LABORATORY STUDIES OF PERMEABILITY EVOLUTION:
ROLES OF FRACTURE, SHEAR, DYNAMIC STRESSING, AND RESERVOIR ROCK PROPERTIES

A Dissertation in
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by
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ABSTRACT

Fault and fracture permeability-stability relationships continually evolve over the seismic cycle. Both static and dynamic changes in mechanical stresses can affect the fluid pressures and vice versa. These changes can be potentially beneficial to energy production, as dynamic stressing has been observed to enhance reservoir permeability in natural and manufactured systems. However, both dynamic and static changes in stress have also been shown to destabilize faults, triggering earthquakes. It is clear a fundamental understanding of controlling mechanisms is necessary for safely enhancing reservoir productivity and understanding seismic hazard assessment.

In this dissertation, I strive to illuminate the underlying mechanisms that govern permeability evolution, including transient changes in permeability associated with dynamic stressing and fault shear. While the relationships between fault slip, dynamic stressing, and permeability have been studied separately, little data are available on their combined effects. In each chapter, I present results from suites of carefully controlled laboratory experiments to investigate the effect of mode II fault failure and shear on permeability and poromechanical properties.

In Chapter 1, I investigate the effects of dynamic stressing on highly porous reservoir rock, Berea sandstone, at various stages of shear displacement. I demonstrate that porous rock is sensitive to dynamic stressing only via fluid pulsing and that both reservoir permeability and sensitivity to dynamic stressing declines with shear. Chapter 2 extends this work into low porosity, low permeability reservoir rock, Westerly granite and Green River shale. Here I show that frequency of imposed fluid oscillations has the greatest control over permeability enhancement. Finally, chapter 3 focuses on friction and permeability responses across multiple
reservoir rock types throughout the seismic cycle, simulated via Slide-Hold-Slide and velocity step testing. Here, I use in situ fractured samples alongside traditional, saw cut samples to highlight the effect of fracture roughness on the fluid response across varying rock mineralogy.

This dissertation provides insight to the controlling mechanisms and data that can be used to predict reservoir behavior, including the feasibility of shear failure and dynamic stressing as reservoir permeability management techniques. I demonstrate that permeability-stability relationships evolve as a result of dynamic stressing and are dependent upon properties of the reservoir: porosity, fracture roughness, and stiffness as well as the properties of imposed dynamic stressing: frequency and amplitude. The evidence provided shows differing results from exercising the same mechanism when applied to different types of reservoir rock.
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Introduction

Large scale heat diffusion from the earth’s interior drives tectonic motion in the earth’s shallow crust. In geologic systems, tectonic strain accumulates along rock interfaces until the shear stress is greater than a combination of the effective normal stress, cohesion, and angle of internal friction. While cohesion and angle of internal friction are dependent on rock properties, the effective normal stress is a result of regional stresses consisting of a combination of mechanical compressive stresses acting normal to the rock interface and pore pressure acting in all directions within the rock. A sudden increase in pore pressure can reduce the effective normal stress; potentially lower than the shear stress acting on the interface causing shear failure. This relation is fully explained for failure of intact rock and pre-existing fractures through Mohr-Coulomb and Byerlee failure criterion, respectively.

Interestingly, just as rapid changes in fluid pressure can cause fault and fracture destabilization, seismicity has been shown to enhance fluid pressures. Perhaps more interesting is that these effects can be observed thousands of kilometers from the main shock via enhanced fluid flow in petroleum reservoirs, tidal responses, and well water levels. These reservoirs are too far away from the fault slip to for the magnitude of permeability enhancement to be explained by a static change in the regional stress field. Dynamic shaking as a result of fault failure has proven an effective mechanism of permeability enhancement at this range. Dynamic stressing is the driver to mobilize fine particles within the rock matrix and fracture plane. Permeability can be enhanced from particle mobilization as particulates can be cleared through pore throats critical to flow paths. With the small amount of energy this requires, dynamic stressing can redistribute fluid pressures at great distances, creating greater differential pressures and enhancing
permeability. Loosening or dissolution of precipitates, promoted by dynamic shaking, can redistribute pore pressures in a similar manner. Enhanced permeability can then generate positive feedback by enhancing comminution and pressure dissolution. If flow is enhanced in close proximity to critically stressed faults, dynamic shaking can even act as a triggering mechanism for further fault rupture.

Large scale dynamic stressing and the effects on fault and fracture stability have been well documented in the field. Recently, several laboratory studies have recreated natural observations by utilizing well controlled dynamic stressing via mechanical or pore fluid pulsing. These laboratory studies have greatly improved understanding of mechanisms controlling the permeability response to dynamic stressing. Yet, fundamental controls on the permeability-stability relationship remain poorly constrained, particularly with regard to dynamic stressing. This is largely due to the narrow scope and design limitations of prior studies. The laboratory scale constrains environmental variables and allows for precise measurement and documentation, but presents its own problems. Historically, fluid flow experiments have been plagued by edge effects due to small sample sizes and tightly confined experimental designs that limit the amount of feasible instrumentation. Extensive thought must be given to design parameters as some controlling mechanisms may be in greater competition on the small, laboratory scale than on the field scale of entire fault zones.

Enhanced reservoir permeability from passing seismic waves showed that dynamic stressing is a feasible method for improving recovery in energy systems. It has since been employed for fracture stimulation in petroleum and enhanced geothermal systems. However, without a fundamental understanding of controlling mechanisms, the application of these techniques will be unable to produce the most efficient results. In this dissertation, I use well controlled laboratory experiments of novel design and broad scope to further develop the
understanding of controlling mechanisms necessary for upscaling to industrial practices and an enhanced academic understanding of natural systems. I attempt to study the generality of controlling mechanisms throughout the seismic cycle and broaden the knowledge base by varying reservoir rock and fracture roughness. My main contributions are demonstrations of fluid response variability with fracture, shear, and dynamic stressing across rock samples of different representative reservoirs throughout the seismic cycle.
Chapter 1

Permeability Evolution as a Function of Fracture, Shear, and Dynamic Stressing Under True Triaxial Load

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1.1 Abstract:

We study the effects of fracture, shear, and dynamic stress on the permeability of Berea sandstone and Westerly granite. Intact samples are fractured and sheared under true triaxial loading conditions at effective normal stress of 20 MPa. Experiments are conducted using L-shaped, prismatic samples that are fractured in-situ while monitoring permeability and strength evolution during shear. Fractures are rough, with peak to trough distances up to 5 mm; nominal fracture area is 45x50 mm². We find that matrix permeability of Berea decreases with increasing differential stress during triaxial loading to failure. Fracture permeability decreases with shear displacement immediately after failure and then exhibits a complex pattern with additional shear. Dynamic oscillations of effective normal stress were imposed via pore pressure and applied normal stress at frequency of 1 Hz and amplitudes from 50 kPa to 1 MPa. Pore pressure oscillations resulted in a transient increase in permeability, while applied normal stress oscillations had no consistent effect on fracture or matrix permeability. Normalized permeability changes scale with the amplitude of stress perturbations for both rock types. For Berea sandstone, the magnitude of transient permeability enhancement diminishes with shear displacement, likely due to an abundance of fine particle generation. Our results show how fracture creation and shear can be used in stimulation of natural and engineered reservoirs.
1.2 Introduction:

Reservoir productivity is reliant on the presence and quality of flow pathways. The creation or stimulation of fracture networks is often used to improve the efficiency of energy production and recovery in petroleum, geothermal, and groundwater reservoirs. The impact of static stresses on permeability and poromechanical properties are well known (Brace et al., 1968; Faoro et al., 2012; Faulkner, et al., 2011; Frash et al., 2017; Zoback and Byerlee, 1975). However, recent works show that transient, dynamic stress perturbations can also impact reservoir permeability at both field and lab scales (Beresnev and Johnson, 1994; Brodsky et al., 2003; Candela et al., 2014; Carey et al., 2016; Elkhoury et al., 2011; Frash et al., 2017; Kouznetsov, 1998). In sandstones, the primary mechanism for this increase has been identified as the mobilization of fine particles (Brodsky et al., 2003; Candela et al., 2014, 2015; Ikari et al., 2009; Liu and Manga, 2009; Oliviera et al., 2014; Roberts, 2005). Several of these studies investigated flow dependent mobilization of fines and permeability change with fracture aperture (Candela et al., 2014; Ikari et al., 2009; Samuelson et al., 2009). The generality of this mechanism, and whether it applies in granites or other igneous rocks is unknown. Prior laboratory work examined reservoir rocks that were either intact or pre-fractured (Brace et al., 1968; Zhu and Wong, 1997; Zoback and Byerlee, 1975).

The impact of shear displacement on fracture permeability and fluid flow in fault zones is poorly constrained. Shear displacement has been shown to reduce local permeability (Fang et al., 2017; Faoro et al., 2012; Ikari et al., 2009; Im, et al., 2018; Mitchell and Faulkner, 2008; Mohanty and Hsiung, 2011). Proposed explanations for observed permeability changes with shear displacement are fracture aperture dilation and compaction (Faoro et al, 2012; Witherspoon et al.,
1980; Zimmerman and Bodvarsson, 1996), development of shear fabrics (Ikari et al., 2009), and fouling of pore throats from fine particles generated as wear products (Candela et al., 2014; Oliviera et al., 2014; Roberts and Abdel-Fattah, 2009). Our laboratory study offers the opportunity to identify the primary mechanisms of permeability change throughout fracture formation and evolution.

Here, we examine both sandstone and granite samples and study the impact of in-situ fracturing and shear displacement on permeability evolution. Our work involves rough, natural fractures that are analogous to reservoir fracture networks and tectonic faults, and thus our results complement and extend existing studies of fracture permeability which have focused primarily on saw-cut, smooth fractures (Brace et al., 1968; Fang et al., 2017; Ikari et al., 2009; Im et al., 2018; Ishibashi et al., 2016; Mohanty and Hsiung., 2011; Tanikawa et al., 2010).

1.3 Methods:

1.3.1 Experimental Configuration

Experiments were conducted in a true-triaxial pressure vessel and biaxial load frame (Figure 1.1). We modified the design of previous studies (Candela et al., 2014, 2015; Elkhoury et al., 2011; Faoro et al., 2012; Ikari et al., 2009; Samuelson et al., 2009) for improved fracture plane reproducibility and sample isolation from the confining pressure fluid. True triaxial deformation is achieved via two applied loads and an independently-controlled confining pressure. All stresses and pressures are servo-controlled and recorded continuously throughout experiments using a multi-channel 24-bit analog-to-digital converter. Data are collected at 10-kHz and averaged for storage in the range 1–1000 Hz depending on the experimental stage.

We used intact samples of Berea sandstone (100 mDarcy type; Cleveland Quarries,
Vermilion, OH) and Westerly granite (Camoli Granite Inc., Ashaway, RI) to cover a broad range of intrinsic permeability. Samples were cut into L-shaped blocks measuring 68 x 45 x 50 x 20 mm, following the approaches of Elkhoury et al., (2011) and Candela et al. (2014, 2015) with modifications as noted in Figures 1.1 and 1.2. The smaller section of the L-shaped block was notched to control the fracture plane orientation and increase reproducibility across our suite of experiments (Table 1.1). Berea samples were cut such that fluid flow was parallel to bedding.

