Collaborative Research: Permeability Enhancement by Fluid Pressure Oscillations

Intellectual Merit of the Proposed Research

Elastic waves produced during earthquakes can trigger a range of phenomena including seismicity, volcanic eruptions, and geyser activity. Dynamic stressing via the passage of seismic waves (or from other sources of transient loads) can also increase spring discharge, fluid flow in streams, and oil production, in some cases tripling the effective permeability of the natural system. These observations have been attributed to shaking-induced changes in permeability of shallow aquifers. However, the underlying mechanisms and the affect of dynamic stresses on poromechanical properties of rocks are poorly understood.

Here we propose to investigate permeability enhancement by dynamic stressing using a multidisciplinary approach. Our preliminary work, describe herein, is primarily laboratory based and shows clear evidence of permeability enhancement in fractured rock subject to fluid pressure oscillations. The proposed work will expand the laboratory data while developing the theory and focusing on the underlying mechanisms. We will use knowledge of the processes and mechanisms operative in the laboratory to address the problem of upscaling our results to field conditions.

We propose a series of experiments and models informed by observations of natural systems to (1) establish clear relationships between the controlling variables and the resulting changes in permeability, (2) analyze the physics of the enhancement and identify the underlying processes and (3) build appropriate numerical models of the results that can be applied at the laboratory and field scales.

Broader Impacts of the Proposed Research

Societal benefits: Results of the proposed experiments are expected to have significant impact on understanding fluid flow in the Earth’s crust and seismic hazard. Understanding the physical basis for transient changes in permeability will lead to improved engineering approaches for oil reservoir and hydrological use.

Encourage interactions between geoscience and engineering rock-mechanics communities: This project will bring together members of different backgrounds and vocabularies, but similar problems and data. This cross-discipline synergy will benefit students and research progress.

Promote teaching, training and learning: This project will train a graduate student at UC Santa Cruz under the advisement of Brodsky in collaboration with Marone, Elsworth, and Elkhoury. The student will have opportunities to present research at professional meetings, to collaborate with colleagues at other institutions, and to develop a broad understanding of interdisciplinary problems involving fault mechanics, earthquake physics, and fluid flow.

Postdoctoral mentoring activities: This project will support Dr. Jean Elkhoury as a postdoctoral scholar. Mentoring activities are a fundamental part of the proposed project and will include training in publication and research presentations, experience and guidance on developing teaching skills, experience with professional collaborations in a multi-PI project, and guidance on engaging graduate and undergraduate students.
Introduction and Proposal Overview

Shaking of Earth’s crust—or more generally, dynamic stressing—can result in significant changes in the physical properties of rocks. Earthquake triggering by elastic stresses generated in a distant mainshock is one such manifestation of dynamic stresses. Such transient stresses can alter the elastic properties of a rock mass and the frictional strength of faults within it. They can also cause transient and permanent changes in fluid pressure, flow properties, and the state of effective stress within the crust. The interplay between dynamic stresses, rock properties, and the state of stress in Earth’s crust can result in complex changes in flow properties and poromechanical behavior of rock.

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., Coble 1965; Hill et al., 1993; Felzer and Brodsky, 2006; Manga and Wang, 2007; Rubinstein et al., 2007; Gomberg et al., 2008]. Seismically-induced stresses have also been linked to transient changes in local fluid flow and permeability, both near and distant form the mainshock [Sibson, 1981, 1990, 1996; Muir-Wood and King, 1993; Roijstaczer et al., 1995; Zoback and Townend, 2001; Manga et al., 2003; Manga and Brodsky, 2006; Elkhoury et al., 2006; Brenguier, et al., 2008]. One explanation for such effects involves transient changes in fluid pressure driven by seismically-induced shaking [Elkhoury et al., 2006]. Based on measurements of hydraulic head oscillations in water wells, it is thought that the pore pressure oscillations play a major role in the resulting permeability changes. The dilatational strain of the seismic waves generates large fluctuations in pore pressure that appear to be linked to the permeability changes [Brodsky et al., 2003]. However, neither the mechanism of fluid pressure generation by dynamic stressing nor the poromechanical processes responsible for transient changes in permeability are well understood. We propose to investigate the affect of dynamic stressing on permeability of fractured rock.

