LABORATORY OBSERVATIONS OF PERMEABILITY ENHANCEMENT 
BY FLUID PRESSURE OSCILLATION OF IN-SITU FRACTURED ROCK

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Abstract

We report on laboratory experiments designed to investigate the affect of pore pressure oscillations on the effective permeability of fractured rock. Berea sandstone samples were fractured in-situ under triaxial stresses of 10's of MPa, and deionized water was forced through the incipient fracture under conditions of steady and oscillating pore pressure. We find that short-term pore pressure oscillations induce long-term transient increases in effective permeability of the fractured samples. The magnitude of the effective permeability enhancements scale with the amplitude of pore pressure oscillations, and changes persist well after the stress perturbation. Maximum values of effective permeability enhancement are 5x10⁻¹⁶ m² over a background permeability of 1x10⁻¹⁵ m². We evaluate poroelastic effects and show that hydraulic storage release does not explain our observations. Effective permeability recovery following dynamic oscillations occurs as the inverse square root of time. The recovery indicates that a reversible mechanism, such as clogging/unclogging of fractures, as opposed to an irreversible one, like microfracturing, is responsible for the transient effective permeability increase. Our data suggests the feasibility of dynamically controlling the effective permeability of fractured systems. The result has consequences for earthquake triggering and permeability enhancement in fault zones due to dynamic shaking from near and distant earthquakes.

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1 Introduction

Fluid flow in Earth’s crust shows a strong sensitivity to dynamic stressing [e.g., Manga and Wang 2007]. The passage of seismic waves can increase both the frequency of geyser eruptions and the local rates of stream flows [Rojstaczer and Wolf, 1992; Muir-Wood and King, 1993; Manga and Brodsky, 2006; Manga et al., 2003; Manga and Wang 2007]. Seismic waves can also temporarily enhance oil production and spring discharge [Beresnev and Johnson, 1994; Roberts et al., 2003; Manga et al., 2003]. Dynamic stresses associated with the passage of seismic waves have also been observed to cause transient changes in water well levels [Coble, 1965; Brodsky et al., 2002; Elkhoury et al., 2006].

These observed flow phenomena have been suggested to result from transient changes in local permeability due to the dynamic shaking [Manga et al., 2003; Manga and Brodsky, 2006; Elkhoury et al., 2006, Doan et al., 2007]. Dynamic stresses in the elastic waves can produce large oscillations in pore pressure that appear to drive these permeability changes [Brodsky et al., 2003]. In addition, dynamic stresses produced by the passage of seismic waves can trigger seismicity, tremor, and other modes of fault slip, even at great distances from the mainshock [e.g., Hill et al., 1993; Felzer and Brodsky, 2006; Manga and Wang, 2007; Rubenstein et al., 2007; Gomberg et al., 2008; Shelly, 2010]. One explanation for these triggered slip events involves transient changes in fluid pressure due to flows resulting from permeability enhancement in the fault zone [Brodsky et al., 2003]. However, the mechanism of the permeability increase from dynamic stressing is not well understood for either the flow phenomena or the seismic observations. The purpose of this study is to investigate the effect of dynamic stressing on the effective permeability of fractured rock in order to improve the understanding of these observations.

In this study, we address the mechanisms of permeability enhancement by dynamic stressing using controlled laboratory tests. We produced fractures under true-triaxial stresses with fully saturated conditions and then applied sinusoidal oscillations in the upstream pore pressure while holding the downstream pore pressure and the applied stresses on the sample boundaries constant. We measured the permeability of the sample, via fluid flow, continuously during the experiment and found that the permeability after the pressure oscillations increased systematically with increasing amplitude of the oscillations.
This paper begins with a description of the experimental procedure and laboratory results. We then translate the flow measurements to permeability while addressing poroelastic effects, boundary conditions of the applied loads, and issues of fluid flow in porous media such as specific storage. We interpret the resulting permeability enhancements by examining both the repeatability of the permeability recovery and the functional form of the relationship between transient pore pressure amplitude and permeability increase. Finally, we discuss possible applications of the results to field conditions applicable to reservoir engineering and earthquake physics.

2 Experimental Procedure

The goal of our experiments was to measure the permeability response of fractured rock to dynamic stresses created by fluid pressure oscillations. The experimental procedure consists of two stages. In the first stage, we fracture intact samples within the testing apparatus while flowing fluid through the samples under controlled conditions (Figure 1). Once the fluid flow through the fractured sample reaches steady state and flow rates at the inlet and outlet are the same, we examine the role of dynamic stressing on effective permeability of the samples in the second stage of the experiment. We measured fluid flow rates independently at both the inlet and outlet of the sample (Figure 2), and all stresses, strains, fluid pressures and fluid volumes were measured continuously throughout the experiment. Digital data were collected with a 24-bit A/D system recording at a rate of 10kHz and averaged to rates of 10Hz. The testing apparatus consisted of a pressure vessel within a biaxial load frame (Figure 1). A true-triaxial stress state is achieved via two loads applied through the pistons and the confining pressure. Each stress is controlled independently via a fast-acting servo controller (for details of the apparatus see Samuelson et al., 2009 and Ikari et al. 2009).