Our sample assembly included a number of components and the set-up for each experiment was performed in a series of steps to ensure reproducibility between experiments (Figure 1.2). A thin, flexible latex jacket separated the pore fluid and sample from the confining pressure. Metal shims were used at the top and bottom of the eventual fracture plane to ensure that the jacket did not intrude into the fracture. Jackets were sealed against the front and back of the sample to eliminate the possibility of fluid flow along these surfaces (Figure 1.2b). We used porous metal frits to produce a line source of fluid, maintained at constant pore pressure via servo control, at the top and bottom of the eventual fracture plane (Figure 1.2). An in-house clamp design was used to seal the latex jackets against O-rings in the loading blocks (Figure 1.2). A support block underneath the static, smaller side of the L-shaped sample (Figure 1.2) was used to prevent tilting of the sample during shear loading and fracture and in turn increase the reproducibility of fracture plane orientation. This support block is T-shaped (Figure 1.2b) with a cylindrical shaft that passes through the jacket to provide direct contact with the base of the loading platen (item 15 in Figure 1.2b). The jacket is sealed against the T-support shaft using steel wire. Pore pressure lines were flushed with DI water prior to each experiment and at the start of each experiment to eliminate air from the system before saturating the sample.
1.3.2 Experiment Procedure:

Sample were placed into the pressure vessel, accessed via removable high pressure doors, before sealing the vessel and applying a nominal normal stress and confining pressure of 5 MPa. A flow gradient was then established by independently controlling pore pressure intensifiers (Figure 1.1d). We used a 400 kPa pore pressure gradient $\Delta P$ for Berea sandstone experiments, with typical pressures of 3.1 MPa and 2.7 MPa for the inlet and outlet respectively (see details in Table 1.1). A larger gradient was required in Westerly granite ($\Delta P = 2$ MPa, with 4 MPa and 2 MPa for the inlet and outlet respectively). We monitor the volumetric flow rate $Q$ in and out of the sample continuously (Figure 1.3) and report permeability values only for steady-state flow conditions, indicated by $Q_{in} = Q_{out}$ to ±5%. We calculate effective permeability $k$, based on Darcy’s law (Figure 1.3a);

$$k = \frac{\mu L Q}{S \Delta P}$$

where $\mu$ is the fluid viscosity ($8.9 \times 10^4$ Pa s for DI water at T=25$^\circ$ C), $L$ is flow path (50 mm), $S$ is the cross sectional area of the sample perpendicular to the flow direction (45×29 mm), $Q$ is flow rate, and $\Delta P$ is the pore pressure differential (Figure 1.1; Table 1.1). The flow rate is calculated using the displacement rates of the inlet and outlet pore pressure intensifier pistons over a time window appropriate for the conditions (typically 1-2 seconds). The unique L-shape of the sample allows for a constant flow path length and width as the sample is sheared. As illustrated in Figure 1.3, we only report permeability when the inflow and outflow rates are equal to within ±5% in Berea sandstone (steady-state flow conditions) and ±2% in Westerly granite.

We studied the effect of oscillations in effective normal stress on shear strength, matrix permeability prior to fracture, and fracture permeability. Normal stress oscillations were imposed as a proxy for the affect of passing seismic waves on reservoir permeability and poromechanical
properties. We used sinusoidal oscillations with a frequency of 1 Hz and amplitudes that ranged from 50 kPa to 300 kPa in Berea sandstone and up to 1 MPa in Westerly granite (Table 1.1). We performed effective normal stress oscillations by changing either the applied normal stress or pore pressure. For pore pressure perturbations, we oscillated the inlet pore pressure while maintaining a constant outlet pressure and applied normal load (Figure 1.4), following previous work (Candela et al., 2014; Elkhoury et al., 2011). We focus on permeability measurements taken 10 s before and 10 s after the imposed oscillations to ensure that the measurements are not contaminated by fluid storativity or other transient poro-elastic effects. For applied normal stress perturbations, we oscillated the stress perpendicular to the fracture, using the same range of frequency and amplitude (Table 1.1), while maintaining a constant differential fluid pressure between the inlet and outlet.

Shear loading was applied to intact samples by advancing the vertical piston, in contact with the top of the L-shaped block, at a servo-controlled displacement rate of 11 µm/s. The notch at the top and bottom of the eventual fracture plane, as well as the sample geometry, guided the fracture plane and helped ensure reproducibility in the gross fracture geometry. Once the sample was broken (Figure 1.5), shear sliding was imposed in steps of controlled displacement. The physical parameters of the experiment allowed for shear displacement of approximately 15 mm after fracture.

We measured stresses, shear and normal displacement across the fracture, and fluid flow volumes continuously throughout each experiment. We also used a small, high-resolution LVDT within the pressure vessel to measure displacement normal to the fracture plane (Figure 1.1). Perturbations in effective normal stress oscillations were performed at various times throughout each experiment: before and after fracture, as well as after each discrete shear sliding step of 0.1 mm, 1 mm, and 10 mm displacements (Figure 1.6). After fracture and each shear displacement
step, the vertical piston was stopped and held in place during stress oscillations and permeability measurements. Our typical sequence for pore pressure oscillations is shown in Figure 1.4; 1 Hz oscillations were imposed for 20 s after which we waited for 40 s before repeating the oscillations at a different amplitude.

1.4 Results:

1.4.1 Permeability Evolution and Shear Displacement:

We show data for one complete experiment (p4670) with Berea sandstone in Figure 1.5. Note the application of pore fluid pressure early in the run. Permeability measurements are shown after steady state flow was attained (Figure 1.3). The matrix permeability measured prior to fracture is in the range 1-5x10^{-14} m^2, or a few tens of millidarcy, as expected. Permeability begins to decrease when shear stress reaches about 50% of the ultimate strength and then drops dramatically upon fracture. The fracture surfaces are complex, with 3D roughness, breccia, and extensive microcracking. The peak to trough roughness of the bounding surfaces is generally several mm and after even a small amount of shear the fractures are essentially laboratory fault zones with fault gouge and damaged wall rock.

For our suite of experiments with Berea sandstone, we find that sample permeability decreases upon fracture (Figures 1.5 and 1.6). Our observations indicate destruction of matrix permeability via grain crushing and microcracking associated with development of the macroscopic fracture. The fracture process is complex and typically occurs over 10’s of seconds, with a series of small stress drops (Figure 1.5) followed by one or more large, dynamic stress drops that produce audible acoustic emission. Permeability decreases progressively during fracture and typically shows a smooth reduction with occasional sharp drops during the large
stress drop. The measurements of sample thickness, made perpendicular to the shear direction via the LVDT internal to the pressure vessel (Figure 1.1d) corroborate the complex set of processes that occur during fracture (Figure 1.5b). We observe sample dilation of up to 100 µm, which corresponds to a linear strain of 0.3%, prior to fracture, followed by compaction as the shear stress drops and the fracture slips (Figure 1.5b). We typically stopped shear loading immediately after fracture in order to allow fluid pressure to equilibrate and flow to reach steady state, which occurred within a few seconds (Figure 1.3).

After fracture, we measured the evolution of permeability as a function of shear displacement (Figure 1.5) and dynamic stressing (Figure 1.6). We find that permeability increases transiently immediately following the onset of shear, but then decreases with additional shear displacement. Figure 1.6 shows data for a Berea sandstone experiment with pore pressure oscillations, before and after fracture (just prior to 4 hr), and after a series of shear displacement increments. Permeability reduction is observed with fracture as well as with increasing shear displacement. Westerly granite samples show a similar general behavior as a function of loading and shear. We did not measure permeability of intact Westerly granite due to the length of our samples and the time necessary to establish steady state flow. Previous works shows that permeability of Westerly granite increases by 2-4 orders of magnitude upon fracture (Brace et al., 1968; Hazzard and Young, 2000; Summers et al., 1978).

Fracturing of sandstone samples was always associated with a decrease in permeability (Figures 1.5 and 1.6). The drop in permeability was typically 1-2 x 10^{-14} m^2, which represents a reduction of about 50-60% compared to the matrix permeability. Figure 1.5b furthers highlights the loading and fracturing processes. During shear loading, permeability reduction began with the onset of shear-induced dilation at about 40% of the fracture stress (Figure 1.5b). This is consistent with previous work where permeability reduction has been associated with cataclasis.
and microcrack closure in porous rocks (Candela et al, 2014; Elkhoury et al, 2011; Scuderi et al., 2015; Zhu and Wong, 1997). We find that fracture formation is associated with a sudden drop in shear stress and compaction normal to the fracture plane. With additional shear, the sample typically continued to compact. The final thickness measured perpendicular to the fracture plane (Figure 1.1) was smaller than the initial by ~10-20 μm, consistent with grain crushing and pore collapse during fracture.

Permeability of fractured Berea samples continued to decrease with shear displacement (Figures 1.5-1.7). These data are consistent with a combination of shear induced compaction and gouge generation during shear. Figure 1.7 shows permeability data as a function of the log of shear displacement for several Berea samples. In each experiment, permeability was measured immediately before fracture (intact), after fracture (fractured), and then after measured shear displacements ranging from 100 μm to 10 mm. Small increases in permeability, possibly associated with breakage of asperities along the flow path, were occasionally observed during shear sliding (Figures 1.5 and 1.6).

Westerly granite samples show a complex evolution of permeability as a function of fracture and shear, as expected for low porosity rock (Brace et al., 1968; Summers et al., 1978; Zhu and Wong, 1997). We find a trend of decreasing permeability with fault shear displacement (Figure 1.8), which is similar to that for sandstones. We collect the data on permeability as a function of shear displacement and dynamic stressing for one experiment in Figure 1.8. Data for each dynamic stressing sequence is aligned at zero time and shown as a function of time, following the procedure outlined in Figure 1.4. The full experiment is shown in Figure 1.9b and here we focus on the evolution of permeability as a function of time and dynamic stressing following a sequence of slip increments (Figure 1.8). The fracture and slip history follows that for Berea samples as shown in Figure 1.6. For granite, we find that permeability increases after each
slip increment (compare the end of the ‘Fracture’ data with the start of the trace labeled 0.1 mm). Permeability increases from $\sim 5 \times 10^{-16} \text{ m}^2$ to $6.5 \times 10^{-16} \text{ m}^2$ for the 0.1 mm shear interval imposed after fracture, and then it decreases continuously as a function of time and flow (Figure 1.8). The overall reduction in permeability is interrupted by dynamic stressing associated with pore pressure oscillations (Figure 1.8). The same trends are seen for each slip interval, with varying magnitudes of permeability change (Figure 1.8). After a net slip of 11.1 mm, we find that an additional 10 mm of slip does not change permeability (compare the purple with the green curve in Figure 1.8).

The impact of shear slip on fault permeability in granite is significantly different than that for mode II faulting in sandstone. For granite, shear sliding induces transient and in some cases large increases in permeability (up to $1 \times 10^{-15} \text{ m}^2$ in Figure 1.9b) that are significantly greater than any permeability increase observed in the porous Berea sandstone samples (Figure 1.9). The increases in fault permeability for granite are associated with stress drops, which are in many cases associated with audible acoustic emissions, indicating breakage of surface asperities in the flow path. This same trend is not apparent in faults formed in Berea sandstone. These preliminary data show that permeability evolution with fault shear in low porosity rock is more variable and sensitive to asperity breakages than porous rock (Figure 1.9).

1.4.2 Transient Permeability Change via Dynamic Stressing:

Dynamic stressing imposed by pore pressure oscillations produces transient and in some cases long-lasting changes in the permeability of laboratory fault zones. The magnitude of permeability change scales with the amplitude of the imposed pore pressure oscillations (Figure 1.10a).
For faults in Berea sandstone, we also evaluated the affect of applied fault normal stress on permeability to investigate the principle of effective stress and isolate the role of fluid pressure vs. applied stress (Figure 1.11). Comparing the results of Figures 1.10 and 1.11, and in particular Figure 1.11a and 1.11b shows that for the same range of effective normal stress oscillations (a few hundred kPa) pore pressure oscillations have a direct impact on fault permeability whereas applied normal stress oscillations do not (Figures 1.10 and 1.11). For fluid pressure oscillations, we show both the permeability, derived during steady state flow, and the flow rates measured at the inlet and outlet (Figure 1.10). For a sequence of increasing amplitude oscillations, fault permeability shows a transient increase after each set (Figure 1.10a). On the other hand, for a set of oscillations of equal amplitude, only the first set produces an increase in fault permeability (Figure 1.10b).

Taken together, these data show that fault permeability is most sensitive to dynamic stressing when it produces a change in fluid flow rate, and that the effect is ephemeral such that only the first set of flow rate oscillations produce a measureable change in fault permeability (Figures 1.10 and 1.11).

1.4.3 Sensitivity to Transient Permeability Change with Shear Displacement:

For sandstone, fault permeability evolves with shear displacement and dynamic stressing associated with pore pressure oscillations. Figure 1.12 presents a summary of results for a suite of tests to evaluate transient changes in permeability as a function of stressing amplitude and fault slip. The susceptibility of fault permeability to dynamic stressing appears to decrease with shear displacement (Figure 1.12). The variation is larger for the pre-slip permeability changes, but comparing the impact of a 0.2 MPa amplitude oscillation we find that the fractures subject to
shear sliding of 10 mm have a mean permeability change of 0.03 compared to ~0.1 for unsheared fracture (Figure 1.12b). Here, we compare data for a broad suite of samples, by normalizing the changes in permeability by the magnitude of permeability prior to dynamic stressing (Figure 1.12). At all stages of shear displacement there is a direct correlation between the amplitude of the oscillation and the normalized permeability change; however, the permeability changes appeared to be lesser after shear sliding than right after the sample had been fractured in Berea sandstone.