A major impediment to developing a full understanding of permeability changes has been the lack of systematic laboratory data that can be used to test physical models and make predictions about field observations. This problem has been partially addressed by recent work documenting examples of repeated permeability increase that is well-correlated to an observable variable in a natural system (Figure 1). Elkhoury et al. [2006] showed that permeability of a shallow fractured aquifer is altered in a significant and repeatable fashion by the passage of seismic waves. They used the tidal phase response to monitor the evolution of permeability over a 20 year period. The natural forcing, imposed by the solid Earth tides, which continually pump water in and out of the well, provides a way to continuously monitor permeability. The phase lag between the solid Earth tide and the observed water level is a direct proxy for permeability. Changes in water level are more closely synchronized with the Earth tides as permeability increases. The data of Figure 1 show a repeated and predictable behavior observed at the Piñon Flats Observatory in Southern California. Permeability increased at the time of regional earthquakes. The closest and largest earthquakes generated the largest peak ground velocities near the well and the larger permeability enhancements.

The observations at Piñon Flats show that dynamic stresses rather than static stresses generate the permeability enhancement. The evidence for the role of dynamic stress includes the fact that permeability always increases at the time of an earthquake regardless of the sign of the dilatational static stress change [Elkhoury et al., 2006]. If static stress changes were controlling
the permeability change, then some permeability decreases should have been observed for earthquakes that imposed compressional stresses in this region. In addition, the static stress changes at the well are orders of magnitude smaller than the dynamic stresses. However, the dynamic stress amplitudes (Peak Ground Velocity) measured on seismograms correlate well with the observed permeability change (Figure 1). Similar observations of earthquake-induced flow in streams and water level steps in wells also indicate that the permeability enhancement in those systems results from dynamic stressing associated with the passage of seismic waves [Brodsky et al., 2003; Davis and Elderfield, 2004; Manga et al., 2003; Montgomery and Manga, 2003; Manga and Wang, 2007].

The question of the physical mechanism responsible for permeability enhancement still remains. How do the small dynamic strains of the seismic waves like those in Figure 1 result in permeability enhancement effects that are clearly macroscopic? Moreover, how does an oscillatory stress of a finite duration result in a persistent permeability change? This proposal presents a focused strategy of combined laboratory and modeling work to clarify the mechanism of permeability enhancement from seismic waves.

The first steps in identifying the mechanism of permeability enhancement by oscillatory stresses are to reproduce the effect in the laboratory and establish the dependence of permeability increase on dynamic stress properties (amplitude, frequency, duration). We have made significant headway on this problem in preliminary work [Elkhoury et al., 2010] and completing this analysis will be the focus of the first phase of the project. Phase II will focus on diagnosing the underlying physics through careful analysis of laboratory data. In Phase III we will combine the results of both stages of the laboratory work via a modeling exercise informed by field observations of natural system.

![Figure 1](image1.png)

**Figure 1.** Change in permeability for two well-aquifer systems produced by regional earthquakes. The increase in permeability is plotted against peak ground velocity in the seismic waves from the earthquakes measured at the Piñon Flat Observatory in Southern California where the wells are located. The red squares are one well and blue circles are another [Elkhoury et al., 2006]. In each well, the permeability enhancement is a well-defined function of the peak amplitude of the seismic waves. Peak ground velocities of 1 cm/s correspond to elastic stresses of $10^5$ Pa.
Implications

Substantial effort has gone into developing techniques for reservoir permeability enhancement because of potential economic and societal benefit [Kostrov et al., 2001, Jackson et al., 2001, Roberts et al., 2003a,b]. One such technique is hydrofracture, which provides a targeted, near-well method for transient increases, but more pervasive engineering of the reservoir would be desirable. Another approach involves proppants to hold open fractures in a reservoir. The natural observations of Figure 1 suggest an alternative strategy of utilizing seismic waves.