Each experiment started with an intact, pre-saturated, sample of Berea sandstone (Figure 2a). We chose Berea sandstone because: 1) it is homogeneous, which allows reproducible results on multiple samples, 2) it is considered a representative reservoir rock and its properties are well characterized [e.g., Wang, 2000], and 3) it has a relatively high permeability that is important in ensuring reasonable durations of the experiments.
Samples of Berea were cut into L-shaped blocks that are roughly 3x4x7 cm in dimension (Figure 3a). The blocks were jacketed in a latex membrane and placed in the direct shear configuration (Figure 3b). Horizontal and vertical pistons together with a confining pressure loaded the sample. For all experiments, the normal stress across the eventual fracture plane was held at 23 MPa and the confining stress was set to 9 MPa, so that the effective normal stress was between 19 and 21 MPa, depending on the applied pore pressure (Table 1). These values were maintained constant during the entire experiment via servo-control.

The next step in our experiments was to initialize the flow system (Figure 3c). We implemented a pore pressure gradient by applying fluid pressure to the inlet and flushing the system until clear fluid (deionized water) flowed from the outlet. We then connected the second (outlet) pore pressure intensifier, bled trapped air, and applied a controlled pressure differential, \( \Delta P \), until the flow rate reached steady-state (i.e. equal flow rates at the inlet and the outlet). Pore pressures were servo-controlled and applied via line-sources at the inlet and outlet (Figures 2 and 3b). The fluid inlet and outlet consisted of a narrow channel fed by 3 holes (Figure 2). The channel was covered with 30\( \mu \)m nylon filter paper to avoid clogging.

Pore pressures, \( P_p \), at the inlet and outlet were servo-controlled independently. We measured inlet and outlet flow volumes, to a resolution of 5.1x10\(^{-5} \) cc, via linear variable differential transformers (LVDTs) mounted on the intensifier pistons. The mean value of \( P_p \) was \(~3.0\) MPa with pressure differential, \( \Delta P \), of \(~0.3\) MPa (Table 1). The amplitude, \( A \), of the \( P_p \) oscillation ranged from 0.02 to 0.3 MPa. We applied multiple sets of oscillations during a given experiment (Figure 4).

Permeability was inferred via Darcy’s Law

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

(1)

where \( k \) is the effective permeability of the fractured sample, \( \mu \) is viscosity of water, \( L \) is flow path and \( S \) is the cross-section of the sample and the nominal area of the eventual fracture plane. As long as the flow rates at the inlet and outlet of our sample are equal, the measured changes in flow rate represent changes in effective permeability, because \( \Delta P \), sample volume and water viscosity (i.e. temperature) remained constant. In the data presented below, we always verified that inlet and outlet flow were equal within the measurement resolution.
We began to fracture the sample after it was subject to the nominal triaxial stress state detailed above and after pore fluid flow had reached steady state. Control experiments were also completed in which we applied pore fluid pressure oscillations to the intact sample, and these are presented below. Shear load was applied by advancing the vertical piston in servo-displacement control at 5 $\mu$m/s, which increased stress on the top of the L-shaped block (Figure 3d). Figure 5 shows details of a representative experiment, with shear stress and permeability plotted as a function of the load point displacement during fracture development. The permeability values shown in Figure 5 are derived from the average flow rate computed at the inlet and outlet. We use measurements of the force applied at the top of the sample to compute shear stress on the eventual fracture plane, which has a nominal area of $2.2 \times 10^{-3}$ m$^2$. Permeability is approximately constant until a small stress drop at a shear stress of $\sim 20$ MPa and then begins to increase with further loading. Significant inelastic yielding begins at a displacement of $\sim 9.2$ mm, and permeability shows a sharp increase at that point. The sample fractured at a shear stress of 32 MPa, which was a consistent observation for each experiment (Table 1). A loud acoustic emission and a sudden drop in stress accompanied the mode-II dominated fracture (Figure 5c). These were also consistent observations for each of our experiments. Figure 5b shows a zoomed-in view of the shear stress and flow rates for the region around failure. The inlet and outlet flow rates track one another exactly prior to a displacement of 9.8 mm, but after this point there is clear departure, with the inlet showing higher flow rate. The difference in flow rate is consistent with micro-fracture and eventual brittle failure, which increases the pore volume of the sample. Figure 5 clearly shows that: 1) the storage of the Berea sandstones increases with fracturing and 2) that we can measure storage effects with fidelity should they occur. Comparison of the inlet and outlet flow rates in the vicinity of the fracture provide a sensitive measure of fracture development and indicate clear, transient changes in poromechanical storage of the sample. We discuss storage effects related to transient oscillations of pore pressure more fully below, but for now we simply note that our experiment protocol and testing apparatus are capable of resolving both subtle and significant changes in storage, effective sample permeability, fracture development and strength.