1.5 Discussion:

1.5.1 Discussion of Permeability Evolution with Shear Displacement:

Berea sandstone shows consistent permeability reduction with shear displacement along fractures created in situ. In all Berea sandstone experiments permeability is highest in the intact rock and lowest after the greatest shear displacement (Figure 1.7). Our observations are consistent with pore fouling associated with clogging of flow paths by fines and fault breccia (Candela et al., 2014, 2015; Roberts and Abdel-Fattah, 2009). Our measurements of the matrix permeability of Berea sandstone (intact samples) are consistent with previous work and expectations (Cleveland Quarries quotes 50-100 millidarcy i.e., 5 to 10×10^-14 m²). We generated shear faults under in-situ loads, which produces gouge and fine particles that block previously connected pore throats. With additional shear sliding, more fines are generated as wear products, which inhibit flow paths. These observations imply that shear offset, or fracture, would result in a reduction of permeability in a porous reservoir.

Our data for faults in Westerly granite suggest that reservoir permeability will increase as
fractures form and create networks, but that shear offset of existing fractures may result in a decrease in permeability. The mechanism of fouling, responsible for permeability reduction with shear of faults in porous sandstone, also seems to apply in tight granites; however, it appears to be less effective than in Berea sandstone. Because flow in porous Berea sandstone occurs within both the fault zone and the rock matrix, permeability measurements are less sensitive to fault roughness and fault gouge than in Westerly granite. We report preliminary evidence for this in Figure 1.9, where changes in the ratio of shear stress to normal stress and permeability are plotted as a function of shear displacement. As the normal stress is held constant during shear displacement, any changes in the ratio result from changes in shear stress. Given that the fault plane is known, we can interpret the drops in shear stress (Figure 1.9) as the result of the breakage of asperities. Aside from the initial fault formation, the largest changes in permeability are not correlated with changes in shear stress in Berea (Figure 1.9a). However, in Westerly (Figure 1.9b) the largest increases in permeability are directly related to changes in shear stress. While the results of dynamic stressing indicate that the flow rate controls permeability changes in both Berea sandstone and Westerly granite, the frictional sliding data suggest that surface roughness plays a larger role in controlling the permeability of fractured granite. Our data suggest a shift in the primary controlling mechanism of permeability evolution with shear displacement across rock types of varying intrinsic permeability; however, more data are needed to identify the intrinsic permeability transitions.

1.5.2 Discussion of Transient Permeability Change via Dynamic Stressing:

We find that the magnitude of transient changes in permeability scales with the amplitude of dynamic stress oscillations in cases where flow rate was directly pulsed via pore pressure
oscillations. These observations are consistent with prior studies (Candela et al., 2014, 2015; Elkhoury et al., 2011). However, dynamic stresses imposed by changes in applied normal stress did not create scalable or significant changes in permeability in Berea sandstone. Comparing the two means of effective normal stress oscillations confirm that flow rate controls the transient permeability enhancement, as proposed by Candela et al. (2015). This interpretation is supported by our data for Westerly granite (Figure 1.8). All experimental samples displayed a decrease in permeability during hold times between oscillations (Figure 1.8) similar to the decreases in permeability seen after shear displacement in other studies (Candela et al, 2014; Carey et al., 2016; Elkhoury et al, 2011; Frash et al., 2017; Scuderi et al., 2015; Zhu et al., 1997). The similarity of results in rock types of dramatically different intrinsic permeability suggest that volumetric flow rate could be utilized as a controlling mechanism for transient permeability increases across reservoirs of varying rock properties.

1.5.3 Discussion of Sensitivity to Transient Permeability Change with Shear Displacement:

Both the absolute value of permeability and the magnitude of transient changes in permeability, induced via dynamic stressing, decrease with shear displacement in Berea sandstone (Figure 1.12). We suggest that this result is a product of pore fouling, which increases as a function of shear and fault gouge accumulation. The process of wear at fracture surfaces creates fault gouge, which can lower permeability by blocking flow paths. Our observations show that dynamic stressing via pore fluid fluctuations in this configuration can force fine particles into pore throats and the porous rock matrix. In Berea sandstone, we find that permeability is determined by a combination of fault zone flow and matrix flow. Our results suggest that fracture permeability increases while matrix permeability decreases due to dynamic stressing. We posit
that a threshold exists with shear and fault gouge generation, where the amount of fouling from
gouge material in the rock matrix outweighs the increased fault due to dynamic stressing. This is
consistent with our data showing a decrease in normalized permeability change after shear
displacement relative to immediately after fracture (Figure 1.12). Our data suggest that faults
would be most susceptible to permeability changes via dynamic stressing just after slip events.
We propose this is due to the creation of fresh fracture faces. Gouge material generated during the
slip event would be mobile around fault zone, and in this case the flow path, as shear fabrics have
not yet fully developed. At the field scale this would make shallow faults more susceptible to
permeability changes via dynamic stressing as shear fabrics would be less fully developed (Ikari
and Saffer, 2012).
Future work will expand our suite of experiments for Westerly granite, and add additional rock
types, which will further probe this theory. As all flow during the timespan of our experiments
can be attributed to the fracture plane in Westerly granite, we will be able to eliminate the
possibility of fouling of pore throats in the intact matrix. If this theory holds true after further
testing, then a markedly different approach in the amount of shear fracturing required for optimal
reservoir stimulation would need to be taken.

1.6 Conclusion:

We study the effects of fracturing, shear sliding, and dynamic stressing on L-shaped
samples of Berea sandstone and Westerly granite using a true triaxial deformation apparatus. The
results provide insights on the relationship between fluid flow and shear failure. Our experiments
show that permeability decreases with shear displacement in rough, in situ fractures.
Additionally, we confirm that volumetric flow rate is a viable mechanism for transient increases
in permeability across reservoirs of varying rock properties. We find that normalized permeability
changes scale with the amplitude of stress perturbations in both Berea sandstone and Westerly granite. Finally, we find that transient permeability enhancement as a result of dynamic stressing diminishes with shear displacement in Berea sandstone. This lowered sensitivity, likely due to an abundance of fine particle generation, suggests a potential pitfall for permeability enhancement techniques in heavily fractured porous reservoirs. Our results provide insight to the feasibility of shear failure and dynamic perturbations as a tool to reliably manage reservoir flow paths to a desired permeability.
Figure 1.1:
Experiment configuration (after Candela et al., EPSL, 2014). (a) Schematic of the biaxial apparatus and pressure vessel. Direct Current Displacement Transducers (DCDTs) are attached to the vertical and horizontal pistons to measure displacement. Strain gauge load cells are placed in series with each piston to measure stress. (b) Photo of an L-shaped sample of Berea Sandstone. Red dotted line shows the eventual fracture plane, which is controlled by the sample geometry, loading, and plane of weakness created by notching the sample. (c) Photo of the steel blocks loading the sample in a single direct shear configuration, showing the normal and shear stresses as well as the flow inlet and outlet. (d) Photo of jacketed sample loaded into the pressure vessel with front door removed. Flow lines and loading pistons are also shown. An LVDT (Linear Variable Differential Transformers) is attached to the steel blocks nearest the sample for a precise measurement of sample thickness changes during the experiment.
Figure 1.2:
A: Pressure vessel with front door removed and sealed sample. Fluid inlet pore pressure line (1). Fluid outlet pore pressure line (2). Clamps over O-ring seal preventing confining fluid from infiltrating sample (3). Support block preventing small side of L-shape from sliding during shearing (4).

B: Sample schematic (without sealing jackets). Intact L-shape rock (5). Notches at the top and bottom of the sample (3.75-mm long) promote vertical fracture (6). Porous metal frit at fluid pressure inlet (top) and outlet (bottom) are used to prevent grains and fines from clogging the fluid lines (7). Metal guard separates latex jacket from fracture path and flow outlet (8). A second metal guard separates latex and sample fracture plane at the top of the sample (9). T-shaped metal loading block supports smaller portion of L-shape block during fracture and shear (10). Epoxy seal and thin latex layer prevents flow around sample (11). O-ring seal preventing confining oil pressure from leaking into sample (12). Pore pressure inlet (13). Loading block for larger portion of L-shape sample (14). Loading block for small portion of L-shape sample (15).
**Figure 1.3:**
Permeability Estimation. (a) Flow rate is calculated from changes in inflow and outflow volumes. (b) Permeability is calculated using Darcy’s Law when the inflow and outflow are equal to within 10% in Berea Sandstone (steady-state flow conditions).
Figure 1.4:
Pore pressure oscillations of increasing amplitude. Inlet pore pressure is oscillated while outflow pressure is held constant. Each oscillation set consists of 20 sinusoidal cycles at 1Hz (duration 20s) with amplitudes ranging from 0.05MPa to 1MPa.
Figure 1.5:
A: Berea sandstone experiment with in-situ fracture and shear sliding. Shear stress (black), permeability (blue), inlet pore pressure (red), and outlet pore pressure (cyan). We observe an overall decrease in permeability with shear failure and shear displacement. Transient increases in permeability during shear sliding are associated with asperity breaks in flow pathway.
B: Zoomed view of fracture process in Berea sandstone experiment. Shear stress (black) and permeability (blue). Permeability decrease during shear loading and shear failure. Direction of increasing normal displacement represents dilation.
Figure 1.6:
Berea sandstone experiment with pore pressure oscillations, in-situ fracture and shear sliding steps. Shear stress (black), permeability (blue), inlet pore pressure (red), and outlet pore pressure (cyan).
Figure 1.7: Permeability decrease with shear displacement in multiple Berea Sandstone experiments.
Figure 1.8:
Effect of pore pressure oscillations and shear on the permeability of a fractured Westerly Granite sample. Oscillations consist of four sets (each of them 20 cycles at 1Hz) of increasing amplitudes (0.2, 0.4, 0.7, to 1 MPa). These oscillation sets are conducted after fracture (blue), after 0.1mm shear (red), after 1mm-shear (yellow) and after 10mm-shear (purple and green). Note (i) the overall decrease in permeability with shear, (ii) the larger increase in permeability with increasing oscillation amplitude, as well as (iii) the slow permeability decreases during holds. Blank spaces correspond to oscillation times: permeability cannot be properly estimated during oscillations because flow rate is not steady state (as illustrated in figure 3).
Figure 1.9:
Permeability (blue) and ratio of shear stress to normal stress (black) evolution in Berea Sandstone (a) and Westerly Granite (b). Permeability change is largely independent of changes in shear stress after fracture in Berea while the largest permeability increases are consistently correlated with decreases in shear stress in Westerly Granite sample.
Figure 1.10:
Effect of pore pressure oscillations on permeability. (a) Four oscillation sets of increasing amplitude (0.05, 0.1, 0.2, and 0.3 MPa), showing how permeability change scales with the amplitude of pore pressure oscillations. (b) Four sets of equal amplitude (0.2MPa). In this latter case, the first set induces a significant increase in permeability, while subsequent sets have little or no effect on permeability. Bottom panels show the corresponding evolution of inlet and outlet flow rates during oscillations. Note the large changes in flow rates during oscillations.
Figure 1.11:
Permeability changes with dynamic oscillations in pore pressure (a) and normal stress (b). No significant permeability response is observed due to normal stress oscillations. Bottom panels show the corresponding evolution of inlet and outlet flow rates during oscillations. Note the large changes in flow rates during pore pressure oscillations, while no change is observed during normal stress oscillations.
Figure 1.12:
Permeability change as a function of pore pressure oscillations with varying amplitude in Berea sandstone after fracture (a) and after shear sliding (b). Each dot represents the permeability change after one set of oscillations, consisting of 20 cycles (see figure 4). Permeability change is calculated as the difference between permeability after a hold and the proceeding oscillation (see figure 8). Note the significant decrease in permeability change after shear displacement.
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<td>0.05, 0.1, 0.2, 0.3</td>
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<td>DI Water</td>
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<td>0.2, 0.4, 0.7, 1</td>
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**Table 1.1:**
Parameters of the experiments.
Chapter 2

Frequency Dependence of Dynamic Stressing on Transient Permeability Enhancement

2.1 Abstract:

Seismic waves have been shown to increase permeability in natural and experimental reservoirs, yet the physical controls remain poorly understood. We probe and constrain the current understanding of physical mechanisms behind transient permeability enhancement via well controlled dynamic stress perturbations on laboratory samples. We fracture Westerly granite in situ under true triaxial stresses on the order of tens of MPa to apply the understanding of controlling mechanisms to tight reservoir rock. The mechanism is investigated by applying dynamic perturbations through either normal stress or pore pressure oscillations. Additionally, we explore the effect of both amplitude and frequency of stressing on permeability over three orders of magnitude. By combining these investigations, we show a flow dependent transient permeability enhancement that negatively correlates with frequency and positively correlates with amplitude of the imposed oscillations. A strong flushing effect is present in the low permeability fractures, as the first oscillations create the largest permeability enhancements. We also find that sensitivity to dynamic stressing is not effected by shear displacement in Westerly granite, contrary to the more permeable and porous Berea sandstone. The results suggest that frequency
content is an important consideration for the application of dynamic stressing and flow rate pulsing to engineer reservoir permeability.

