PS3, GRS1=9.68×10$^{-19}$, 5.20×10$^{-19}$, 5.17×10$^{-19}$). Fracture permeability converges to its pre-stimulated value with a 95% recovery of the initial permeability from the transient permeability enhancement during the hold in GRS1. The experiment was terminated at 95% recovery due to injection pump depletion.

Fracture reactivation following the final hold results in a permeability enhancement trend in both in PS2 and PS3 (Figure 2-2e and 2-2a). This enhancement is more pronounced in PS2 with a permeability increase from $1.892 \times 10^{-15}$ m$^2$ to $2.807 \times 10^{-15}$ m$^2$. In PS3, fracture permeability remains similar to that pre-reactivation but a slightly increasing trend is observed during the reactivation. Interestingly, the 1000 s (~15 min) preslip hold period in PS2 has an average permeability decline rate almost double that for PS3.
Figure 2-4 Permeability-friction response to pressure pulses of the same amplitude (final four pulses in each experiment). Panels (a), (b), and (c) display friction, permeability, and pore pressure changes in PS3. Increasing differential pore pressure amplitude between pulse #47 to #53 enhances permeability. Application of the same pressure (1810 kPa) between pulses #53 and #55 results in identical fracture permeability following each pulse (k₅₂ < k₅₃ = k₅₄ = k₅₅). Final permeability increase (k₅₆) is associated with the shear slip since we apply shear stress prior to the final pulse (black dashed lines). Panel (d) displays normalized permeability versus pulse number for the final four pulses of the same amplitude at each experiment. Pore pressures are 2500 kPa for PS1 and PS2, 1810 kPa for PS3, and 1650 kPa for GRS1.
4. Discussion

We observe a rich range of fracture permeability and friction responses throughout these reactivation and hold experiments. Fracture permeability decreases during hold periods both before and after the pore pressure stepping, and enhances with increasing pore pressure, and shear deformation. We codify these responses relative to mechanistic controls.

4.1. Sealing and Healing

Fractures are subject to long hold periods prior to the application of incremented pore pressure pulses - these hold periods broadly representing interseismic repose. The gradual permeability reductions observed in our experiment during hold are commensurate with those observed in natural systems (Elkhoury et al., 2006; Xue et al., 2013) – albeit with an accelerated rate for the experimental observations. Thus, nature is represented in our experiments by holding the fractures over long periods (~10-17 hours), to mimic repose, prior to dynamic stressing and potential reactivation. The slow destruction of permeability observed during hold periods, both pre- and post-stimulation, implies that chemo-mechanical compaction can be a dominant mechanism. This sealing, and possible healing and compaction, may be primarily driven by stress corrosion (Yasuhara & Elsworth, 2008) or aided by pressure solution and mineral precipitation (Yasuhara et al., 2004).

Pre-slip frictional healing and sealing of fractures over such repose periods has been demonstrated to be essential in defining the fracture permeability response following reactivation (Im et al. 2018). The results in this work demonstrate that fluid pressure-pulse-driven permeability enhancement is also strongly influenced by pre-stimulation sealing. Permeability responses to three identical pulses (Figure 2-4a) show that, when shear slip is not associated, the enhanced permeability achieved with a given pressure pulse appears of a uniform magnitude that does not vary with the application of repeated pulses of the same amplitude. If we assume that the
permeability enhancement resulting from the pulse scales with the pulse amplitude, the permeability increment achieved due to a single pulse is accordingly dependent on the magnitude of the sealing prior to application of the pulse. Figure 2-4b shows that, for pulses of same pressure amplitude, the more the fracture seals in the 120 s of repose following each pulse, the higher the permeability increment with the following pulse in order to reach to the pre-ordained enhanced permeability at that given pore pressure. This demonstrates that the pulse-driven permeability evolution is strongly dependent on the pre-stimulation sealing. We observe that sealing-breaching behavior is perfectly reversible and scales with pore pressure (flow rate) perturbation. Pulses #54 and #55 (Figure 2-4a, b, and c) do not result in shear slip but fracture permeability dynamically readjusts over three minutes, first declining during the intermediate hold and subsequently increasing to an enhanced permeability that scales with the pressure pulse amplitude. These short term changes in fracture permeability are systematic and appear to be sealing- and pore pressure-controlled.

Fracture permeability declines once the stress perturbations are terminated. In GRS1 the fractures are held for the longest overall duration after dynamic stressing resulting in an almost full recovery of the entire transient permeability increase achieved during dynamic stressing. Convergence of enhanced fracture permeability to its initial value after the termination of stress perturbations suggests reversible mechanism(s) for the creation and then destruction of permeability.