After fracturing of the sample, we stopped loading and maintained a constant position of the vertical ram. This point occurs at a displacement of 10.4 mm in Figure 5. This concluded the preparatory or first stage of the experiments. At this point we waited until steady state flow (i.e.
constant permeability) was re-established before proceeding, and then commenced dynamic pore pressure oscillations (Figure 3e). We imposed sinusoidal pore pressure oscillations of varying amplitude while maintaining constant period and duration (20 sec and 120 sec, respectively). In order to isolate the effect of amplitude, we keep the frequency and number of the oscillations constant for all of the experiments reported here. For this set of experiments we used a period of 20s period, which is representative of seismic waves. Future work should explore the effects of oscillation frequency and duration. We refer to each set of six oscillations as a single dynamic stress test, and each point in Figure 4 represents one such test.

We measure the effective permeability of the fractured sample, which includes the matrix permeability of the unfractured sample. The effective permeability, \( k \), is used as an interpretive tool to monitor the response of the fractured sample to the pressure oscillations. The fracture we produce, \( \textit{in situ} \), is a complex natural shear fracture containing a combination of mode II and mode I segments. While we do not observe the fluid flow path directly, comparison of the pre- and post-fracture sample (Figure 5) and the permeability data gives a good indication of the fracture flow and permeability. We measure the effective permeability, \( k_a \), by calculating the flow rate over a 2 sec window (Figure 6). For pore pressure oscillations, we start 10 sec after the oscillation to ensure that permeability measurement is not affected by the \( P_p \) oscillation and/or by storage effects, which we address more fully below.

The detailed results presented here (Table 1) are a subset of experiments performed on 22 samples. These additional experiments are not part of our main data set, but were important in developing the protocol for our experiments and thus merit a few comments. We explored the use of smooth artificial fractures produced between two rock surfaces that were prepared by cutting and grinding samples of Berea sandstone. Fracture surfaces were surface ground flat and then roughened with #60 grit SiC polishing compound. Fluid flow rates along these surfaces were very fast and we were unable to observe reproducible permeability enhancement, even at the lowest \( \Delta P \) values we could achieve (~ 50 KPa). The second set of tests considered natural shear fractures, as described in the primary suite of experiments, except that we applied flow-rate boundary conditions at the inlet/outlet and measured the differential pore pressure. This approach was feasible, but not optimal because of the finite fluid volume available from our pressure intensifiers (~125 cc, see Samuelson et al., 2009 and Faoro et al., 2009 for additional details).
Results of these additional tests were otherwise consistent with the main set of experiments, which we focus on below.

3 Results

We present detailed results from experiments on four samples, which were each subjected to multiple sets of $P_p$ oscillations (Table 1 and Figure 4). Between each set of oscillations, the sample was allowed to recover for 30 to 100 minutes (Figure 4). We report changes in permeability as $\Delta k = k_a - k_{ref}$, where $k_a$ is effective permeability and $k_{ref}$ is the initial, reference permeability after fracturing and shearing, but before pressure oscillations began (Figure 7). Table 1 provides details on the sample strength and fracture parameters, which gives a sense of reproducibility between the complex natural fractures we developed in the samples of Berea sandstone. Table 1 also provides sample dimensions and values of the pore pressures used to assess permeability and transient changes in it.

We find that pore pressure oscillations produce transient increases in the flow rate (Figure 6). Oscillations were applied in sets of six, with a constant oscillation period of 20 sec. During the oscillations we controlled the inlet and outlet pressures and monitored flow at both the inlet and outlet. Figure 6a details the $P_p$ history for one set of oscillations. The mean value of $\Delta P$ before, during and after oscillations is unchanged, and thus the average driving force for fluid flow remains constant. Figure 6b shows details of the flow rates before and after oscillations. The heavy black line shows the data. The dashed yellow lines show the trend of the flow rates for both the inlet and the outlet prior to $P_p$ oscillation. The solid yellow line is a fit to the overall trend after the oscillation, which is clearly different than the pre-oscillation trend. We note that the increase in flow rate is immediate upon initiation of the pressure oscillations. Detail of the flow rates measured at the inlet and outlet are shown in Figure 6c. These data indicate that flow through the fractured sample was rapid, but small differences between inlet and outlet existed, with phase shifts of ~ 2 seconds and amplitude damping of up to $3 \times 10^{-9}$ m$^3$/s in flow rate. Note that flow rates for the inlet and outlet track one another after the $P_p$ oscillations end. Key observations include: 1) post-oscillation flow rates exceed the pre-oscillation flow rates, and 2) flow rate decays following the oscillation (Figure 6c). For each test, we found results like those in Figure 6.
We calculated effective permeability of the fractured sample using the flow rates before and after $Pp$ oscillations (Figure 7). These values represent effective permeability of the fractured sample, given that flow occurs within the fracture, in the damaged region around the fracture, and within the sandstone matrix. Our data consistently show that oscillatory forcing causes a step increase in permeability, followed by a gradual reduction to the pre-oscillation values (Figure 7). The decay of permeability towards its initial value follows a power law $t^p$, where the exponent $p$ is between 0.3 and 0.7. Additional detail on this is provided below.