Permeability increase caused by the passage of seismic (elastic) waves through a reservoir has been suspected for decades, but is not routinely exploited for large-scale production [e.g., Wright, 1980, Barabaranov et al., 1987; Beresnev and Johnson, 1994; Rojstaczer et al., 1995; Brodsky et al., 2003; http://www.onthewavefront.com/]. Some of the major barriers for greater use of seismic waves in engineering applications include a lack of empirical data documenting permeability enhancement as a function of wave properties (frequency and amplitude) and a poor physical understanding of the enhancement mechanism. In the course of the basic science work of Phase I and II of this proposal, we will address these two issues.

The systematic behavior shown in Figure 1 also suggests that permeability enhancements should be understood for effective design of long-term storage facilities such as those envisioned for carbon sequestration. Current sequestration study sites include locations in the intermountain US that can have ground motions within the range of effects in Figure 1.

History of the Proposal

A previous version of this proposal was submitted to the CMMI-Geomechanics Program in February 2009 and was transferred to the EAR-Hydrology Program and then to the EAR-Geophysics Program. The reviewers from the multiple communities raised a variety of issues that we have attempted to address. We have also now specifically targeted the work towards explaining the natural observations rather than developing the engineering applications and therefore this proposal has now been sent to the Geophysics Program.

Phase I: Assessing the Controlling Variables

The initial goal of the project is to obtain robust and quantitatively reproducible laboratory observations between permeability enhancement and dynamic stress properties such as amplitude, frequency and number of cycles of the applied oscillatory stresses. The field observations suggest that clearly defined relationships exist (Figure 1).

Our preliminary work, supported by internal funds, shows that a reproducible permeability increase can be generated in the laboratory. This preliminary work is described fully in Elkhoury et al., [2010]. As this paper is under review at the same time as this proposal, we outline the material from the manuscript below and include significant technical information in the extended caption to Table 1 and in the figures below. More details are available in the submitted manuscript (http://www.pmc.ucsc.edu/~seisweb/emily_brodsky/publications.php).

In the exploratory work, we applied sinusoidal oscillations of pore pressure to a fractured rock sample and measured the permeability response using the Penn State deformation apparatus (Figure 2). We fractured the rock samples in the pressure vessel under controlled true-triaxial stresses: \( \sigma_1 \) is vertical, applied via a piston and parallel to the eventual fracture plane, \( \sigma_2 \) is horizontal, applied via a piston and normal to the fracture plane, and \( \sigma_3 \) is horizontal, applied via
a confining pressure and parallel to the fracture plane (Figures 2 and 3). Fluid pressure is applied via two line-sources at the top and bottom of the eventual fracture plane (Figure 3).

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**Table 1:** Summary of stress conditions and sample dimensions for preliminary experiments. Each column lists the property for a single experimental sample. Each sample was subject to 1-3 sets of oscillations for 2-18 oscillations per set for a total of 50 oscillations over the four individual samples. The experimental procedure was as follows: intact samples of Berea sandstone were first placed under 20 MPa of normal stress on the incipient fracture plane and then subjected to hydrostatic stress of 9 MPa. Throughout the experiment, deionized water was forced through the saturated sample via servo-controlled pore pressures at the inlet and outlet (Figure 3). Then shear stress on the candidate fracture plane was increased to failure, and the fractures were sheared to net offsets of 3 to 4 mm. Mean values of pore pressure were ~ 3.0 MPa with pressure differential $\Delta P \sim 0.3$ MPa (Figure 4). Inlet- and outlet-flow were measured by two independent pressure intensifiers and flow rate $Q$ was obtained from digital data sampled at 10 Hz using a 24-bit recorder. For the preliminary experiments, the period and duration of the stress oscillation were 20 and 120 sec, respectively, and the amplitude, $A$, ranged from 0.02 to 0.3 MPa. We assumed water viscosity $\mu = 8.89 \times 10^{-4}$ Pa s for the effective permeability calculations.