4.2. Pore Pressure-Induced Permeability Enhancement and Contribution of Shear Deformation

These experiments demonstrate that fracture permeability enhances with increasing pore pressure amplitude, both in the absence and presence of shear slip. Permeability increase scales with the pore pressure amplitude and permeability increment scales with the amount of pre-pulse
sealing. Shear deformation inevitably results from increasing the pore pressure, decreases effective normal stress and promotes slip. We observe that the initiation of hydraulically-induced shear slip (in PS3 and GRS1) is manifest as an increase in the rate (slope change) of fracture permeability increase (Figure 2-2 and 2-3) with successive pulse number. Permeability enhancement is accelerated by shear deformation and this increase in (slope change) permeability increment rate may reflect the contribution of shear dilation added to other (normal stress-only) mechanisms involved in injection-induced permeability enhancement in the absence of shear slip. We identify shear dilation as a key mechanism based on the observation that permeability creation at shear slip is much larger over rougher fracture surfaces (Figure S5).

Interestingly, both PS3 and GRS1 show that the second pressure pulse following the initiation of shear slip results in a much larger displacement and permeability increment than the very first pulse. This may be due to the linear distribution of effective stress from upstream to downstream in the apparatus. The first pulse (#12 in PS3 and #25 in GRS1) initiates slip in the upstream portion of the fracture. Only once the strongly sealed and healed interlocking asperities are completely sheared off by the first shear slip, does the slipping patch extend over the full fracture, and sliding initiates. Displacement due to the second pulse produces more wear products due to the larger displacement, with these wear products immediately discharged with the flux as soon as they are generated. This results in a much larger permeability enhancement scaling with larger amount of mobilized particles and unclogging in the second pulse than relative to the first. This behavior also fits with the spontaneous nature of the mobilization phenomena. This explanation assumes that the amount of wear material generation due to frictional sliding increases with the shear displacement offset of the fracture (Queener et al., 1965; Power et al., 1988; Wang and Scholz, 1994).

Permeability enhancement, both with and without shear slip, appears to scale systematically and consistently with pressure pulse number, albeit with a different rate constant
(Figures 2-3a and 2-3b) for shear-absent and shear-present reactivations. However, simultaneously, we observe spontaneous permeability sticks and jumps in all experiments, but especially pronounced in GRS1. These jumps in permeability increase occur under particular circumstances – such as with the second shear slip – where particle mobilization and unclogging of existing pathways is manifest. The observed systematic increase in permeability, however, may be a more complex process incorporating multiple mechanisms in addition to particle mobilization and shear dilation. In particular, the reversible nature of sealing demonstrated in identical pore pressure pulses, where shear slip is no longer induced, leaves uncertain the source of consistent and fast-generated wear material in the absence of shear slip if pure clogging/unclogging is assumed for pulse-driven permeability enhancement.

5. Conclusions

The experiments reported in this work elucidate the complex interaction between mechanisms controlling the evolution of fracture permeability and friction under the combined effect of dynamic stressing and injection-induced shear deformation. We find that fracture permeability is enhanced with effective stress perturbations even in the absence of shear slip – although the magnitude of the enhancement is typically less where shear reactivation is absent. Permeability increase scales with pore pressure amplitude and permeability increment scales with the amount of pre-pulse sealing. This sealing and unsealing behavior is systematic, scales with the pore pressure and is reversible, even in the very short term. The initiation of injection-induced shear slip due to the application of pore pressure pulses accelerates permeability increase – over the case where shear slip is absent. This increase in the per-pulse rate of permeability enhancement is not immediate, but is delayed by a single pore pressure pulse (coincident with the second pulse). The effect of particle mobilization may be the primary mechanism responsible for the spontaneous
enhancement in permeability in addition to the steady increase trend resulting from pure normal stress perturbations. Permeability eventually recovers from the transient enhancement once the stress perturbations cease. These results have implications in better constraining the mechanics of dynamic triggering of earthquakes and in designing efficient stimulation treatments for depleted or unconventional hydrocarbon and enhanced geothermal reservoirs.

6. References


7. **Supporting Information**

Table S1: List of pore pressure stepping experiments and procedures followed after the initial shear-in and extended hold periods.