For amplitudes of pore pressure oscillation in the range 0.02-0.3MPa, the transient increases in permeability, $\Delta k = k_a - k_{ref}$, scale with amplitude (Figure 8). The absolute values of $\Delta k$ increase are in the range $2 \times 10^{-18}$ m$^2$ to $5 \times 10^{-16}$ m$^2$, and vary slightly from sample to sample (Figure 8a), but the dependence on amplitude is consistent. To compare permeability changes between experiments quantitatively, we normalized changes by $k_{ref}$, the background permeability (Figure 8b). We also normalized the pore pressure amplitude, $A$, by the pore pressure differential, $\Delta P$, driving the background flow. Figure 8b shows remarkable similarity between experiments, with all data falling on the same curve given by

$$\log\left(\frac{\Delta k}{k_{ref}}\right) = m \frac{A}{\Delta P} - f$$

where the slope $m$ is 2.1 with a 95% confidence interval given by the range 1.7 to 2.5, the constant $f$ is 1.67 with a 95% confidence interval given by 1.5 to 1.8 and a goodness of fit measured by an $R^2=0.7$. Equation (2) is used because it is simple and consistent with the experimental data. However, it is only valid for the range of amplitudes in pore pressure oscillations considered in our experiments. We explore the permeability fit beyond the experimental conditions in section (4.3).

Figure 8 demonstrates that effective permeability as defined by Equation (1) is a well-defined quantity, despite details of the complex flow structure in the sample. The proof that the effective permeability is useful in a comparative sense is simply the reproducibility of the normalized permeability results of Figure 8. If our measure of permeability were poorly defined, then Equation (2) would have no predictive power for the laboratory experiments, which is clearly not the case.
3.1 Transient Permeability Enhancement and Decay

To the best of our knowledge, the transient increases in permeability reported here provide the first consistent experimental evidence of flow enhancement by pore pressure oscillations. We observe step increases in permeability upon oscillatory forcing, followed by gradual recovery (Figure 7) akin to that observed in natural systems (Figure 9) [Elkhoury et al., 2006]. Furthermore, the magnitude of our observed permeability enhancement increases systematically with increasing amplitude of the pore pressure oscillation (Figure 8).

The decay of permeability toward background levels, following oscillatory forcing is of interest. A power law fit of the form $t^{-p}$ best represents the recovery of permeability to pre-oscillation values (Figure 7). The exponent $p$ ranges between 0.3 and 1.0 for our suite of experiments (Figure 10). Using $p=0.5$ as a representative decay results in a slightly reduced, but still acceptable, goodness of fit (Figure 10). The square root dependence on time suggests a diffusive process like the migration of pore pressure that would be expected in a porous medium [e.g., Bear, 1979; Faoro et al., 2010]. However, this permeability recovery is distinct from a poroelastic release of storage as will be discussed below (Sect. 4.2).

We probed the effect of fracture complexity and gouge development on transient permeability enhancement by progressively shearing the fracture after it was formed (Figure 11). Shear offset of the fracture decreased the effective permeability significantly as indicated by the region marked by the dashed line in Figure 11. These data support the idea that most of the flow occurs within the fracture zone, rather than in the sandstone matrix. In the other experiments, the samples were sheared immediately after fracturing, which further reduced permeability and therefore lowered the reference permeability.

4 Discussion

4.1 Potential mechanisms of permeability enhancement

The increase in permeability induced by oscillatory pore pressure can be explained by a number of mechanisms. We focusing on: 1) microfracturing and shear and 2) clogging/unclogging of fracture flow paths. In the first mechanism, the oscillation of the stress field due to the change in effective stress from the pore pressure oscillations results in (micro)failure of the solid material. These new cracks form an increased number of pathways for
the flow and hence an effective permeability increase. In the second mechanism, pore pressure oscillations drive a faster flow through existing fracture flow paths by removing transient barriers, such as rock powder from the fracturing process. The flow mobilizes the particulates and removes them from constrictions in the fracture network resulting in unclogged fractures with larger effective permeability than prior to the oscillations. As dynamic stressing vanishes, permeability of the system is recovered due to clogging of the fracture mediated by diffusive processes and settling of fine particles [Bear, 1979]. Below, we detail four experimental observations that favor the mechanism of unclogging mechanism over microfracturing for the laboratory experiments: (1) the recoverability of the permeability state, (2) the dependence of the permeability enhancement on the initial permeability of the sample, (3) a lack of permeability increase for unfractured, intact samples and (4) a lack of observed normal stress oscillations.