The rest of the experiment proceeded without removing the newly fractured sample. The inlet pressure to the fracture was oscillated as the outlet pressure was kept fixed (Figure 4a). We measured the fluid flow rate before and after the oscillations. Effective permeability change was inferred from Darcy’s law. The elevation change along the flow path is <4 cm (corresponding to <0.4 kPa hydrostatic pressure) and the imposed pressure drop over the same sample length is at least 200 kPa. Since the gravitational contribution to flow is negligible we use Darcy’s law in terms of the pressure difference as

$$k = (\mu L/S) (Q/\Delta P),$$  \hspace{1cm} (1)

where $k$ is the apparent permeability, $Q$ is the volumetric flow rate, $\Delta P$ is the pore pressure differential across the sample, $\mu$ is viscosity of water, $L$ is flow path and $S$ is the cross-sectional area of the sample. Since pore pressure differential, sample volume and water viscosity (i.e. temperature) remain constant, flow rate changes map directly into effective permeability. The effective permeability of the dual-porosity fractured sample is not directly the micro-mechanical
permeability. However, the effective permeability provides a convenient bulk property measure that is roughly comparable to the integrated properties that are measured in the field.

![Figure 2. 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 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 on the candidate fracture plane. A latex jacket is used to separate pore fluid and confining pressure (See Figure 3). Elkhoury et al., [2010]](image)

We applied multiple oscillations to each experimental sample and waited up to 100 minutes between sets to allow permeability to recover its pre-oscillation value. We report changes in permeability as $\Delta k = k_a - k_{ref}$ where $k_a$ is permeability after the oscillation and $k_{ref}$ is the permeability before the first oscillation. Permeability values after the oscillations are obtained by averaging the permeability over a 2 sec window starting 10 sec after the oscillation. The 10 sec gap ensures that post-oscillation permeability is not affected by the oscillation itself.

Figure 4 shows that pore fluid pressure oscillations have a dramatic effect on permeability. Permeability shows a step increase after the oscillation followed by a gradual recovery. Both the inlet and outlet flow measurements show the same effect. This consistency between the inlet and outlet is important because it demonstrates a permeability change rather than a transient storage effect associated with the poroelastic response of the system. If water were stored and then squeezed out of the sample, the apparent permeability would be higher at the outlet. (Of course, permeability is a material property and the “apparent permeability” would in this case be an incorrect interpretation of a flow rate. However, apparent permeability is an interpretation of macroscopic observations of flow-rate that assists in evaluating the potentially confounding effects of storage.) Because the inlet and outlet flow rates are equal, the observed increase in flow rate represents a real change in the fracture permeability.

Our preliminary data show that pore pressure oscillations produce transient increases in the flow rate and permeability by as much as 50% (Figure 5). For amplitudes of fluid pressure oscillation in the range 0.02-0.3 MPa, transient increases in permeability scale with amplitude (Figure 5). The absolute values of transient permeability increase are in the range $2\times10^{-18}$ m$^2$ to $5\times10^{-16}$ m$^2$, and vary somewhat from sample to sample, but the dependence on amplitude is consistent. The reference permeability was somewhat higher for one of the experimental samples.
(p1605) because this rock was not subject to shear immediately after the fracture formed but at a later time during the experiment. In the other experiments, post-fracture shear reduced permeability and therefore lowered the reference permeability. To quantitatively compare permeability changes between experiments we normalized changes by $k_{ref}$. Figure 5b shows remarkable similarity between experimental samples, 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 $m = 2.1$ with a 95% confidence range given by the interval $[1.7, 2.5]$, the constant $f = 1.67$ with a 95% confidence interval of $[1.5, 1.8]$ and a goodness of fit measured by an $R^2 = 0.7$.

To the best of our knowledge, the transient increases in permeability reported here provide the first consistent experimental evidence of flow enhancement produced by oscillations in pore

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**Figure 3:** Outline of the experimental sequence. (a) Experiments started with an intact sample (dimensions are in millimeters). The area $A$ 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 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, 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.
pressure. Furthermore, the magnitude of the permeability enhancement increases systematically with increasing amplitude of the pore pressure cycles (Figure 5). Clearly, dynamic and transient pore pressure variations can produce a significant and persistent permeability change.