2.2. Introduction:

Dynamic stressing has been observed to increase permeability on both natural and manufactured reservoirs (Beresnev and Johnson, 1994; Brodsky et al., 2003; Candela et al., 2014; Carey et al., 2016; Elkhoury et al., 2011; Frash et al., 2017; Kouznetsov, 1998). In these cases, dynamic stresses can redistribute the fluid pressures creating a large pore pressure differential leading to the increased flow rates. At both the field and laboratory scale this process is characterized by a dynamic perturbation followed by a sharp uptick in permeability, and then a gradual, log-scale, recovery of the permeability. Mobilization of fine particles as a result of shaking has been identified as a key mechanism for permeability enhancement at the field scale (Brodsky et al., 2003; Ikari et al., 2009; Liu and Manga, 2009; Oliviera et al., 2014; Roberts, 2005) and directly observed as the primary mechanism in laboratory fractured samples of Berea sandstone (Candela et al., 2014, 2015;). In explanation of the observed results, dynamic shaking causes the movement of fine particles from pore throats critical to the flow pathway. The slow recovery of permeability can by then explained by the settling of find particles back into pore throats critical to the flow path. Previous laboratory studies were designed to observe this in the most likely scenarios. This includes in situ fractured rock samples of Berea sandstone (Candela et al., 2014, 2015;). The in situ fracturing process generates an abundance of fine particles, which could then be mobilized, and Berea sandstone allows for a highly porous rock, which is most likely to be sensitive to the dislodging fine particles from pore throats. However, no current work has demonstrated whether this mechanism applies to igneous rock like granite. Prior laboratory studies exploring igneous rock were either intact or pre-fractured, so they are unable to offer
insight as to the applicability of this mechanism (Brace et al., 1968; Zhu and Wong, 1997; Zoback and Byerlee, 1975).

To best probe the permeability enhancement as a result of dynamic stressing, we will use in situ fractured samples as done in previous studies (Candela et al., 2014; Elkhoury et al., 2011; Liu and Manga, 2009; Madara et al., 2018; Oliviera et al., 2014; Roberts and Abdel-Fattah, 2009). We will use the experimental design described in Madara et al., 2018 to allow for in situ fracture as well as continued shear displacement with a constant flow area. Shear displacement has been shown to reduce local permeability in rock types of varying properties (Fang et al., 2017; Faoro et al., 2012; Ikari et al., 2009; Im, et al., 2018; Mitchell and Faulkner, 2008; Mohanty and Hsiung, 2011, Madara et al., 2018). Recently, the sensitivity of the reservoir to dynamic stressing has been shown to decrease with substantial shear displacement in highly porous rock (Madara et al., 2018). Our experiments will take place over varying stages of shear displacement, representative of slip distances in reservoir fractures, to investigate any such sensitivity.

This paper builds on the understanding of particle mobilization as the mechanism for permeability increase as the result of dynamic stressing and probes its applicability to igneous rock in a suite of laboratory experiments under true triaxial stresses. We expand on prior work that identifies the permeability enhancements to be a flow driven process in porous rock (Brodsky et al., 2003; Candela et al., 2014; Elkhoury et al., 2011; Madara et al., 2018). Volumetric flow is tested as a key parameter to engineering transient permeability enhancements by applying a series of dynamic stresses through either pore fluid pressure or by normal stress. As in prior studies, we identify the presence of a flushing effect, a suggestions of flow driven processes, by repeating several sets of dynamic perturbations. Comprehensive testing over three orders of magnitude for both the applied amplitude and frequency of the imposed dynamic perturbations grant insight to the underlying mechanism as well as the most effective means of enhancing permeability. We
begin with an overview of the experimental set up and procedure before taking the reader through a point by point comparison of our results to the results reported in previous studies on Berea sandstone and the implications for reservoir application.

2.3 Methods:

2.3.1 Experimental Apparatus:

Experiments were conducted in a true-triaxial pressure vessel and biaxial load frame (Figure 2.1). The experimental setup follows Madara et al., 2018; a slight modification from previous studies (Candela et al., 2014, 2015; Elkhoury et al., 2011; Faoro et al., 2012; Ikari et al., 2009; Samuelson et al., 2009). True triaxial deformation is achieved via two applied loads from the pistons and independently-controlled confining pressure via oil for confining fluid. The horizontal piston provides the normal stress, as it is normal to the eventual fracture plane; the vertical piston applies the shear stress (Figure 2.2). All stresses and pressures are servo-controlled and recorded continuously throughout experiments using a multi-channel 24-bit analog-to-digital converter. Data are collected at 10-kHz and averaged to recording rates ranging from 1–1000 Hz depending on the experimental stage.

We used intact samples of Westerly granite (Camoli Granite Inc., Ashaway, RI). These were cut into L-shaped blocks measuring 68 x 45 x 50 x 20 mm, following the approaches of Elkhoury et al., (2011) and Candela et al. (2014, 2015) with modifications as noted in Figures 1 and 2. The smaller section of the L-shaped block was notched to control the fracture plane orientation and increase reproducibility across our suite of experiments (Table 2.1).

The samples were then fitted into the L-shape loading blocks and jacketed with a latex
membrane. This process included many components and steps to ensure reproducibility between experiments (Figure 2.2). Following Madara et al., 2018, a thin, flexible latex membrane was epoxied to the exposed front and back of the sample prior to jacketing. This eliminated the potential for fluid flow around the sides of the sample (Figure 2.2b). Metal shims were used at the top and bottom of the eventual fracture plane to ensure that the jacket did not intrude into the fracture. We used porous metal frits between the sample and the loading block at both the top and bottom of the eventual fracture plane to produce a line source of fluid, maintained at constant pore pressure via servo control (Figure 2.2). An in-house clamp design was used to seal the latex jackets against O-rings in the loading blocks (Figure 2.2). A support block underneath the static, smaller side of the L-shaped sample (Figure 2.2) was used to prevent tilting of the sample during shear loading and fracture. This significantly increased the reproducibility of fracture plane orientation. This support block is T-shaped (Figure 2.2b) with a cylindrical shaft that passes through the jacket to provide direct contact with the base of the loading platen (item 15 in Figure 2.2b). The jacket is sealed against the T-support shaft using steel lacing wire. Pore pressure lines were flushed with DI water prior to each experiment and at the start of each experiment to eliminate air from the system before saturating the sample.

2.3.2 Experiment Procedure:

Samples were placed into the pressure vessel, accessed via removable high pressure doors, before sealing the vessel and applying a nominal normal stress and confining pressure of 5 MPa. A flow gradient was then established by independently controlling pore pressure intensifiers (Figure 2.1d). We used a pore pressure gradient of 2 MPa in Westerly granite samples, with 4 MPa and 2 MPa for the inlet and outlet respectively. This large a pressure
gradient was required to ensure the fluid flow rate never dropped below our detection threshold. To that end, we monitor the volumetric flow rate $Q$ in and out of the sample continuously (Figure 2.3) and report permeability values only for steady-state flow conditions, indicated by $Q_{in} = Q_{out}$ to ±3%. We calculate effective permeability $k$, based on Darcy’s law (Figure 2.3a);

$$k = \frac{\mu L Q}{S \Delta P}$$

where $\mu$ is the fluid viscosity ($8.9 \times 10^4$ Pa s for DI water at $T=25^\circ$ C), $L$ is flow path (50 mm), $S$ is the cross sectional area of the sample perpendicular to the flow direction (45×29 mm), $Q$ is flow rate, and $\Delta P$ is the pore pressure differential (Figure 2.1; Table 2.1). The flow rate is calculated using the displacement rates of the inlet and outlet pore pressure intensifier pistons over sample window appropriate for the conditions (typically 1-2 seconds). The unique L-shape of the sample allows for a constant flow path length and width as the sample is sheared.

2.3.3 Dynamic Stressing:

We studied the effect of oscillations in effective normal stress on shear strength and fracture permeability. Effective normal stress oscillations were imposed as a proxy for dynamic shaking that would occur from the passing of seismic waves; the resulting effect on reservoir permeability and poromechanical properties were observed. We applied several types of sinusoidal oscillations. Amplitude oscillations were performed with a constant frequency of 1 Hz and amplitudes that ranged from 20 kPa to 1 MPa (Table 2.1). Frequency oscillations were performed with a constant amplitude of 1 MPa at frequencies of 0.1, 1, and 10 Hz. Oscillations varying in frequency maintained the same number of oscillations cycles at each frequency, 20. In some cases tests were performed for constant duration of 30s at each frequency as well (Figure 2.4).
We performed effective normal stress oscillations by changing either the applied normal stress or pore pressure. For pore pressure perturbations, we oscillated the inlet pore pressure while maintaining a constant outlet pressure and applied normal load (Figure 2.4), following previous work (Candela et al., 2014; Elkhoury et al., 2011). We focus on permeability measurements taken 10 s before and 10 s after the imposed oscillations to ensure that the measurements are not contaminated by fluid storativity or other transient poro-elastic effects. For applied normal stress perturbations, we oscillated the stress perpendicular to the fracture, using the same range of frequency and amplitude (Table 2.1), while maintaining a constant differential fluid pressure between the inlet and outlet.

2.3.4 Shear Failure and Sliding:

Shear loading was applied to intact samples by advancing the vertical piston, in contact with the top of the L-shaped block, at a servo-controlled displacement rate of 11 µm/s. The notch at the top and bottom of the eventual fracture plane, as well as the sample geometry, guided the fracture plane and helped ensure reproducibility in the gross fracture geometry. Once the sample was broken (Figure 2.5), shear sliding was imposed in steps of controlled displacement. The physical parameters of the experiment allowed for shear displacement of approximately 15 mm after fracture.

We measured stresses, shear and normal displacement across the fracture, and fluid flow volumes continuously throughout each experiment. We also used a small, high-resolution LVDT within the pressure vessel to measure displacement normal to the fracture plane (Figure 2.1). The internal LVDT grants us precision within 0.025 microns and sits on either side of the sample; so our dilation and compaction data throughout the experiment are not subjected to any potential
strain effects of the support blocks in our set up. Perturbations in effective normal stress oscillations were performed at various times throughout each experiment: after fracture, after 5 mm of shear, and after 10 mm of shear displacement (Figure 2.6). After fracture and each shear displacement step, the vertical piston was stopped and held in place during stress oscillations and permeability measurements. Our typical sequence for pore pressure oscillations is shown in Figure 2.4; 1 Hz oscillations were imposed for 20 s after which we waited for 40 s before repeating the oscillations at a different amplitude. The time between perturbations was the same when frequency oscillations were imposed (Figure 2.4).

2.4 Results

2.4.1 Shear Fracture and Sliding:

The results from one typical, complete experiment (p4975) in figure 2.5. Although a pressure gradient is established before the onset of shear loading, no permeability is recorded. This is due to the long time scales that would be required to establish flow for intact Westerly granite. The lack of recorded permeability demonstrated the successful jacketing of the sample, as well as guaranteeing that no flow goes around the eventual fracture plane. Flow is first recorded after the shear loading and failure of the sample which typically occurs from 50 – 60 MPa. The in situ fractures generate permeabilities ranging from $10^{15}$ to $10^{16}$ m$^2$.

2.4.2 Dynamic Stressing and Permeability:

Dynamic stressing is imposed after fracture and at various stages of additional shear displacement. The results of the amplitude oscillations from pore pressure are shown in figure
2.3. Permeability data is shown for the time before and after oscillations; the oscillations themselves are removed as permeability was not calculated when inflow and outflow have greater than a 3% difference. In p4572, 4 amplitudes were tested, 0.2, 0.4, 0.7, and 1 MPa at the following shear displacement stages: post fracture, 0.1 mm, 1 mm, 10 mm, 10 mm. Permeability decrease at each stage of shear displacement is evident through the first section of data, near time 50 s. Most importantly, the permeability increase is greater with each larger amplitude oscillation set. Very little permeability change is observed at 0.2 MPa while the largest change occurs with 1 MPa oscillations. All Westerly granite experiments showed a positive correlation between amplitude of oscillation and transient permeability increase.