As demonstrated in Figures 7 and 10, permeability returns to pre-oscillations values over a period of 10’s of minutes after the oscillations. This recovery requires a reversible mechanism, like unclogging of fractures, as opposed to a permanent change of the matrix properties, like microfacturing. If an irreversible mechanism like microfacturing were responsible for the permeability enhancement, then an additional mechanism of unusually rapid healing would be required to account for permeability recovery.

The importance of the initial permeability, \( k_{ref} \), in predicting the permeability changes, reflected in the collapse of all data points in Figure 8b onto the same curve, indicates a strong memory in the system. It implies that permeability enhancements after a given period of dynamic stressing are not affected by previous excitations, as would be expected for the formation of new pathways by microfacturing. Instead, the degree of permeability enhancement is controlled by a parameter that directly measures the propensity for flow suggesting a role for fluid flow in directly controlling the subsequent structure.

We also performed experiments on intact rock samples of Berea Sandstone (Figure 12) and Westerly Granite (no fracturing) where we did not observe changes in permeability under the influence of pore pressure oscillations. This points at the importance of fine particles along the flow path and the heterogeneity of the natural fracture in controlling the flow and subsequent response to dynamic stressing. Microfacturing would have been expected to be effective in the intact samples.
The effective permeability enhancements are not affected by fluctuations in the effective normal stress. The amplitude of the pore pressure oscillations was ~0.2 MPa over a fixed background effective stress of 20 MPa. Therefore, variations in effective normal stress are about 1% of the total effective normal stress. Moreover, we impose the dynamic stressing through pore pressure oscillations around a constant pre-oscillation pore pressure value. Hence, the average effective normal stress during the oscillations is the same as the background stress. This lack of normal stress oscillations in the solid matrix makes failure through microfracturing unlikely [Townend and Zoback, 2000; Nemoto et al., 2009].

Taken together, our observations strongly favor clogging/unclogging as the potential mechanism for transient changes in permeability. However, there is one potentially conflicting observation. If particle mobilization is controlling permeability, either clogging or unclogging of fracture throats should be possible. Therefore, we could potentially observe either permeability increases or decreases. For our full suite of experiments, only one occasion of dynamic stressing in 50 produced a transient decrease in permeability. The sign of shaking-induced permeability changes could vary with rock properties and fracture characteristics. Additional work to explore this aspect of the experiment will require significant technical enhancements to the experimental setting to directly monitor particulate flow and thus is beyond the scope of this paper.

Based on the current evidence, we conclude that unclogging is the mechanism that best explains our experimental observations of permeability increase by pore pressure oscillations. It is consistent with a larger number of the observations than the alternative mechanism of microfracturing.

4.2 Poroelastic Contribution of Storage

Apparent changes of permeability could be produced by transient storage in the sample. In principle, a release of fluid trapped within the sample could mimic an effective permeability increase. However, in our experiments storage effects were small as indicated by comparison of the input and output flow (Figures 6 and 7). Given the importance of this point, we now evaluate the contribution from such poroelastic effects and quantitatively demonstrate that they are not controlling the inferred effective permeability increases. We calculate the volume of fluid released from storage in the sample during and after an applied pore pressure oscillation based
on the measured poroelastic properties and compare it to the volume of fluid involved in the inferred effective permeability increase.

In order to measure the specific storage of the sample, we first calculate the hydraulic diffusivity based on the observed time lag of the outlet flow relative to the inlet flow. The average time delay, $\Delta T$, between maxima in the inlet and outlet flow rates during pressure oscillations is 2 seconds (Figure 6c). Given the flow path length scale, $L = 2\sqrt{\nu \Delta T}$, of 49.4 mm (for the case of experiment p1605), we obtain diffusivity $\nu = 3.05 \times 10^{-4}$ m$^2$/s for the fractured sample. The specific storage, $S_s$, defined as [Wang, 2000]

$$S_s = \frac{k}{\mu \nu}$$

is $S_s = 3.28 \times 10^{-9}$ Pa$^{-1}$, for a permeability, $k$, of $10^{-15}$ m$^2$ (Figure 7).