We propose to replicate and extend the preliminary results shown above. In the Penn State deformation apparatus, we will test several different geometries of natural rock samples: intact samples such as shown in Figure 3, pre-fractured samples with ground surfaces roughened to various degrees, intact rock core, rock core fractured along the axis and a saw cut sample with a sandwich of synthetic fault gouge of variable thickness and particle diameter. These samples will be subjected to both dynamic stressing applied directly to the solid and pore pressure oscillations. Permeability changes will be measured as a function of dynamic stress conditions. Frequency, amplitude, duration and mode of stimulation will be correlated with the permeability data to provide the desired empirical relations for the different systems. For comparison, pore pressure steps of comparable amplitude will also be applied. These tests will constitute the proposed work of Phase I.

Figure 4. (a) Example of pore pressure oscillations at the inlet (blue) with fixed pore pressure at the outlet (green). Pressure conditions before and after the oscillation are identical. (b) Effective permeability before and after the pore pressure oscillation shown in (a). Note difference in time scale with panel a; the oscillation and the time immediately afterward are not included here. The effective permeability is directly proportional to the flow rate via Equation (1). The two curves (blue and green) show the permeability measurements based on flow rates obtained independently at the inlet and outlet. 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. From Elkhoury et al. [2010].
Phase II: Evaluating the Microphysics

In the second phase, we will concentrate on identifying the microphysics behind the empirical relationships. The key data of Figure 5 requires a non-poroelastic process to explain the persistent permeability change from the oscillatory forcing. The field observations also seem to depend on the oscillatory, rather than quasi-static, stresses. The challenge of this stage of the work will be to identify the correct mechanism for translating the oscillatory stress excitations into a persistent permeability change.

The primary candidate processes are microfracturing of the rock, mobilization of particles that constrict flow within the fractures, and shear dilation of existing fractures. Microfracturing results in increased permeability by opening new pathways through the rock. Particle mobilization can clean existing fractures to create open conduits or clog fractures to close conduits. Shear dilation is an anisotropic effect due to a coupling between opening and shear when slip occurs on pre-existing fractures.

Each of these mechanisms provides a clear and testable hypothesis that will be investigated in the laboratory work:

1) Initiation of microfractures [Elliot et al., 1985] from the elevated fluid pressures could easily increase the permeability. Such fracture-enhanced permeability is common in the nearfield of faults [Caine et al., 1996, Mitchell and Faulkner, 2008].

Figure 5. (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 \( k_{ref} \) and the pressure amplitudes are normalized by the pore pressure differential, \( \Delta P \), driving the flow. When appropriately normalized, data collapses onto one curve (dashed line is Equation 2). Note that permeability increases by nearly two orders of magnitude for our range of amplitudes. From Elkhoury et al. [2010].
Microfracturing will have two observable effects that are distinct from the other two mentioned mechanisms. First, new microfractures heal slowly [e.g., Brantley et al., 1990] and therefore the baseline permeability is expected to change after each successive oscillation. Secondly, the samples subject to oscillatory pore pressure should have some evidence of the fracture damage after the rock sample is removed from the apparatus.

Our initial data argue against the microfracture hypothesis and suggest that this is not the correct mechanism [Elkhoury et al., 2010]. The first clue to the dominant mechanism in both the lab and the field is the recovery of permeability. Both the field and laboratory systems appear to return to the original permeability some time after the initial enhancement (Figure 6). In fact, recovery of permeability enhancement in the preliminary lab experiments is well-represented by a function of the form $D/t^{0.5}$ where $D$ is a constant and $t$ is the time since the permeability increase. 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].

![Figure 6](image)

**Figure 6.** (a) Permeability response to shaking at the Piñon Flat Observatory from the 1999 Hector Mine earthquake (Elkhoury et al. [2006]). (b) Permeability response to oscillatory changes in pore pressure as in Figure 4 above (from Elkhoury et al. [2010]). Notice the clear similarity between the two behaviors. At Piñon Flat 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. Dashed line shows fit to the permeability decay of the form $D/t^{0.5}$ where $D$ is a constant and $t$ is time.

If the permeability recovery holds through the new set of experiments, then microfracture is not the preferred mechanism. However, since the healing rates of microfractures are highly variable [Renard et al., 2000; Polak et al., 2003; Yasuhara et al., 2004], the search for fracture damage after the sample is removed from the apparatus will be carried out as well to be absolutely certain of the results. Thin sections of the samples will be taken after the dynamic oscillations and compared to samples that have been fractured, but not oscillated. If microfracturing is occurring, the cracks should be visible under a petrologic microscope.