Results from a set of frequency oscillations are shown in Figure 2.6. Here we report the percent change in permeability after the oscillation relative to the permeability value averaged over a 1-2 second time window before the oscillation. The most obvious, and important, result is that the lowest frequency, 0.1 Hz, shows an order of magnitude greater increase in permeability than either the 1 Hz or 10 Hz oscillations. While figure 2.6 shows data from 1 experiment for clarity, this result was consistent across every Westerly granite experiment at each stage of shear displacement. While significantly lower, the 1 Hz oscillations also generate consistently positive changes in permeability. Finally, the 10 Hz oscillations do not generate any consistent transient permeability changes when stressing is imposed for the same number of cycles as 1 Hz and 0.1 Hz. At every frequency normal stress oscillations are less effective than pore pressure (Figures 2.6 and 7). This is readily explained by the lower impact on fluid flow (Figure 2.4b). However, even with the dampened effect we observe that lower frequency oscillations in normal stress create larger permeability enhancements than those at higher frequency (Figure 2.6). We can then state that there exists a consistent negative correlation between oscillation frequency and transient permeability enhancement as a result of dynamic stressing.
Looking closer at figure 2.6 we note that the largest percentage change in permeability occurs after the 1\textsuperscript{st} oscillation at all frequencies. If we average the transient permeability changes across every experiment by oscillation order, we find that the 1\textsuperscript{st} oscillation consistently creates the largest permeability change (Figure 2.7). Furthermore, the 2\textsuperscript{nd} oscillation creates the 2\textsuperscript{nd} largest permeability change in most cases. This result shows a strong flushing effect is present in Westerly granite; an indication of the fluid driven permeability enhancement mechanism.

We further probe the mechanism and verify our procedure by comparing the transient permeability enhancement observed with those predicted by a parallel plate model (Figure 2.8). By using the internal LVDT we can directly measure changes in sample thickness within 0.025 microns. Because of the location of the LVDT, on either side of the sample, we can relate these changes to the fracture aperture. Changes in fracture aperture are then related to predicted changes in permeability via the parallel plate approximation (Candela et al., 2015; Ouyang and Elsworth, 1993; Silliman, 1989; Snow, 1969; Witherspoon et al., 1980).

\[ \Delta b = \left( \frac{k_1}{k_0} \right)^{1/3} - 1 \right]^{3/k_0} \cdot \frac{w}{12} \]

Where \( \Delta b \) is the change in aperture, \( k_0 \) is the permeability prior to oscillation, \( k_1 \) is the permeability after oscillation, and \( w \) is the width of the fracture. We improve our comparison by approximating as a time series, rather than individual points. Once this is done, the clear result is changes in permeability observed are much greater than what would be predicted by the changes in aperture created during the 0.1 and 1 Hz oscillations (Figure 2.8). The dynamic shaking induces compaction of the sample and yet permeability is shown to increase; while the permeability recorded is increases, the predicted permeability is decreasing in response to the closing aperture (Figure 2.8). This highlights the effect of mobilizing fine particles by dynamic shaking. By comparing the 0.1 Hz and 1 Hz pore pressure oscillations side by side we can plainly see the degree to which the lower frequency is more effective. Additionally, we use a parallel
plate model to verify our methods. Permeability measurements are recorded 10s before and after each oscillation to avoid specific storage effects, but the parallel plate model shows that even the storage effects observed during the oscillations by the internal LVDT are small.

### 2.4.3 Shear Displacement and Sensitivity to Dynamic Stressing:

Finally, we perform oscillation sets at various stages of shear displacement in order to determine if the sensitivity to dynamic shaking is affected as in other rock types (Madara et al., 2018). For comparison, we average all Westerly granite experiments by the normalized permeability change, \( (k_1 - k_0 / k_0) \) by oscillation order at 3 stages of shear displacement: after fracture, after 5 mm shear, and after 10 mm shear (Figure 2.9). At every stage of shear displacement pore pressure oscillations generated greater increases in permeability than normal stress oscillations. However, there was no consistent effect on sensitivity to dynamic shaking with shear displacement. As permeability decreased significantly with shear displacement we can also state that base permeability had no effect on the sensitivity of the sample to dynamic stressing.

### 2.5 Discussion:

#### 2.5.1 Discussion of Shear Fracture and Sliding:

Westerly granite shows an increase in permeability after fracturing. Intact measurements from previous studies report permeabilities ranging from \( 10^{-18} \) to \( 10^{-19} \) m\(^2\); given our post fracture permeability measurements, this yields a permeability increase of 2-4 orders of magnitude (Brace et al., 1968; Hazzard and Young, 2000; Selvadurai et al., 2005; Summers et al., 1978). After creating a highly permeable flow path from in situ fracture, we observe permeability to decrease
significantly with shear displacement (Figure 2.5). Reduction of local permeability as a result of shear displacement has been well documented (Fang et al., 2017; Faoro et al., 2012; Ikari et al., 2009; Im, et al., 2018; Madara et al., 2018; Mitchell and Faulkner, 2008; Mohanty and Hsiung, 2011). Several explanations have been previously reported. Studies looking at porous, highly permeable rock found that fine particle and fault breccia generation from shearing clogging flow paths was the primary mechanism of permeability decline (Candela et al., 2014, 2015; Roberts and Abdel-Fattah, 2009). Additional gouge generated with continued shear which could explain the continued decrease in permeability with further shear displacement observed. We note that the permeability of Westerly granite shows a close relation to shear stress (Figure 2.5), unlike what has been observed in Berea sandstone (Madara et al., 2018). As flow is only possible through the fracture during the timescale of our experiments in Westerly granite, the breakage of asperities will directly affect potential flow paths. In Berea sandstone this is not the case; flow could be occurring in any combination of the fracture plane and matrix depending on where fine particles have accumulated to block pore throats or fluid pathways. Our results suggest that fracture roughness likely plays a larger role for tighter rock in permeability reduction with shear displacement. After fracture, the samples show a peak to trough roughness reaching the millimeter scale. As the fractured Westerly granite samples are sheared we observe smaller drops in shear stress associated with asperity breakages. This would reduce fracture aperture that was previously dominating flow and, with further shear displacement, the fracture face would become smoother and transmit continuously decreasing amount of fluid.

2.5.2 Discussion of Dynamic Stressing and Permeability:

Our dynamic stressing experiments show a direct relation between the amplitude of the imposed oscillation and the resulting transient permeability enhancement (Figure 2.3). For a pore pressure oscillation, a higher amplitude directly corresponds to a higher peak flow value from
Darcy’s law. Higher peak flow has been shown to be more effective at clearing fine particles from fractures (Candela et al., 2014). Further evidence for a fluid driven flushing of fine particles is provided by an investigation of transient permeability change as a function of oscillation number. Each time dynamic oscillations are imposed, they are performed in sets with 40-60s in between. We find that the largest permeability change occurs from the 1st oscillation and then lessens with each successive oscillation (Figure 2.7). Fluid driven permeability enhancements would also explain why normal stress oscillations consistently show a lesser effect on permeability than the corresponding pore pressure oscillations of the same amplitude (Figures 2.6 and 2.9). While pore pressure oscillations directly affect flow, normal stress oscillations directly affect fracture aperture. The dilation or compaction of fracture aperture greatly affects permeability (Faoro et al, 2012; Ikari et al., 2009; Samuelson et al., 2009; Witherspoon et al., 1980; Zimmerman and Bodvarsson, 1996). Using the parallel plate assumption, we can separate the permeability responses from dynamic stressing and changes in fracture aperture. By doing so, we can clearly demonstrate that the permeability response from dynamic stressing is significantly greater than the predicted result from changes in fracture aperture (Figure 2.8). This allows us to state with confidence that the transient permeability enhancement is driven by fluid flow.

Frequency of dynamic stressing shows a negative correlation with transient permeability enhancement. As stated above, pore pressure oscillations have a much greater effect on permeability than normal stress oscillations. Low frequency, 0.1 Hz, pore pressure oscillations demonstrate an order of magnitude greater percent increase in transient permeability than higher frequency, 1 Hz and 10 Hz, (Figure 2.6). We propose that this dramatic difference in effectiveness can be explained by attenuation at higher frequencies. At low frequencies the fluid pulse can travel from the fluid inlet to outlet without losing much energy to attenuation; conversely, the higher attenuation at 1 Hz and 10 Hz greatly reduces the energy of the pulse felt at the fluid outlet (Figure 2.4b). This offers a clear explanation for the non-linear decrease in
transient permeability changes seen from low to high frequency oscillations. We show that oscillations at the fluid flow inlet at low frequency create the largest flow response at the pore pressure outlet (Figure 2.4b). This result is critical to the understanding of dynamic stressing causing permeability enhancement as a flow driven model. It also explains why our normal stress oscillations are always less effective at every frequency, as normal stress oscillations do not create nearly the same fluid flow response (Figure 2.4b). We acknowledge that a negative correlation between oscillation frequency and transient permeability enhancement runs counter to what has been recently observed in porous media (Candela et al., 2014; 2015). In both cases, ours and the previous studies, attenuation of the fluid pulse works as a satisfactory explanation of observed phenomena. Candela et al., 2015 explains, as we have above, that the fluid pulse travels through a combination of both the fracture plane as well as the highly permeable matrix in Berea sandstone. In this respect, our system is far more simple as flow is confined to the fracture plane in the highly impermeable Westerly granite.

2.5.3 Discussion of Shear Displacement and Sensitivity to Dynamic Stressing:

Recently, the sensitivity of a laboratory reservoir to dynamic stressing has been show to decrease with shear displacement (Madara et al., 2018). Following previous work, we ran oscillations of varying frequency and amplitude at sever shear displacement steps during the course of the experiment. However, when transient permeability changes produced from dynamic stressing are normalized and averaged across all experiments, we find no consistent trend in sensitivity (Figure 2.9). Again, this result runs counter to what was observed in the more porous Berea sandstone. As the permeability measurement in Berea is highly dependent on the matrix permeability, the abundance of fine particles generated from shear would make potential flow paths more tortuous and the clearing effect due to dynamic shaking would push more fines away
from the flow path and into the rock matrix that is already fouled to a degree from the previous shear displacement and oscillation sets. It then follows that bulk permeability and sensitivity to dynamic stressing would lower as less dead ends become available for fines. With flow confined to the fracture plane in Westerly granite, any fines generated could only be cleared away from flow paths to other portions of the fracture plane. As no change in sensitivity due to dynamic stressing is present, our results suggest that flow in Westerly granite is dominated by channel flow. Were it laminar flow, the sensitivity should decrease as more fines are generated with each shear displacement step. So long as the dominant flow path remains clear, fine particles can be flushed to other parts of the fracture plane with similar effects on permeability at each shear displacement step.

2.6 Conclusion:

Our experiments show that a flow driven model of permeability enhancement is applicable to igneous rock. Importantly, we find a negative correlation between frequency of imposed oscillations and transient permeability enhancement, and a positive correlation between amplitude and transient permeability enhancement. When taken with comparison to previous studies in rock of high intrinsic permeability, our investigation highlights the necessity of understanding the reservoir’s poroelastic properties, as dynamic shaking can result in different, and in this case opposite, effects on reservoir permeability. This study has direct application for the engineering of reservoir permeability in enhanced geothermal systems as well as tight reservoirs in petroleum geosystems.
Figure 2.1:
Experiment configuration (after Candela et al., EPSL, 2014). (a) Schematic of the biaxial apparatus and pressure vessel. Direct Current Displacement Transducers (DCDTs) are attached to the vertical and horizontal pistons to measure displacement. Strain gauge load cells are placed in series with each piston to measure stress. (b) Photo of an L-shaped sample of Berea Sandstone. Red dotted line shows the eventual fracture plane, which is controlled by the sample geometry, loading, and plane of weakness created by notching the sample. (c) Photo of the steel blocks loading the sample in a single direct shear configuration, showing the normal and shear stresses as well as the flow inlet and outlet. (d) Photo of jacketed sample loaded into the pressure vessel with front door removed. Flow lines and loading pistons are also shown. An LVDT (Linear Variable Differential Transformers) is attached to the steel blocks nearest the sample for a precise measurement of sample thickness changes during the experiment.
Figure 2.2:
(a) Pressure vessel with front door removed and sealed sample. Fluid inlet pore pressure line (1). Fluid outlet pore pressure line (2). Clamps over O-ring seal preventing confining fluid from infiltrating sample (3). Support block preventing small side of L-shape from sliding during shearing (4).