We verify this poroelastic specific storage value by checking the inferred volume release during the experiment (Figure 6) with the direct measurements of fluid flow. For this example, the amplitude of the pore pressure oscillation is 0.3 MPa (Table 1). Therefore, the fraction of stored volume is $S_s = 3.28 \times 10^{-9}$ Pa$^{-1} \times 3.00 \times 10^5$ Pa = $9.83 \times 10^{-4}$. Given the sample volume of 6.05 $\times 10^{-5}$ m$^3$, the resulting inferred volume released is $5.95 \times 10^{-8}$ m$^3$. This inference is consistent with direct measurements of the total volume difference of $5.18 \times 10^{-8}$ m$^3$ between the inlet and outlet fluid volume. On the other hand, the integrated volume of fluid during the 15 minutes of permeability recovery, immediately after the cessation of the pore pressure oscillation, at the inlet and outlet is $7.04 \times 10^{-6}$ m$^3$. This volume is orders of magnitude higher than the storage volume released and cannot be accounted for by poroelastic effects. Moreover, the poroelastic response is dissipated within the first 4 seconds after the culmination of the dynamic stressing. This is well within the window (10 sec) that we omitted from the analysis (Figures 6 and 7).

4.3 Permeability Recovery

Because we are interested in the permeability response to pore pressure oscillations, we focus on values of permeability before and after oscillations (Figure 7); however, the experiments contain additional information. Figure 10 shows the permeability recovery after dynamic stressing for two sets of pore pressure oscillations in one experiment. These data allow evaluation of the natural variability in peak permeability enhancement and in recovery among the repeat tests conducted in each experiment. Although there is some variability, the data are
generally consistent with power law exponents ranging from 0.3 to 1. A fixed exponent $p$ of 0.5 is a reasonable overall fit to each of the pore pressure oscillations tests (Figure 10). The exponent $p$ could be related to the fractal flow dimension of the fracture, which can vary from oscillation to oscillation [Walker and Roberts, 2003]. Therefore, $p$ can be interpreted as the inverse of the dimension, $d$, of the system, $p \sim 1/d$. Since our samples develop two dimensional shear fractures, the average flow dimension is $d = 2$. Hence $p \sim 0.5$ appears to be a good average exponent value to represent the overall recovery of the permeability as suggested previously by Bear, 1979 and Barker, 1988.

### 4.4 Flow-driven Permeability Enhancements

Our data indicate an exponential relationship between permeability enhancements (Equation 2) and the amplitude of the applied pore pressure oscillation. The exponential relationship means that permeability increase is proportional to the pre-existing permeability for the fractured samples. The easier it is for water to flow through the fractured sample, the greater the permeability increase. This dependency suggests that the mechanism for permeability enhancement may be water flowing through and opening up the fractures. For instance, if the water flow is removing fine particles in the fracture and thus opening up (or widening pathways) new pathways, we might expect that the cross-sectional area of the fracture cleaned would be proportional to the ratio of the excess flow rate over the background flow. In this case, the effective permeability increase would also be proportional to the excess flow and thus

$$dk_f \propto u_f$$  \hspace{1cm} (4)

where $k_f$ is the permeability in the fracture and $u_f$ is the excess flow in the fracture. According to Darcy's Law, for a fixed path length

$$u_f \propto k_f A$$  \hspace{1cm} (5)

where $A$ is the amplitude of the imposed pressure oscillation. Combining Equations (4) with (2) and integrating results in
\[ \ln(k_f) \propto A \] \hspace{1cm} (6)

as observed. The consistency means that a flow-driven mechanism for permeability enhancements is concordant with a flow-rate threshold for permeability enhancement. Micromechanically, this flow-rate threshold could be generated through mobilization of fine particles.

### 4.5 Permeability Fit Beyond the Experimental Conditions

The fit of Equation (2) used in Figure 8b was restricted to a logarithmic relationship. However, it is only valid for the range of amplitudes in pore pressure oscillations explored. In particular, the relationship is problematic for very small amplitudes. If \( A = 0 \), Equation (2) has the unphysical behavior that \( \Delta k/k_{ref} \) is finite, i.e., there is a permeability increase in the absence of any oscillations. To remedy this problem and extend the correlation beyond the experimental range, we suggest an equivalent relation of the form

\[ \frac{\Delta k}{k_{ref}} = a \left( \frac{A}{\Delta P} \right)^b \] \hspace{1cm} (7)

where \( a = 0.7 \) and \( b = 1.7 \) are fitting constants and goodness of fit given by an \( R^2 = 0.88 \). The opposite limit of a larger value of \( A \) relative to \( \Delta P \) is more problematic. In their present simplified form, neither Equation (2) nor Equation (7) extrapolates successfully to the field data of Elkhoury et al., 2006. In the field \( A/\Delta P = 10^3 \), where \( A \) is the amplitude of oscillatory strains provided by seismic waves and the pressure differential \( \Delta P \) is that of the Earth tides. In contrast, \( A/\Delta P = 10^1 \) for the experiments presented here. An extrapolation of Equation (7) to the field observations predicts \( k/k_{ref} \sim 1000 \) rather than \( k/k_{ref} = 3 \) or 4 as observed [Elkhoury et al., 2006].