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Rock Type</th>
<th>Abrasive Grit</th>
<th>(P_0) (kPa)</th>
<th>(Pp) increments (kPa)</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS1</td>
<td>Poorman schist</td>
<td>#320</td>
<td>70</td>
<td>50</td>
<td>Shear stress application before starting the pulses, (Pp_1 = 300) kPa, (Pp_{48} = 2500) kPa, 45 pulses of step-increase, #46 – 48: recurring pulses of (Pp=2500) kPa with shear stress reapplication before (Pp_{48})</td>
</tr>
<tr>
<td>PS2*</td>
<td>Poorman schist</td>
<td>#320</td>
<td>130</td>
<td>50</td>
<td>(Pp_1 = 300) kPa, (Pp_{47} = 2500) kPa, 44 pulses of step-increase, #45 – 47: recurring pulses of (Pp=2500) kPa with shear stress reapplication before (\Delta Pp_{47}), hold (~ 15 min), slip (~5.5 mm).</td>
</tr>
<tr>
<td>PS3</td>
<td>Poorman schist</td>
<td>#320</td>
<td>220</td>
<td>30</td>
<td>(Pp_1 = 250) kPa, (Pp_{56} = 1810) kPa, 53 pulses of step-increase, #54 – 56: recurring pulses of (Pp=1810) kPa with shear stress reapplication before (Pp_{56}), hold (~ 15 min), slip (~5.5 mm)</td>
</tr>
<tr>
<td>GRS1</td>
<td>Green River shale</td>
<td>#150</td>
<td>150</td>
<td>25</td>
<td>(Pp_1 = 175) kPa, (Pp_{63} = 1650) kPa, 60 pulses of step-increase, #61 – 63: recurring pulses of (Pp=1650) kPa with shear stress reapplication before (Pp_{63}), hold (~ 4 hours)</td>
</tr>
</tbody>
</table>
Figure S5: Full experimental procedure performed in PS3. Details of the procedure is in Table S1.
Figure **S6**: Fracture permeability and friction evolution at dynamic stressing, hold and slide for samples from Poorman schist in PS1. Panels (a), (b), and (c) exhibit friction, permeability, and pore pressure changes. This part of the experiment belongs to the pore pressure stepping portion of PS1 after the initial long hold. Panel (b) is identical to Figure 2-2f.
Figure S7: Fracture permeability and friction evolution at dynamic stressing, hold and slide for samples from Poorman schist in PS2. Panels (a), (b), and (c) exhibit friction, permeability, and pore pressure changes. This part of the experiment belongs to the pore pressure stepping portion of PS2 after the initial long hold. Panel (b) is identical to Figure 2-2e.
Figure S8: Fracture permeability and friction evolution at dynamic stressing and post-stimulation hold for samples from the Green River shale (GRS1). Unlike the fractures in PS experiments, GRS fracture surfaces are grinded with rougher abrasive powder (#150 grit). Panels (a), (b), and (c) exhibit friction, permeability, and pore pressure changes. This part of the experiment belongs to the pore pressure stepping portion of GRS1 after the initial long hold. Panel (b) is identical to Figure 2-2d.
Figure S9: (a) Absolute permeability increase versus pore pressure amplitude, and (b) normalized permeability increase versus normalized pore pressure amplitude. Insets in both panels zoom in to results from Poorman schist only.
Chapter 3
Conclusions

This thesis examines fracture permeability–seismicity relationships in two separate studies. These combined studies separately elucidate (1) the role of preslip frictional healing, and (2) the combined effect of dynamic stressing and fluid-pressure-induced shear deformation on the evolution of fracture permeability and friction throughout the phases of the seismic cycle.

In order to investigate the role of pre-slip fracture healing as a determining factor on the mode of permeability evolution upon fracture reactivation, we report a series of slide-hold-slide and pore pressure stepping experiments, monitored for the co-evolution of fracture permeability and friction (Chapter 1). These experiments broadly represent the response through the phases of seismic cycle. We find that interseismic repose plays a critical role in enabling fracture healing and sealing and ultimately defines the mode of permeability change that results upon fracture reactivation. The magnitude of permeability increase from each reactivation is strongly dependent on the degree of fracture healing achieved during the pre-slip hold period. Pore pressure stepping experiments demonstrate that seismicity induced by fluid injection enhances the permeability presumably by shear dilation and flux driven unclogging. Pressure pulses and permeability enhancement are positively correlated although the maximum rate of permeability increase is achieved following the first injection pulse.

The experiments reported in Chapter 2 of this work elucidate the complex interaction between mechanisms controlling the evolution of fracture permeability and friction under the combined effect of dynamic stressing and injection-induced shear deformation. We find that fracture permeability is enhanced with effective stress perturbations even in the absence of shear
slip – although the magnitude of the enhancement is typically less where shear reactivation is absent. Permeability increase scales with pore pressure amplitude and permeability increment scales with the amount of pre-pulse sealing. This sealing and unsealing behavior is systematic, scales with the pore pressure and is reversible, even in the very short term. The initiation of injection-induced shear slip due to the application of pore pressure pulses accelerates permeability increase – over the case where shear slip is absent. This increase in the per-pulse rate of permeability enhancement is not immediate, but is delayed by a single pore pressure pulse (coincident with the second pulse). The effect of particle mobilization may be the primary mechanism responsible for the spontaneous enhancement in permeability in addition to the steady increase trend resulting from pure normal stress perturbations. Permeability eventually recovers from the transient enhancement once the stress perturbations cease. These results have implications in better constraining the mechanics of dynamic triggering of earthquakes and in designing efficient stimulation treatments for depleted or unconventional hydrocarbon and enhanced geothermal reservoirs