(b) Sample schematic (without sealing jackets). Intact L-shape rock (5). Notches at the top and bottom of the sample (3.75-mm long) promote vertical fracture (6). Porous metal frit at fluid pressure inlet (top) and outlet (bottom) are used to prevent grains and fines from clogging the fluid lines (7). Metal guard separates latex jacket from fracture path and flow outlet (8). A second metal guard separates latex and sample fracture plane at the top of the sample (9). T-shaped metal loading block supports smaller portion of L-shape block during fracture and shear (10). Epoxy seal and thin latex layer prevents flow around sample (11). O-ring seal preventing confining oil pressure from leaking into sample (12). Pore pressure inlet (13). Loading block for larger portion of L-shape sample (14). Loading block for small portion of L-shape sample (15).
Figure 2.3:
Adapted from Madara et al., 2018. A) Effect of pore pressure oscillations and shear on the permeability of a fractured Westerly Granite sample. Oscillations consist of four sets (each of them 20 cycles at 1 Hz) of increasing amplitudes (0.2, 0.4, 0.7, to 1 MPa). These oscillation sets are conducted after fracture (blue), after 0.1 mm shear (red), after 1 mm shear (yellow) and after 10 mm shear (purple and green). Note (i) the overall decrease in permeability with shear, (ii) the larger increase in permeability with increasing oscillation amplitude, as well as (iii) the slow permeability decreases during holds. B) Permeability estimation. Flow rate is calculated from changes in inflow and outflow volumes shown above. Permeability is calculated using Darcy’s Law when the inflow and outflow in steady state conditions, defined as inlet and outlet volumes within 3%. Note that permeability is not calculated during pore pressure oscillations (blank spaces in 3a) as the inlet flow varies above the 3% threshold.
Figure 2.4:
A) Pore pressure oscillations of varying frequency with constant duration. Inlet pore pressure is oscillated while outflow pressure is held constant. Each oscillation set is 30s in duration ranging with an amplitude of 1 MPa. Note that these constant duration oscillations are different than the amplitude oscillations described in Figure 3 which have the same number of cycles with a 20s duration. Typical frequency oscillations contain 4 sets of the same frequency; constant duration test above shows changing frequency every set. B) Corresponding inflow and outflow data for constant duration tests for normal stress oscillations (left) and pore pressure oscillations (right). Not the outflow response is greatest for pore pressure oscillations and oscillations of lower frequency.
Figure 2.5:
Westerly granite experiment with in-situ fracture and shear sliding showing shear stress (black) and permeability (blue). We observe an overall decrease in permeability with shear displacement. Transient increases in permeability during shear sliding are consistently associated with asperity breaks in flow pathway, shown by drops in shear stress.
Figure 2.6: Percent change in permeability after each set of dynamic stressing. Each series of imposed dynamic stresses includes 4 oscillation sets. Permeability change is calculated \( \% \Delta k = \frac{k_1 - k_0}{k_0} \times 100 \) Where \( k_1 \) is the permeability after dynamic stressing averaged over 50 points and \( k_0 \) is the permeability before averaged over 50 points.
Figure 2.7:
Showing the average permeability change by oscillation order across all Westerly granite experiments as a percent of the first oscillation as permeability change consistently greatest from the 1st oscillation.
Figure 2.8:
Parallel plate approximation as time series. Comparing the observed permeability change as a result of dynamic oscillations with the predicted permeability as a result of the parallel plate model (black), which uses normal displacement as the input variable. Note that the parallel plate model predicts permeability should decrease while the observed permeability increases after each oscillation. Additionally, the frequency effect can be seen as permeability increases significantly more for pore pressure oscillations at 0.1 Hz (left) than pore pressure oscillations at 1 Hz (right).
Figure 2.9:
Showing normalized permeability change averaged across all experiments by oscillation number as a function of shear displacement. Normalized permeability change is calculated as: $\Delta k = \frac{k_1 - k_0}{k_0}$ where $k_1$ is the permeability after dynamic stress averaged over a 50 point window, and $k_0$ is the permeability before dynamic stressing averaged over a 50 point window. As in previous figures, pore pressure oscillations are shown to be significantly more effective than normal stress oscillations at every stage of shear displacement. No significant change in sensitivity, effectiveness of oscillations, occurs with shear displacement.
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<th>Pρ (MPa)</th>
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Table 2.1:
Experimental parameters.
Chapter 3

Frictional Permeability Relationships Varying Roughness and Rock Type

3.1 Abstract:

Permeability and frictional evolution throughout the seismic cycle are key components of fault and fracture stability for tectonic plates as well as stimulation of fractured reservoirs. Reports of permeability and friction independently throughout the seismic cycle are plentiful; however, investigations combining fluid flow and frictional data spanning the seismic cycle are sparse, so the controlling mechanisms remain poorly understood. We report on a series of laboratory experiments including saw cut as well as in situ fractured Westerly granite and Green River shale samples. Samples are run under true triaxial stresses on the order of tens of MPa and are subjected to slide-hold-slide (SHS) shearing tests with hold times ranging 3 order of magnitude as well as shear velocity stepping tests. By comparing saw cut and in situ fractured samples of the same rock type we find that in situ fractures show significantly higher stiffness and lower frictional healing than their saw cut counterparts. Changing mineralogy highlights differences in frictional permeability responses in SHS and velocity step tests. During SHS tests we observe unique behavior in saw cut Green River shale where permeability reproducibly decreases with the onset of shear and recovers during interseismic hold time. We propose a mechanism combining fracture stiffness and roughness to explain these results.
3.2 Introduction:

Large scale fluid pressure changes as a result of static and dynamic stressing have been shown to destabilize faults and fracture planes in natural systems and manufactured reservoirs (Beresnev and Johnson, 1994; Brace et al., 1968; Brodsky et al., 2003; Carey et al., 2016; Elkhoury et al., 2011; Faoro et al., 2012; Faulkner, et al., 2011; Frash et al., 2017; Kouznetsov, 1998; Zoback and Byerlee, 1975). The fluid response is dependent a combination of physical and chemical processes within the fault and fracture zone. Mineralogy and roughness are two key parameters that can control fluid response through pressure solution (Chen and Spiers, 2016; Yasuahara et al, 2006;), shear dilation (Faoro et al, 2012; Ishibashi et al., 2016; Witherspoon et al., 1980; Zimmerman and Bodvarsson, 1996), or shear fabric development (Bos and Spiers, 2000; Ikari et al., 2009). Understanding the effects of mineralogy and roughness are important to predicting fluid response as a function of static of dynamic stresses.

Varying mineralogy yields drastically different frictional responses to laboratory slide-hold-slide tests meant to simulate the seismic cycle (Summers et al., 1978; Carpenter et al., 2016; Karner and Marone, 1998; Marone, 1998; Saffer and Marone, 2003). Our study seeks to tie these differing frictional responses to their corresponding fluid responses. In addition to differences in fault healing, the use of Westerly granite and Green River shale offers reservoir analogs of differing matrix permeability and stiffness.

Roughness plays a large role in dictating the fluid response to shear. With large initial roughness, a fracture may self prop with the onset of shear, enhancing permeability (Ishibashi et al., 2016). However, low initial roughness may create a decrease in local permeability with shear initiation (Fang et al., 2017; Faoro et al., 2012; Ikari et al., 2009; Im, et al., 2018; Mitchell and Faulkner, 2008; Mohanty and Hsiung, 2011). Changes in fracture permeability are highly dependent gouge generation with shear displacement and the destruction of asperities. For this
reason, varying the stiffness and roughness will be used in our study. Fracturing samples in situ under true triaxial stresses will produce rough, natural fractures, while the use of saw cut, uniformly roughened, samples will produce smoother surface of reproducible roughness.

This paper explores permeability and friction relationships with a particular focus on the reinitiation of shear. We expand on previous studies to further understand the role of roughness by use of in situ fractures in addition to the well studied saw cut, smooth fractures (Brace et al., 1968; Fang et al., 2017; Ikari et al., 2009; Im et al., 2018; Ishibashi et al., 2016; Mohanty and Hsiung, 2011; Tanikawa et al., 2010). Differing mineralogy of Westerly granite and Green River shale broadens our investigation to include a range in stiffness and corresponding frictional responses. Friction and permeability relationships will be probed by means of typical laboratory slide-hold-slide tests and well controlled up steps and down steps in shear velocity under true triaxial stresses. This study improves the understanding of mechanisms critical to the usage of static and dynamic stressing for reservoir stimulation techniques well as modeling seal capacity.

3.3 Methods:

3.3.1 Experimental Apparatus:

Experiments were conducted in a true-triaxial pressure vessel and biaxial load frame (Figure 3.1). The experimental setup follows Madara et al., 2018; a slight modification from previous studies (Candela et al., 2014, 2015; Elkhoury et al., 2011; Faoro et al., 2012; Ikari et al., 2009; Samuelson et al., 2009). True triaxial deformation is achieved via two applied loads from the pistons and independently-controlled confining pressure via oil for confining fluid. The horizontal piston provides the normal stress, as it is normal to the eventual fracture plane; the
vertical piston applies the shear stress (Figure 3.2). All stresses and pressures are servo-controlled and recorded continuously throughout experiments using a multi-channel 24-bit analog-to-digital converter. Data are collected at 10-kHz and averaged to recording rates ranging from 1–1000 Hz depending on the experimental stage.

We used intact samples of Westerly granite (Camoli Granite Inc., Ashaway, RI) and Green River shale (Grand Junction, Colorado). These were cut into L-shaped blocks measuring 68 x 45 x 50 x 20 mm, following the approaches of Elkhoury et al., (2011) and Candela et al. (2014, 2015) with modifications as noted in Figures 3.1 and 3.2. The smaller section of the L-shaped block was notched to control the fracture plane orientation and increase reproducibility across our suite of experiments (Table 3.1). For the saw cut samples, the L-shaped blocks were cut down the notch and each side was flattened and smoothed with a surface grinder with micron precision. Samples were cut or notched such that the eventual fracture plane was along bedding planes in Green River shale. The flattened, smoothed surfaces were then uniformly roughened with #60 grit grinding powder at a constant rate.

The samples were then fitted into the L-shape loading blocks and jacketed with a latex membrane. This process included many components and steps to ensure reproducibility between experiments (Figure 3.2). Following Madara et al., 2018, a thin, flexible latex membrane was epoxied to the exposed front and back of the sample prior to jacketing. This eliminated the potential for fluid flow around the sides of the sample (Figure 3.2b). Metal shims were used at the top and bottom of the eventual fracture plane to ensure that the jacket did not intrude into the fracture. We used porous metal frits between the sample and the loading block at both the top and bottom of the eventual fracture plane to produce a line source of fluid, maintained at constant pore pressure via servo control (Figure 3.2). An in-house clamp design was used to seal the latex
jackets against O-rings in the loading blocks (Figure 3.2). A support block underneath the static, smaller side of the L-shaped sample (Figure 3.2) was used to prevent tilting of the sample during shear loading and fracture. This significantly increased the reproducibility of fracture plane orientation. This support block is T-shaped (Figure 3.2b) with a cylindrical shaft that passes through the jacket to provide direct contact with the base of the loading platen (item 15 in Figure 3.2b). The jacket is sealed against the T-support shaft using steel lacing wire. Pore pressure lines were flushed with DI water prior to each experiment and at the start of each experiment to eliminate air from the system before saturating the sample.