One alternative is that the \( \Delta P \) dependence is incompletely captured by the current experiments as the current work explored a range of values of \( A \), not \( \Delta P \). Another alternative is introduced by the fact that the field system is clearly more complex than the small-scale laboratory samples. The multiple fractures and highly heterogeneous matrix likely have different composite behavior than a single fracture [Doan et al., 2007]. For now, we note that either Equation (2) or (7) successfully explains laboratory data showing permeability enhancement by dynamic stressing.
5 Conclusions and Implications

We observe systematic increases in effective permeability due to dynamic stressing produced by pore pressure oscillations. We used relatively small peak pressures ($10^{-2}$ - $10^{-1}$ MPa) and found effective permeability changes of up to 50% in a fracture-dominated system. Our results show that: 1) effective permeability enhancements can be reliably and reproducibly induced by pressure oscillations in the laboratory, 2) accurate prediction of the effective permeability changes requires normalization by the initial permeability of the system, indicating a memory of the initial state of the system, and 3) oscillating the pore pressure results in a logarithmic enhancement, under the experimental conditions considered, which is consistent with a flow-driven mechanism. Mobilization of fine particles and associated clogging/unclogging of the fracture flow path appear to explain most of our laboratory observations.

The effects of dynamic stressing show that permeability is a dynamically controlled variable. Our result has consequences ranging from hydrology and oil reservoir engineering to geophysics and earthquake triggering mediated by permeability enhancement in fault zones due to shaking from near and distant earthquakes. The experiments suggest that dynamically controlling permeability of fractured systems is feasible.

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6 References


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<td>2.5</td>
<td>2.4</td>
<td>2.3</td>
<td>2.8</td>
</tr>
<tr>
<td>$k_{\text{ref}}$ [10^{-16} m²]</td>
<td>10.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Flow Length L [mm]</td>
<td>49.4</td>
<td>49.7</td>
<td>49.8</td>
<td>49.9</td>
</tr>
<tr>
<td>Flow Cross-Section S [10^{-3} m²]</td>
<td>1.28</td>
<td>1.27</td>
<td>1.28</td>
<td>1.28</td>
</tr>
</tbody>
</table>