2) In particle mobilization, fines within the fractures are mobilized by seismically-induced oscillatory pore pressures, initially removing blockages and then re-occluding the fractures as driving pressure gradients abate. The unblocking hypothesis has been invoked for explaining field data of hydrological changes, but has not been fully investigated in the lab [Brodsky et al., 2003; Harrington and Brodsky, 2006; Elkhoury et al., 2006].
The test of this mechanism utilizes the inference that the degree of permeability enhancement should be affected by the degree of adhesion between the colloids and the walls and/or the degree of jamming in the case of granular particles lodged in pore throats [Sims et al., 1996, Chen et al., 2009]. Mechanical colloid detachment has been investigated previously, but has not been systematically studied for the kinds of oscillatory forcing that accompany a seismic wave [e.g., Bergendahl and Grasso, 2000]. The previous work has shown that colloid attachment and detachment from capillary or fracture walls is sensitive to ionic strength of the pore fluid [Mays and Hunt, 2005, 2007]. Therefore, this mechanism can be explored by applying pore pressure oscillations of different amplitudes and frequencies with fluids of different ionic composition, to examine the evolution of permeability. If pore detachment is the primary mechanism of permeability enhancement, adjustment of the ionic strength should affect the relationships between permeability and dynamic stress amplitude established in Phase I. We will repeat the experiments of Phase I with varying ionic strengths to test this hypothesis.

3) Shear dilation relies on the seismically-induced excess fluid pressures in the fractures to reduce effective stresses, induce shear-slip and shear-dilation in the fractures thereby increasing permeability [Olsson and Brown, 1993]. In this case, the slow reduction in permeability is due to either creep of the bridging asperities [Peach and Spiers, 1996], or changes in effective stress as fluid pressure dissipates [Bai and Elsworth, 2000].

Previous work shows that stress oscillations degrade friction and may cause failure of granular fault gouge and/or bare rock surfaces in contact [e.g. Richardson and Marone, 1999; Boettcher and Marone, 2004; Hong and Marone, 2005; Savage and Marone, 2007, 2008; Johnson et al., 2008; Faoro et al., 2009]. Similarly, velocity-stepping experiments [Samuelson et al., 2009] have illustrated that a quasi-static increment in shear velocity results in a single-sensed change in porosity in a given material irrespective of the direction of shearing. These changes in porosity ($\phi$) or fracture aperture ($b$) are typically dilatory [Samuelson et al., 2009] and since permeability scales positively with augmented porosity ($k \sim (\phi/\phi_0)^3$) or fracture aperture ($k \sim (1+db/b_0)^3$) then permeabilities are anticipated to increase, regardless of the sense of shear loading.

If shear dilatancy is the dominant mechanism, then shear stresses applied directly to the solid sample should mimic the behavior of the pore pressure oscillations [Elsworth and Goodman, 1986]. Since the Penn State triaxial device was originally designed to apply just such stresses to the rock samples, the instrument provides a straightforward test of the shear dilation mechanism. The entire suite of experiments in Phase I will be reproduced in Phase II using shear stresses applied to the solid pistons rather than pore pressure oscillations. If the same permeability enhancement behavior is recovered (including the frequency and amplitude dependencies), then shear dilation is the likely dominant mechanism.

In addition to each of the above tests, we will carefully monitor poroelastic effects [Elsworth and Bai, 1992] and measure specific storage effects in the investigations of each mechanism. Our preliminary experiments show no such effects as indicated by the equality of measured flow rate at the fracture input and output (Figure 4b). However, we need to test the extent to which this observation holds over a wider range of conditions. The storage monitoring is important in ascertaining that the observations reflect true permeability changes.
Both the particle mobilization and shear dilation hypothesis are only effective in the presence of topographic roughness on the fracture plane. Preliminary results suggest that this is the case as we have not been able to reproduce the results of Figure 5 with saw-cut, smooth samples. Moreover, the degree of permeability enhancement should be dependent on the degree of roughness for both mechanisms. As an additional tool to diagnose mechanisms, we will test and quantify this prediction by measuring the roughness of the fracture after each experiment using the UC Santa Cruz Zygo Newview 7000 White Light Interferometer (Figure 7). The instrument can easily measure fracture roughness to sub-micron resolution. We will compare the measured roughness of each sample to the enhancement factor \( m \) of Eq. 2 to investigate the role of topography on controlling the permeability change. We can also use the results to assess the consistency with our effective permeability measurements with previous work on permeability in a rough fracture under stress [e.g., Nemoto et al., 2009].