3.3.2 Experiment Procedure:

Samples were placed into the pressure vessel, accessed via removable high pressure doors, before sealing the vessel and applying a nominal normal stress and confining pressure of 5 MPa. A flow gradient was then established by independently controlling pore pressure intensifiers (Figure 3.1d). For saw cut samples we applied a pore pressure gradient of 200 kPa with the 3.1 MPa at the inlet and 2.9 MPa at the outlet. For in situ fractures a larger pore pressure gradient was required to ensure the fluid flow rate never dropped below our detection threshold: 2 MPa with 4 MPa at the inlet and 2 MPa at the outlet. To that end, we monitor the volumetric flow rate \( Q \) in and out of the sample continuously (Figure 3.3) and report permeability values only for steady-state flow conditions, indicated by \( Q_{\text{in}} = Q_{\text{out}} \pm 3\% \). We calculate effective permeability \( k \), based on Darcy’s law (Figure 3.3);

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

where \( \mu \) is the fluid viscosity (\( 8.9 \times 10^4 \) Pa s for DI water at \( T=25^\circ \) C), \( L \) is flow path (50 mm), \( S \) is the cross sectional area of the sample perpendicular to the flow direction (45×29 mm), \( Q \) is...
flow rate, and $\Delta P$ is the pore pressure differential (Figure 3.1; Table 3.1). The flow rate is calculated using the displacement rates of the inlet and outlet pore pressure intensifier pistons over sample window appropriate for the conditions (typically 1-2 seconds). The unique L-shape of the sample allows for a constant flow path length and width as the sample is sheared.

We measured stresses, shear and normal displacement across the fracture, and fluid flow volumes continuously throughout each experiment. We also used a small, high-resolution LVDT within the pressure vessel to measure displacement normal to the fracture plane (Figure 3.1). The internal LVDT grants us precision within 0.025 microns and sits on either side of the sample; so our dilation and compaction data throughout the experiment are not subjected to any potential strain effects of the support blocks in our set up.

3.3.3 Shearing:

Shear loading was applied to intact samples by advancing the vertical piston, in contact with the top of the L-shaped block, at a servo-controlled displacement rate of 11 $\mu$m/s. The notch at the top and bottom of the eventual fracture plane, as well as the sample geometry, guided the fracture plane and helped ensure reproducibility in the gross fracture geometry. Intact samples were loaded until broken, which typically occurred at ~40 MPa in Green River shale and ~55 MPa in Westerly granite (Figure 3.4). Once the sample was broken (Figure 3.4) shear sliding was imposed in steps of controlled displacement with slide-hold-slides as well as velocity steps. Slide-hold-slide tests were performed at a shearing velocity of 11 $\mu$m/s with hold times of 1, 10, and 100 s in a manner consistent with previous work (Brace and Byerlee, 1966; Brace et al., 1968; Dieterich, 1972, 1978; Marone, 1997; McLaskey et al., 2012). Velocity step tests are performed
by servo controlled changes in shear velocity of uniform displacement, typically 500 microns. Velocity up steps were: 2 to 10 to 20 \( \mu \text{m/s} \); down steps were 20 to 10 to 2 \( \mu \text{m/s} \). The physical parameters of the experiment allowed for shear displacement of approximately 30 mm.

### 3.4 Results

#### 3.4.1 Shear Fracture and Run In:

Permeability is shown to decrease with shear displacement (Figure 3.4). All saw cut samples show sharp permeability reduction during shear loading, prior to sliding (Figure 3.4a-c). In all rock types, this decline occurs from \(~10\text{-}12\) MPa. After shear run in, permeability continues to decline at a much lower rate. Permeability is lowest for all samples after substantial shear displacement. In situ fractured samples of low matrix permeability show a permeability increase with fracture (Figure 3.4d; 3.4e). For these samples the intact permeability was not measured due to the time constraints of our experiments, so intact permeability measurements are supplemented with prior studies (Brace et al., 1968; Hazzard and Young, 2000; Selvadurai et al., 2005; Summers et al., 1978). Comparison of previous work and our own show a permeability increase ranging from \(10^{-18}\) to \(10^{-19}\) m\(^2\) intact, to \(10^{-15}\) to \(10^{-14}\) m\(^2\) with fracture of Westerly granite and Green River shale. For in situ fractured Berea sandstone the drop in permeability was typically \(1\text{-}2 \times 10^{-14}\) m\(^2\), which represents a reduction of about 50\%-60\% compared to the matrix permeability (Figure 3.4f). With intact Berea we observe that permeability decline begins during shear loading, prior to fracture. This occurs with the onset of shear-induced dilation around 40\% of the fracture stress and is attributed to well documented cataclasis and microcrack closure in porous rock.
3.4.2 Fracture Healing Frictional Response:

We perform Slide-Hold-Slide tests on all samples to study fracture healing with hold time (Figure 3.5). Changes in frictional strength, $\Delta \mu$, are calculated as the difference between friction at the end of the hold period and the peak friction upon the reinitiation of shear. Significant increases in fracture healing are observed with increased hold time for all samples. Saw cut samples show greater healing than in situ fractured samples of all rock types (Figure 3.5). Additionally, we observe the greatest amount of fracture healing in Green River shale and the least amount of healing in Westerly granite for both saw cut and in situ fractured samples.

3.4.3 Fracture Healing Fluid Response:

Figure 3.6 shows a comparison of mechanical and fluid responses as a result of Slide-Hold-Slide tests in saw cut Westerly granite (Figure 3.6a) and saw cut Green River shale (Figure 3.6b) where hold times are 10 seconds and slides are 100 microns of shear displacement at a shear velocity of 11 $\mu$m/s. We highlight the results of saw cut samples as they are more simple and repeatable than their in situ fractured counterparts. We report the response of parameters critical to the understanding of controlling mechanisms: permeability, normal displacement, and shear stress. In Westerly granite we observe onset of shear, dilation, and permeability enhancement occur together as well as the reverse: hold time, compaction, and permeability decline. The opposite permeability response is observed in Green River shale: onset of shear yields dilation.
and permeability decline while permeability enhancement is observed during hold times as the sample compacts.

3.4.4 Velocity Step Tests:

We perform velocity stepping tests of constant shear displacement (Figure 3.7). As may be expected, mechanical responses are sharper and more consistent in the saw cut samples than in situ fractures as the fracture planes are more uniform. Similar to the Slide-Hold-Slide tests, we observe opposite fluid responses in Westerly granite (Figure 3.7a) and saw cut Green River shale (Figure 3.7b). Figure 3.7a shows an in situ fractured Westerly granite sample with velocity steps of 500 µm. Here, the fluid response follows the mechanical: down stepping results in permeability decline and up stepping causes permeability enhancements. Figure 3.7b shows permeability decline with up steps in velocity and permeability enhancement with down steps. These are most clearly observable in the transitions between 10 µm/s to 100 µm/s and vice versa. Each velocity step in p5037 (Figure 3.7b) lasts for 200 µm of shear displacement.

3.5 Discussion:

3.5.1 Discussion of Shear Fracture and Run In:

Berea sandstone shows consistent permeability reduction with shear fracture and displacement in both saw cut and in situ fractured samples (Figure 3.4). This permeability decrease is associated with pore throat clogging via fine particles generated during shear consistent with previous studies (Candela et al., 2014, 2015; Madara et al., 2018; Roberts and Abdel-Fattah, 2009). Our measurements of the matrix permeability of Berea sandstone (intact
samples) are consistent with previous work and expectations (Cleveland Quarries quotes 50-100 millidarcy i.e., 5 to $10 \times 10^{-14}$ m$^2$). We typically observe a decrease in permeability of 1-2 orders of magnitude with shear displacement (Figure 3.4).

We do not measure the intact permeability of Westerly granite or Green River shale due to the time scale of our experiments and use of liquid pore fluid. However, intact measurements from previous studies reporting permeability range from $10^{-18}$ to $10^{-19}$ m$^2$ for Westerly granite and Green River shale, respectively (Brace et al., 1968; Hazzard and Young, 2000; Selvadurai et al., 2005; Summers et al., 1978). Given our post fracture permeability measurements, this yields a permeability increase of 3-5 orders of magnitude for both rock types. After in situ fracture, we observe permeability to decrease significantly with shear displacement. This is consistent and more clearly observable in saw cut samples (Figure 3.4a, b, c). The significant permeability reduction with initial run in has been observed in prior studies when the initial roughnesses of the fracture surfaces are smooth (Faoro et al., 2009; Giwelli et al., 2016).

In situ fractured Westerly granite and Green River shale show a close relation between permeability and shear stress (Figure 3.4d, e). Our results show this relation is present in the saw cut samples of Westerly granite and Green River shale, but the effect is significantly dampened (Figure 3.4a, b). There is no clear relation between permeability and shear stress observed in saw cut or in situ fractured Berea sandstone. This difference is readily explained by the matrix permeability of each rock type. In the timescale of our experiments, flow is only possible through the fracture plane in Westerly granite and Green River shale, so the breakage of asperities will directly affect potential flow paths. Fluid flow could be occurring in any combination of paths through the fracture plane and matrix in Berea sandstone, so asperity breakages in the fracture plane will not have the same effect on the measured bulk permeability.
3.5.2 Discussion of Fracture Healing Frictional Response

We compare fracture healing between the saw cut and in situ fractured samples of Westerly granite, Berea sandstone, and Green River shale (Figure 3.5). While all rock types show greater healing with increased hold time, the saw cut samples show significantly greater healing at every hold time. We attribute this primarily to the greater contact area of the smoother, better mated, saw cut samples. Looking more closely, we observe that the Green River shales consistently have the highest amount of frictional healing followed by Berea sandstone and Westerly granite shows the least healing. This is consistent with previous investigations findings that stiffer rocks show lower healing rates and less contact growth during the interseismic period (Beeler et al., 1994; Carpenter et al., 2016; Marone, 1997; McLaskey et al., 2012).

3.5.3 Discussion of Fracture Healing Fluid Response:

Slide-hold-slide tests in Westerly granite show a sharp permeability increase with the onset of shear and permeability decline during the hold time (Figure 3.6a). The mechanism is easily explained by the accompanying subplot of sample dilation. The high stiffness allows for self propping of the fracture and permeability increases as a result of the shear induced dilation. During the hold time we observe sample compacting which readily explains the decreased permeability. This is seen in both the saw cut and in situ fractured Westerly granite as well as the in situ fracture Green River shale (Figure 3.6).

Slide-hold-slide tests in the saw cut Green River shale show the opposite result (Figure 3.6b). Figure 3.6b shows permeability declining with the onset of shear and a gradual permeability recovery during the hold. This is initially puzzling as permeability is observed to
decline during shear while the sample is dilating and then increase as the sample compacts during the hold. We propose a mechanism that carefully considers the stiffness and roughness of the sample. The saw cut shale is smooth at the beginning of the experiment. The initial shearing run in would create shear fabrics and, as a result, dominant flow paths. These flow paths would be shallow and determined primarily by the fine grain gouge material generated from shearing. This accounts for the transition observed between high permeability laminar flow to significantly lower permeability channel flow (Figure 3.4b). As the dominant flow paths are based off of the soft gouge material, the onset of shear in the slide-hold-slide tests would destroy the flow paths by redistributing the gouge material. This would create a more tortuous pathway for the pore fluid, resulting in the lower permeability observed even as the sample dilates. This mechanism relies on shallow flow channels that develop from gouge material, so we would not anticipate its application for in situ fractures of the same material. We do not observe this effect for the in situ fractures of Green River shale, because the fracturing process would create significantly greater long wave roughness on the fracture face. Greater roughness yields flow paths that would not be easily destroyed by the onset of shear from the slide-hold-slide tests. In this case, the depth of dominant flow paths causes observed permeability to be more similar to the flow pipe model where fracture aperture has lesser effect on permeability. Westerly granite samples are too stiff for the application of this mechanism as asperities act to self prop the fracture and flow paths have greater long wave roughness.

The above mechanism can be applied to explain the gradual permeability recovery observed during the hold phase of the slide-hold-slide test in saw cut Green River shale. The wear products generated from the slide phase are then gradually cleared from the dominant flow path, either by fine particle mobilization due to the fluid pressure head or by rapid dissolution. Either
possibility explains the gradual permeability recovery as well as the absence of this effect in granite or in situ fractured shale.

3.5.4 Discussion of Velocity Step Tests:

Velocity step tests yield frictional results consistent with prior work, where up steps in velocity create increases in the ratio of shear stress to normal stress and down steps decrease that same ratio (Dieterich, 1978; Marone, 1997; Ruina, 1983; Scholz, 1998). The fluid response to velocity stepping in Westerly granite shows permeability changes that mirror the direction of velocity stepping, increases with up stepping and decline with down stepping (Figure 3.7a). This is readily explained by shear induced dilation self propping the fracture and allowing greater fluid flow. As with the Slide-Hold-Slide tests, the observed results in Green River shale run counter to that in Westerly granite (Figure 3.7). Figure 3.7b highlights the fluid response during velocity stepping in saw cut Green River shale. There is a strong decline in perm with increased shear velocity. Further investigation of the normal displacement during this time shows that the sample is dilating during the permeability decline as in the Slide-Hold-Slide tests. Utilizing the previously detailed mechanism for permeability reduction during shear in Slide-Hold-Slide tests we can explain these otherwise perplexing results.