**Table 1:** Summary of parameters for the main suite of experiments, including experiment number, stress conditions, sample dimensions and hydraulic properties. Viscosity of water, $\mu = 8.89 \times 10^{-4}$ Pa s, is used in Equation (1).
**Figure 1:** Schematic of the testing apparatus. (a) Loading frame showing horizontal and vertical pistons, which provide normal and shear stresses on the eventual fracture plane, and pressure vessel where confining fluid pressure provides the third stress component. (b) Detail of pressure vessel showing L-shaped rock sample (blue). The single direct shear configuration is used with a frictionless roller-way bearing (orange) to fracture the sample in direct shear under applied load normal to the candidate fracture plane.
**Figure 2:** Sample configuration with main components arranged on a bench-top (note that the sample jacket and load support blocks are not shown and that alignment is not complete). a) Orange dashed line highlights the sample location. A latex jacket covers the sample during an experiment (see Figure 3b). b) Enlargement of the sample loading platen (left side of panel a) shown without the jacket sealing collar. Fluid ports and internal conduits in the platen provide flow through the rock sample. Pore pressures are servo-controlled and applied via line-sources at the inlet and outlet, which consisted of a narrow channel fed by 3 holes. The channel was covered with 30μm nylon filter paper to avoid clogging. Inflow port (at the back of the platen) is not seen in this photo.
Figure 3: Schematic of the experimental sequence. (a) Experiments started with an intact sample. Dimensions are in millimeters. The area S given in Table 1 is defined by the sample width and thickness, 28 mm and 45 mm. (b) Photo of pressure vessel with door removed showing the sample (within jacket), internal fluid pipes and loading configuration. Fluid lines are connected to servo-controlled intensifiers (Panel c) through high-pressure fittings in the vessel wall. (c) Schematic diagram of the fluid pressure system. Pressure intensifiers are servo-controlled and can apply flow rate or fluid pressure boundary conditions at the top and bottom of the eventual fracture plane. (d) Fractured sample with fluid flow. The stress normal to the fracture plane was applied as a constant force boundary condition at the edge of the rock sample. Shear load along the fracture was applied as a displacement boundary condition at the top of the sample. (e) Once fluid flow from the inlet to the outlet had reached steady state flow, pore pressure oscillations were applied at the inlet while keeping outlet pressure constant. We observe changes in steady state flow rate before and after fluid pressure oscillations.
**Figure 4:** Time sequence of the applied pore pressure oscillations in a complete experiment (p1605). Each point represents a set of oscillations with period of 20 sec duration of 120 sec. Intervals between oscillations sets were typically 30 to 60 minutes. Here, time=0 corresponds to the point at which the sample fractured. Dashed vertical line shows when fracture was sheared for 600μm at a rate of 5μm/s (see Figure 11). Boxed region denotes data shown in Figure 10.
Figure 5: Fracture of the intact sample. (a) Strength and effective permeability are shown as a function of loading displacement during fracturing. Note that permeability increases slowly as stress rises to failure, and then permeability decreases dramatically. The permeability value is computed from the average inlet and outlet flow rates. (b) Comparison of strength data and flow rates measured at the inlet and outlet (see Figure 2 for flow geometry). Note that as the failure stress is approached, inlet flow exceeds outlet flow, indicating changes in porosity and specific storage. (c) Photograph of a fractured sample. The fracture is rough and predominantly mode II.
Figure 6: Example of dynamic stressing and the corresponding flow rate measurements for a set of pore pressure oscillation in experiment p1605. (a) Imposed pore pressure oscillations at inlet and fixed pore pressure at the outlet. Pressure conditions before and after the oscillations are identical. (b) Inlet fluid flow. Black line shows displacement of the piston in the upstream fluid pressure intensifier before (dashed), during, and after (solid line) pressure oscillations. Green lines shows fit to pre-oscillation slope (dashed) and post-oscillation slope (solid). Piston displacement measures the volume of fluid that flows into the sample. The slope is flow rate, after accounting for compressibility and specific storage. Note the clear increase in flow rate induced by the pressure oscillation. (c) Measured flow rates at the fracture inlet (blue) and outlet (red). Notice the small time lag (≤2 sec) between the maxima of the inlet and outlet flow rates. Here, time = 0 is an arbitrary reference that indicates the middle of the oscillation.
Figure 7: Effective permeability before and after the pore pressure oscillation shown in Figure (6). Note difference in time scale with Figure 6; the oscillation and the time immediately afterward are not included here. The effective permeability is directly proportional to the flow rate (Figure 6c) via Equation (1). The two curves (blue and green) show the permeability measurements based on flow rates obtained independently at the inlet and outlet (Figure 6c). The striking overlap demonstrates that the permeability change is not related to storage or other poroelastic effects. Permeability shows a step increase followed by a gradual recovery. A power law $t^{-p}$ (dashed line) with exponent $p = 0.32$ fits the permeability recovery (dashed line) with a goodness of fit $R^2=0.96$. Here time $t=0$ corresponds to the initiation of pore pressure oscillations. Horizontal red dashed line is the reference permeability $k_{ref}$ defined as the permeability after fracture and shear but before the application of any pore pressure oscillations.
Figure 8: (a) Permeability increase, $\Delta k$, as a function of pore pressure oscillation amplitude. Oscillations were applied in sets of increasing amplitude (Figure 4). Permeability increases significantly as a function of oscillation amplitude. (b) Same data as in (a) except permeability changes are normalized by $k_{\text{ref}}$ and the pressure amplitudes are normalized by the pore pressure differential, $\Delta P$, driving the flow. Data collapse onto one curve (dashed line is Equation 2). Note that permeability increases by nearly two orders of magnitude for our range of amplitudes.
Figure 9: Permeability response to shaking at the Piñon Flat Observatory, in Southern California, from the 1999 Hector Mine earthquake. Notice the clear qualitative similarity with Figure 7 (but differences in time scale). Permeability shows a step increase at the time of shaking with a gradual decrease over a time scale of months. In the lab permeability recovery is achieved on the order of hours. (From Elkhoury et al., 2006).
Figure 10: Recovery of permeability after fluid pressure oscillations for several sets of oscillations from experiment 1605 (black lines). Y-axes are permeability changes $\Delta k$ and x-axes are time in minutes after the oscillation. Values of the amplitude of the oscillation, $A$, are in MPa. Dashed blue lines show power-law fit $t^{-p}$ with $p$ values given in each panel. Note that $p$ values range from 0.3 to 1.0. Red dashed lines show fits for $p = 0.5$; in this case goodness of fit, $R^2$, ranges from 0.7 to 0.9.
**Figure 11:** Permeability evolution as a function of shear displacement on the fracture (applied at the time of the vertical dashed line in Figure 4). Note that permeability drops from $4.4 \times 10^{-15}$ m$^2$ to $1.1 \times 10^{-15}$ m$^2$. The near vertical drop in stress represents an unstable, stick-slip event. Dashed bracket at top represents a net shear displacement along the fracture of 600 μm.
Figure 12: Effective permeability of the intact sample during pore pressure oscillations (as in Figure 6a). Permeability is determined from measured flow rates (see Figure 6b). Time zero is arbitrary here. Note that permeability does not change following pressure oscillations; compare to Figure 6c and Figure 7.