![Figure 7. Example of white light interferometer topographic data of a natural fault surface. Data shown covers a 1 mm x 1 mm square with an elevation range from blue to red of 133 microns [e.g. Piggott and Elsworth, 1992]](image)

**Phase III: Upscaling**

The last phase of the project will focus on developing a theoretical and numerical framework for applying the laboratory results to the field. Our aim will be to provide predictive power geared towards the selection of amplitudes and frequencies of the oscillatory stress best suited for efficient permeability enhancement in natural systems. The work will connect the thresholds in Phase I with the microphysics elucidated by Phase II.

A preliminary numerical model developed at UC Santa Cruz generates aquifer-scale effective permeability changes by locally perturbing the permeability structure [Doan et al., 2007]. The model computes pressure changes in a homogeneous, isotropic aquifer due to input seismic waves and the resulting local flow in and out of a well. Following previous work on dilatationally driven flows in porous media, water is driven in and out of the well by a farfield head oscillation using Darcy’s Law combined with a constant head boundary condition at the edge of the well [Hsieh et al., 1987]. Whenever and wherever the flow rate, \( u \), exceeds a
threshold value, $u_{th}$, the local permeability suddenly increases by a modeled factor $C$. Larger seismic waves create larger pressure changes and thus generate flows fast enough to increase the permeability in a larger volume around the well. Results for such calculations are shown in Figure 8 where phase is a direct measure of permeability as discussed in Elkhoury et al. [2006].

The simplified bulk model is successful at predicting some of the permeability changes in Figure 1 based on the recorded seismic waves and a simple hydrological structure (Figure 8), but has no physical process constraining the value of the flow threshold for permeability enhancement. The threshold $u_{th}$ is arbitrarily fit to the field data as is the permeability enhancement factor $C$. The goal of Phases I & II of the proposed work will be to provide such a physical process that then can be integrated into the model to constrain $u_{th}$ and $C$ in a self-consistent way. For instance, Phase I & II will provide refinement or replacement of Eq. 7. The resulting upscaled model will then be used in a predictive sense to compare with the data in Figure 1.

Once the homogenous model like that in Figure 8 is established, the same calculation will be repeated with a range of permeability models including dual porosity and anisotropic structures. The phase change will be affected by the permeability structure through the resultant changes in the forced velocity $u$. We will perform a sensitivity analysis to determine how robust the results of Figure 8 are in view of probably heterogeneity and therefore assess how likely the laboratory processes are to generate macroscopically observable effects.

A mechanistic approach is also feasible using rate-state behaviors to represent the augmentation of permeability and its ultimate reduction to background magnitudes. Empirical rate-state models have been shown capable of representing a broad range of behaviors including fault strength and healing rates together with related physical properties such as the evolution of porosity implicated in mechanisms of dilatant hardening [e.g. Samuelson et al., 2009, 2010]. These models for quasi-dynamic shear-related hardening evolution will be used to develop macroscale models for permeability evolution. Spring-slider models [Samuelson et al., 2010] enable the evolution of local velocity to be followed for an initial impulse that accommodates the stiffness of the surrounding loading system. This allows the evolution of local porosity to be followed and this porosity evolution to be converted into an equivalent permeability that may be examined to determine its congruence with both field and laboratory observations.

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Figure 8. Simulated and observed changes in tidal phase lag, which is the observable proxy for permeability, in a well at the Piñon Flat Observatory in Southern California at the time of regional earthquakes. The dashed line has a slope of 1 and indicates the values at which the predictions would match the observations.

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References


Coble, R.W., (1965), The effects of the Alaskan earthquake of March 27, 1964, on ground water in Iowa, Iowa Acad. Sci, 72, 323–332.