3.6 Conclusion

We explore the relation and evolution of friction and permeability through laboratory Slide-Hold-Slide and velocity step experiments. The use of saw cut and in situ fractured samples allows for the investigation of key mechanisms which may control permeability changes
throughout the seismic cycle on well mated surfaces. We find that fracture stiffness and roughness play a large, interconnected role in determining permeability enhancement or decline during the interseismic period and reinitiation of shear.
Figure 3.1:
Experiment configuration (after Candela et al., EPSL, 2014). (a) Schematic of the biaxial apparatus and pressure vessel. Direct Current Displacement Transducers (DCDTs) are attached to the vertical and horizontal pistons to measure displacement. Strain gauge load cells are placed in series with each piston to measure stress. (b) Photo of an L-shaped sample of Berea Sandstone. Red dotted line shows the eventual fracture plane, which is controlled by the sample geometry, loading, and plane of weakness created by notching the sample. (c) Photo of the steel blocks loading the sample in a single direct shear configuration, showing the normal and shear stresses as well as the flow inlet and outlet. (d) Photo of jacketed sample loaded into the pressure vessel with front door removed. Flow lines and loading pistons are also shown. An LVDT (Linear Variable Differential Transformers) is attached to the steel blocks nearest the sample for a precise measurement of sample thickness changes during the experiment.
Figure 3.2:
(a): Pressure vessel with front door removed and sealed sample. Fluid inlet pore pressure line (1). Fluid outlet pore pressure line (2). Clamps over O-ring seal preventing confining fluid from infiltrating sample (3). Support block preventing small side of L-shape from sliding during shearing (4).

(b) Sample schematic (without sealing jackets). Intact L-shape rock (5). Notches at the top and bottom of the sample (3.75-mm long) promote vertical fracture (6). Porous metal frit at fluid pressure inlet (top) and outlet (bottom) are used to prevent grains and fines from clogging the fluid lines (7). Metal guard separates latex jacket from fracture path and flow outlet (8). A second metal guard separates latex and sample fracture plane at the top of the sample (9). T-shaped metal loading block supports smaller portion of L-shape block during fracture and shear (10). Epoxy seal and thin latex layer prevents flow around sample (11). O-ring seal preventing confining oil pressure from leaking into sample (12). Pore pressure inlet (13). Loading block for larger portion of L-shape sample (14). Loading block for small portion of L-shape sample (15).
Figure 3.3:
Permeability estimation. Flow rate is calculated from changes in inflow and outflow volumes shown above. Permeability is calculated using Darcy’s Law when the inflow and outflow in steady state conditions, defined as inlet and outlet volumes within 3%. Here we see a deviation between inflow and outflow during a velocity down step, so permeability is not valid (denoted by the blank space on 3a).
Figure 3.4: Experiment summaries. Saw cut samples (A-C) are shown on the left and in situ fracture samples (D-F) are shown on the right. From the top down the pairs of samples are Westerly granite (A & D), Green River shale (B & E), and Berea sandstone (C & F). Note the high initial permeability of all saw cut samples and significant permeability decrease with initial shear displacement run-in. Permeability decline with shear displacement can be observed for in situ fractured samples as well. Permeability is closely tied to shear stress for in situ fractured Westerly granite (D) and Green River shale (E).
Figure 3.5:
Plot of fracture healing vs. hold time. $\Delta \mu$ values are calculated as the change in friction at the base of the hold time to the peak friction upon reshear. Significantly higher amounts of healing are observed in saw cut samples (black) than in situ fractured samples (blue). Additionally, both saw cut and in situ fractured shale samples show greater healing than other rock types (triangles).
Figure 3.6:
Slide-Hold-Slide tests on saw cut Westerly granite (a) and saw cut Green River shale (B). Each plot shows Permeability (top subplot), Normal Displacement (middle subplot), and Shear Stress (bottom subplot). Direction of dilation is increasing value, up. Holds are 10 seconds long followed by 100 microns of shear displacement at a shear velocity of 11 µm/s. Note (i) permeability increase with shear displacement and decline with hold time in Westerly granite (a). (ii) Permeability is shown to decline during shear sliding and increase during hold time in Green River shale (B). (iii) Sample dilation during shear and compaction during hold time for both rock types.
Figure 3.7:
Velocity step tests on in situ fractured granite (A) and saw cut shale (B). Permeability change follows direction of velocity step in Westerly granite and the inverse in Green River shale. Steps are of consistent displacement at each velocity: 500 µm in p4799 (A) and 200 µm in p5037 (B).
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**Table 3.1:**
Experimental parameters
Bibliography


Summers, R., K. Winkler, & J. Byerlee, (1978), Permeability changes during the flow of water through Westerly granite at temperatures of 100°-400°C, J. Geophys. Res., 83 (B1), 339-344,


Appendix A

Intact Single Direct Shear Sample Preparation

Here you will find the necessary components and steps required to run the single direct shear configuration inside of the pressure vessel. Keep in mind that no piece inside of the latex jacketing can be re-used across experiments as material can be fractured, distressed, or sheared, generating conditions which could potentially prevent or contaminate flow measurements.
Figure A.1. Components for sample preparation:
L-shaped loading blocks (large and small), L-Shape sample block sized to fit into loading blocks, O-rings for loading blocks Buena AS568A sizes 224 and 221, porous metal frits sized to fit small loading block, large and small clamps, O-rings for large and small clamps Buena AS568A sizes 224 and 221, copper T piece for attachment to small loading block and copper base for support of small loading blocking during shear loading, thin latex for attachment to side of sample block, pore fluid injection block (if using acoustic loading blocks), 2 O-rings for pore fluid injection block Buna N size 008, latex rubber jacketing sized 2 3/8”, McMaster Carr rubber size 1/16” x 2”, brass (or other flexible metal) size .007” thickness, Super Glue epoxy, duct tape, and electrical tape.
Figure A.2. Stretch and place O-rings (Buena AS568A sizes 224 and 221) into the grooves of the respective loading blocks (221 for the small loading block and 224 for the large loading block). O-rings will lay flat when applied correctly. Insert porous metal frits into small side of L-shaped loading block. Frits should be press fitted tight. Additional scotch tape can be used, if necessary, on top of the porous metal frit connecting to the side of the loading block so long as no tape blocks the frit in the expected flow direction.
Figure A.3. Slide rock sample into the small side of the L-shaped block and then place on top of the large side of the L-shaped block such that the thicker edges of each side block are in the “down” direction of eventual shear. In the acoustic block design set up this will result in the PZT cables pointing in opposite directions when aligned correctly. Note that both loading blocks have O-Rings applied at this point.
Figure A.4. Apply thin latex across the side of the sample and loading blocks with Super Glue epoxy such that potential flow paths around the sample are eliminated. Do not allow any epoxy to get into the O-ring grooves as this can potentially ruin the seal. Repeat on opposite side.
Figure A.5. Using the .007” thick brass (or other flexible metal), build a guard around the base of the sample and loading blocks. This will serve to prevent any rubber from getting pulled into the fracture plane during shear failure and displacement. Guard should fit in between the two loading blocks and tightly hug the side of the sample. Cut all edges such that there are no sharps or edges which could potentially cut the latex jacketing that will encase the sample. Do not allow any part to cover the O-rings.
Figure A.6. Using the .007” thick brass (or other flexible metal), build a guard around the top of the sample and small loading block. This will serve to prevent any rubber from getting pulled into the fracture plane during shear failure and displacement. Guard should fit in space between sample and small loading block. Cut all edges such that there are no sharps or corners which could potentially cut the latex jacketing that will encase the sample. Do not allow any part to cover the O-rings.
Figure A.7. Secure the copper T shaped piece to the base of the small side of the L-shaped loading block with electrical tape. This piece will provide support to the sample during shear loading, so it is critical that it is secured smoothly against the edge of the small side of the L-shaped loading block. Again, do not allow any part of the piece, or tape, to cover the O-ring.
Figure A.8. Apply duct tape around entire sample such that all additional pieces and guards are covered, particularly on edges. This will provide smoother contact between the sample and latex jacketing which will decrease the potential for ripping the jacket. Cut duct tape such that the neck of the T-shaped piece is exposed. Do not allow tape to cover any part of the O-rings.
Figure A.9. Cut McMaster Carr rubber (1/16” thickness) such that it can wrap entire around sample. Be sure to cut space to fit the neck of the T-shaped piece (shown near middle of long rubber strip). Cut separate rubber piece that will lay on the top of both loading blocks (shown head on in view above). The piece will be one singular rectangle and is shown at the bottom of the above image.
Figure A.10. Adhere small rectangular rubber piece to the tops of both loading blocks with electric tape (above). Do not allow tape or rubber to cover any part of the O-rings.
Figure A.11. Adhere long rubber strip around entire sample with electrical tape. This will protect any sharps or edges from cutting into latex jacketing. Do not allow tape or rubber to cover any part of the O-rings.
Figure A.12. Smooth all edges and ensure no pieces are protruding or blocking O-rings paying particular attention to T-shaped copper piece.
Figure A.13. Cut 2 sections of 2 3/8” latex jacket each roughly the height of the sample and loading blocks combined (this can be trimmed down later).
Figure A.14. Stretch first section of latex jacket over sample and loading blocks. Pre-stretching the jacket will make this easier, but be sure not to over stretch the jacket as it may permanently deform. Do not bend acoustic wires at sharp angles during this process as they will break. Smooth out the rubber so tension is equal in all portions. Look for paler colored sections as that shows stress accumulation. When done, apply thin coating of baby powder to rubber jacket to decrease friction prior to stretching second latex jacket over the sample.
Figure A.15. Very carefully cut through both jackets at the base of the T-shaped copper piece by making a small hole in the center and swaging outwards until the base is exposed. Both latex jackets should cling tightly to the sides of the neck as this is where a lacing wire seal will be applied. Do not allow the opening to extend beyond the neck of the T-shaped copper piece or new jackets will need to be applied.
Figure A.16. Apply single layer of athletic tape around the neck of the T-shaped copper piece, so lacing wire seal doesn’t cut into the latex jacket. Apply 2 lacing wire seals on top of the latex jacket that is clinging to the neck of the T-shaped copper piece in opposite directions. Make sure the lacing wire is flat and does not cross itself as this will prevent it from sealing properly. Do not allow any athletic tape to cover area of O-ring seal.
Figure A.17. Once again, ensure the latex jacket is smoothed so there are no stress concentrations or bunched areas. Take large and small O-rings for clamps, Buena AS568A sizes 224 and 221, respectively, and stretch them over the jacketed loading blocks to fit into O-ring grooves of loading blocks. The groove should be easily felt and O-rings should be securely in place when correctly applied.
Figure A.18. Clamps have a flat edge, O-ring groove, and beveled edge. When placing clamps around O-rings be sure that the flat edge is always away from the rock sample; the flat edge will lay on the flat part of the loading block. Place clamps around the O-rings (small clamp on small O-ring, large clamp on large O-ring) such that the O-rings fit snugly into the groove on the clamps. Clamps are connected via 4 size #6-32 x 5/8” hex screws. The clamp is designed such that each of the 4 must be tightened in small increments together rather than tightening one entirely and progressing to the others. This ensures a uniform tightness around the O-rings.
Figure A.19. Tighten clamps until all joints are flush. Clamp is numbered at every joint from 1-4 so both joints with 1 go together, 2 to 2, 3 to 3, and 4 to 4. Ensure that O-ring is entirely inside of the clamp groove.
Figure A.20. Prepare to connect the pore fluid injection block on top of the small loading block by placing the 2 Buena 008 O-rings around the fluid injection port.
Figure A.21. Place pore fluid injection block on top of small loading block such that edges are flush (this can only be done one way, so if the edges are flush it is on the correct direction). Securely tighten hex screws to attach the pore fluid injection block. Tighten opposite corners as to create a uniform seal.
Figure A.22. Turn sample such that the large loading block and T-shaped copper piece are supporting the weight. The neck of the T-shaped piece can then be placed inside of the base such that the thinner end faces the middle of the sample.
Figure A.23. Loading block will be placed on top of the large loading block such that the thicker edge points towards the middle of the sample and there is no contact with the clamp when piston applies shear load. The sample is now ready to be placed into the pressure vessel.
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EDUCATION

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